MODELING AND ANALYSIS OF PHOTOVOLTAIC-BASED INDUCTION MOTOR-DRIVEN ELECTRIC VEHICLE SYSTEM

Thesis Submitted for the Award of the Degree of

DOCTOR OF PHILOSOPHY

in

Electrical Engineering

By

Vinay Anand

Registration Number: 41900706

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LOVELY PROFESSIONAL UNIVERSITY, PUNJAB

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Transforming Education Transforming India

LOVELY PROFESSIONAL UNIVERSITY, PUNJAB

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DECLARATION

I, hereby declare that the presented work in the thesis entitled "**Modeling and Analysis of Photovoltaic based induction motor driven Electric Vehicle System**" in fulfillment of the degree of **Doctor of Philosophy (Ph. D.)** is the outcome of research work carried out by me under the supervision **Dr. Himanshu Sharma**, working as Assistant Professor, in the Department of Electronics and Electrical Engineering of Lovely Professional University, Punjab, India, and Co-Supervision of **Dr. Bhagwan Shree Ram**, working as Professor, in the Department of Electrical Engineering of Nalanda College of Engineering Nalanda, Bihar, India. In keeping with the general practice of reporting scientific observations, due acknowledgments have been made whenever the work described here has been based on the findings of other investigators. This work has not been submitted in part or full to any other University or Institute for the award of any degree.

Vinay Anand

(Signature of Scholar)

Vinay Anand

Registration No.: 41900706

Electronics and Electrical Engineering

Lovely Professional University,

Phagwara Jalandhar Punjab, India

CERTIFICATE

This is to certify that the work reported in the Ph. D. thesis entitled **Modeling and Analysis of Photovoltaic based induction motor driven Electric Vehicle System** submitted in fulfillment of the requirement for the reward of degree of **Doctor of Philosophy (Ph.D.)** in the School of Electronics and Electrical Engineering, is a research work carried out by **Vinay Anand, Registration No 41900706**, is bonafide record of his original work carried out under my supervision and that no part of thesis has been submitted for any other degree, diploma or equivalent course.

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ABSTRACT

Transportation is like a lifeline for passengers traveling daily from one place to another in India, along with a working professional. Recent research indicates that China has 230 automobiles per 1000 inhabitants, while India has 210. It is predicted that by 2050, the combined number of automobiles in use in China and India will surpass that of the entire world, with 1.1 billion vehicles in these two countries alone. The average number of people riding in a single four-wheel drive vehicle in the United States is 1.65, indicating a significant underutilization of the current vehicle size. Therefore, both academics and businesses need to give the inefficiencies and flaws in individual mobility platforms top importance. The increasing cost of fuel and the huge amount of pollution in the environment force us to think about the electrification of vehicles. Every country's economy and growth are significantly influenced by the use of electricity. For the economy to grow sustainably, adequate infrastructure must be developed and maintained. The primary drivers of a country's development are its power sectors, such as Electricity is necessary for modern societies. There are plenty of resources to produce electric power. Conventional energy sources, such as thermal sources, are the primary producers of power: hydroelectric, nuclear, oil and gas-based, and hydroelectric plants. The current strength system also includes a variety of non-traditional energy sources in addition to traditional sources, including solar, tidal, geothermal, wind, and so forth. These are known as renewable energy sources that are available freely and abundantly in the environment. The escalating demands of daily travel in India, particularly for working professionals, underscore the critical role of transportation as a lifeline. Against the backdrop of rising fuel costs and environmental pollution, this research explores the imperative of electrifying vehicles, given the profound impact of electricity on a country's economy and growth. The thesis unfolds against the backdrop of the changing energy landscape, where conventional and non-traditional sources coexist. The load requirements in India are rapidly evolving, necessitating a focus on large power-generating capacity to meet the growing electricity

demand. Simultaneously, environmental concerns are escalating due to the detrimental impact of conventional automobiles on air quality and public health. The main focus of this research is to explore the possibility of addressing issues associated with charging electric vehicle batteries, ensuring durable motors, maintaining reliability, and achieving cost efficiency. Its objective is to offer a thorough insight into the technical, environmental, and social aspects of electric transportation. The shift towards environmentally friendly transportation has led to extensive exploration and advancement in electric vehicle (EV) technology. This investigation commences with a comprehensive examination of diverse electric motor technologies, battery setups, and control methodologies. Utilizing MATLAB simulations, it evaluates the operational attributes of Induction Motors (IMs) and Brushless DC (BLDC) Motors. An evaluative comparison, taking into account factors like torque density, efficiency, and cost-efficiency, serves as the foundation for suggesting the most suitable motor choices for varying vehicle categories and usage conditions. As the adoption of electric vehicles continues to grow, the impact on the power system becomes a critical consideration. The trend toward eco-friendly transportation has spurred significant research and progress in electric vehicle (EV) technology. This research begins by thoroughly analyzing various electric motor technologies, battery configurations, and control approaches. Through MATLAB simulations, it assesses the performance characteristics of both Induction Motors (IMs) and Brushless DC (BLDC) Motors. This comparative analysis, considering factors such as torque output, efficiency, and cost-effectiveness, forms the basis for recommending optimal motor options tailored to different vehicle types and operating conditions. The objective is to develop a holistic approach that not only enhances the environmental benefits of electric mobility but also ensures stability and reliability through efficient electric motors in terms of reliability, robustness, and cost-effectiveness. Beyond technical considerations, the study investigates human-machine interaction and user experience in electric vehicles. A life-cycle assessment is carried out to evaluate the comprehensive environmental effects of electric vehicles, considering elements like production, energy origins, and disposal at the end of their lifespan. The goal is to provide a nuanced examination of the environmental footprint of electric mobility and guide future developments toward greater sustainability. The research begins by defining the research domain as the

modeling and analysis of PV-based induction motor-driven electric vehicle systems. The choice of this topic is driven by the imperative to shift from fossil fuels to electric transportation due to their economic and environmental consequences. The central focus on electric motors, as the primary component of electric vehicles, is established, leading to a detailed exploration of the performance parameters of BLDC and Induction motors. The discussion then shifts to the electric energy source for powering the electric motor, advocating for solar power due to its abundance and availability in the environment. The limited number of charging stations and the finite battery life of electric vehicles reinforce the need for alternative energy sources. Solar energy emerges as a viable solution, particularly for scenarios where electric vehicles are parked outdoors, providing a slow charging process that extends the battery's lifespan. The research extensively examines the performance of induction motors, specifically focusing on Squirrel Cage Induction Motors (SCIMs), which constitute over 82% of the industry. The study evaluates IM applications from a different perspective than BLDC motor applications, providing mathematical models for electric motors in solar-powered electric vehicle applications. MATLAB/Simulink simulations illustrate the performance of BLDC Motors and Induction Motors based on proposed PV-based induction motor-driven EVs.

In summary, this thesis significantly adds to the ongoing discussion about electric vehicles by thoroughly examining recent research and advancements. The results provide valuable perspectives for policymakers, industry participants, and researchers working to enhance electric vehicle technologies. The suggestion to implement induction motor-based solar vehicles emerges as a promising approach to address issues such as battery longevity, range constraints, and environmental consequences. The goal of this study is to steer forthcoming innovations in electric transportation towards sustainability and effectiveness, paving the way for a more environmentally friendly and dependable transportation future.

Keywords: BLDC Motor; Electric Vehicle; Induction Motor; MATLAB; Performance Evaluation; Solar PV

PREFACE/ACKNOWLEDGMENTS

All praise goes to **Bhagwan Shree Ganesh Ji** who gave me power and the strength to start a journey towards accomplishing this task. May his infinite mercy be upon us.

I want to give my sincere thanks to my supervisor **Dr. Himanshu Sharma**, Assistant Professor, School of Electronics & Electrical Engineering, Lovely Professional University, Phagwara Jalandhar Punjab, India from the bottom of my heart and with great respect, and Co-supervisors **Dr. Bhagwan Shree Ram**, Professor, Electrical Engineering, Nalanda College of Engineering, Nalanda Bihar for their guidance, encouragement and valuable suggestions throughout my research work.

Dr. Himanshu Sharma has an optimistic personality with a helpful nature, he has always made himself ready to clarify my doubts and motivate me every moment, and it was a great opportunity to work under his supervision. Whenever I felt I was getting nowhere with my research goals, he always clarified. Their diligent work, systematic approach, and one-on-one assistance allowed me to finish this research project on scheduled time.

I want to thank everyone at Lovely Professional University for providing the necessary resources and setting so that I could finish my research project on schedule. Also, I like to thank the Division of Research & Development and the School of Electronics and Electrical Engineering for efficient help and encouragement in my entire Ph.D. journey.

Without the encouragement and support of wonderful people who inspired me throughout my Ph.D. studies, this thesis would not have been possible. I sincerely express my gratitude to everyone who helped me during this work of research in the field of electric vehicles.

I am deeply grateful to my parents for their abundant blessings, consistent support, sacrifices, and unwavering faith in my capabilities. Their steadfast support has been the foundation upon which my academic aspirations have flourished. I sincerely appreciate my wife Rashmi, who has always supported and cooperated with me during the challenging times I have been conducting research. I am also immensely grateful to my son Chiranjiv Aditya, whose curiosity and boundless energy have encouraged me a lot, about the importance of lifelong learning, his presence has added a unique and joyful dimension to this academic research pursuit.

Finally, to all my friends and colleagues who have shared their knowledge, experiences, and camaraderie, I thank you for contributing to the intellectual tapestry of this academic exploration.

Date: 25.02.2025 Vinay Anand

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Abbreviations

ICE	Internal Combustion Engine
CO	carbon monoxide
NOx	nitrogen oxides
PM	particulate matter
NEMMP	National Electric Mobility Mission Plan
ARB	Air Research Board
CO2	Carbon dioxide
VOCs	Volatile organic compounds
IPCC	Intergovernmental Panel on Climate Change
IEA	International Energy Agency
EV	Electrical Vehicle
BEV	Battery Electric Vehicle
HEV	Hybrid Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle

FCEV	Fuel-Cell Electric Vehicle
DC	Direct Current
IM	Induction Motor
PMM	Permanent Magnet Motor
SRM	Switched Reluctance Motor
PF	Power Factor
PMSM	Permanent Magnet Synchronous Motor
BLDC	Brushless Direct Current
Si	Silicon
Ga	Gallium
Cd	Cadmium
As	Arsenic
Ge	Germanium
EMF	Electromotive Force
KW	Kilo Watt
HP	Horse Power
IGBT	Insulated Gate Bipolar Transistors
PWM	Pulse Width Modulation

VSI	Voltage Source Inverter
OC	Open-Circuit
SC	Short-Circuit
TRIAC	Triode for Alternating Current
BLDCMD	Open-End Winding Brushless DC Motor Drive
MATLAB	Matrix Laboratory
$\boldsymbol{\omega_{el}}$	Electrical angular velocity
$\boldsymbol{\omega_{me}}$	Mechanical angular velocity
$\mathbf{f_{el}}$	Electrical frequency
P	Number of poles
RSE	Renewable Source of Energy
ICV	Internal Combustion Engine Vehicle
DOD	Depth of Discharge
GHI	Global Horizontal Irradiance
DNI	Direct Normal Irradiance
KWH	Kilowatt hour
ICE	Internal Combustion Engine

SCIMs	Squirrel Cage Induction Motors
IC	Internal Combustion
NEVs	Neighborhood Electric Vehicles
BMS	Battery Management System
SOC	State of Charge
SOH	State of Health
V2G	Vehicle-to-Grid
EV	Electric Vehicle
NITI	National Institution for Transforming India
FAME	Faster Adoption and Manufacturing of Electric Vehicles in India
AC	Alternating Current
$\mathbf{F_{rr}}$	Rolling Resistance Force
$\mathbf{F_{aero}}$	Aerodynamic Drag Force
$\mathbf{F_{hc}}$	Hill Climbing Force
$\mathbf{F_{xl}}$	Acceleration Force
RPM	Revolution Per Minutes
FOC	Field-Oriented Control
MPPT	Maximum Power Point Tracking

PMDC	Permanent Magnet Direct Current
RETs	Renewable Energy Technologies
SPV	Solar Powered Photovoltaic
V2H	Vehicle to Home
ZEV	Zero-emission vehicle
$\mathbf{t}$	Time parameter
$\mathbf{I_{rated}}$	Rated (RMS) current
$\mathbf{R_s}$	Stator resistance
$\mathbf{n_{rated}}$	Rated speed
$\mathbf{s_{rated}}$	Rated slip
$\mathbf{V_{rated}}$	Rated phase-to-phase (RMS) voltage
$\boldsymbol{\omega}$	Angular speed at the rated supply frequency
$\mathbf{PF_{rated}}$	Rated power factor
$\boldsymbol{\phi}$	Phase angle between voltage and current
Rr	Rotor resistance
$\mathbf{L_m}$	Magnetizing inductance
$\mathbf{L_s}$	Stator inductance
$\mathbf{L_r}$	Rotor inductance
$\mathbf{f}$	Supply frequency
$\boldsymbol{\eta}_{\mathbf{rated}}$	Rated efficiency
$\mathbf{T_e}$	Air-gap torque

$\mathbf{T_{shaft}}$	Shaft torque
$\mathbf{\omega_r}$	Rotor rotation speed
$\mathbf{P_{input}}$	Electrical real power (input power)
BSS	Battery Swapping Station
BS	Battery Swapping

1 The opening section

1.1 Study about the Introduction of Electric Vehicles (EVs)

Electric vehicles (EVs) represent a groundbreaking transformation within the automotive industry, aiming to address environmental concerns, reduce dependence on fossil fuels, and mitigate the impacts of climate change. While the concept of electrically operated vehicles traces back to the early 1800s, recent progress in motor technology, advancements in battery systems, government support through incentives, and an increasing awareness of environmental issues have significantly expedited their advancement and acceptance. The utilization of energy significantly influences the economic progress and advancement of every country. For the sustainable prosperity of economic activity, it is necessary to establish and maintain adequate infrastructure. The country's electricity sectors - modern societies need electricity to function. There are many means available to generate electricity. The most important sources of power are traditional energy sources such as thermal sources, nuclear energy, oil and gas plants, and hydropower. The current system can utilize various alternative energy sources such as solar, tidal, geothermal, and wind, in addition to traditional sources. In India, there is a swift evolution in the demand for freight. The power infrastructure and economically viable activities are fully equipped to cater to the substantial power generation requirements to address the escalating electricity needs. Furthermore, the escalating prevalence of conventional vehicles in traffic exacerbates environmental issues regularly. The detrimental emissions from traditional vehicles pose a threat to the physical health of all living organisms. Globally, individuals are facing health issues caused by harmful gases produced from burning fossil fuels. This has led to a growing interest in electric vehicles as a solution to reduce energy usage and address climate challenges. It's important to note that this thesis will concentrate on modeling and analyzing PV-based Induction Motor Electric Vehicle Systems. The rationale behind selecting this subject lies in the imperative need to substitute fossil fuels with electrified transportation, driven by heightened costs and escalating environmental pollution. Given that electric motors constitute the primary component of electric vehicles (EVs), we delved into a comprehensive examination of these motors and established benchmarks for assessing the efficiency of both BLDC and induction motors.

Afterward, it is essential to explore another crucial aspect of electric vehicles: the origin of the electrical power that propels the electric motor. However, considering the scarcity of charging stations and the extended battery lifespan affected by environmental factors, transitioning to solar energy becomes a viable alternative. Furthermore, solar energy can be harnessed to charge an electric motor parked outdoors at home or the workplace. Battery life can also be extended by power charging. This thesis examines the complete operation of Induction Motors (IM). Induction motors with three phases are widely prevalent and commonly encountered in various industrial settings. They are potentially electric vehicle engines and have several advantages, such as easy maintenance, high waveform reliability, robust and simple construction, and almost constant speeds from zero to full. Also, mathematical models and IM applications of electric motors for solar electric vehicles are reviewed from a different perspective than BLDC motor applications. In addition, the performance of BLDC and induction motors was demonstrated using MATLAB/Simulink based on the proposed PV-based induction motor electric vehicles. Researchers interested in EVs with limited battery life, and in general those who work well with EV solutions with electric motors, would greatly benefit from this study.

1.2 Outdoor air Pollution

Research has consistently identified vehicles as the primary source of outdoor pollution in the environment. Various studies have highlighted their significant contribution to environmental pollution, as depicted in Figure 1-1.

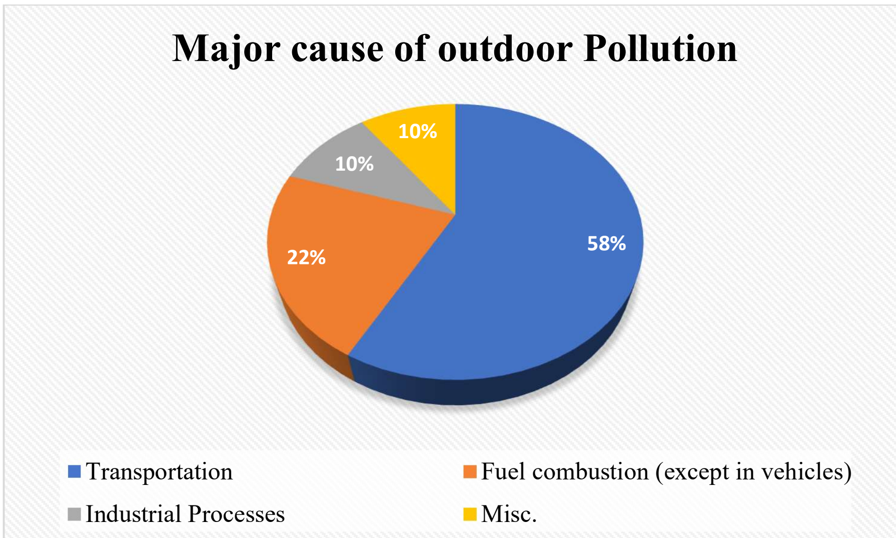

Figure 1-1-Pollution Causes

1.3 Internal Combustion Engine

The primary cause of vehicle pollution is the combustion of fossil fuels [1], particularly gasoline and diesel, in internal combustion engines. The process leads to the release of compounds such as carbon monoxide (CO), nitrogen oxides (NOx), particulate matter (PM), and volatile organic compounds (VOCs) into the atmosphere, thereby adding to environmental pollution [2]. Internal combustion (IC) engines play a crucial role in various sectors, powering automobiles, industrial machinery, and generators which consume fossil fuels and other energy sources shown in Figure 1-2. However, their widespread use is associated with significant environmental and health concerns due to the emission of pollutants. Research has consistently highlighted the adverse health effects of these pollutants, with respiratory and cardiovascular diseases being prominent concerns [3].

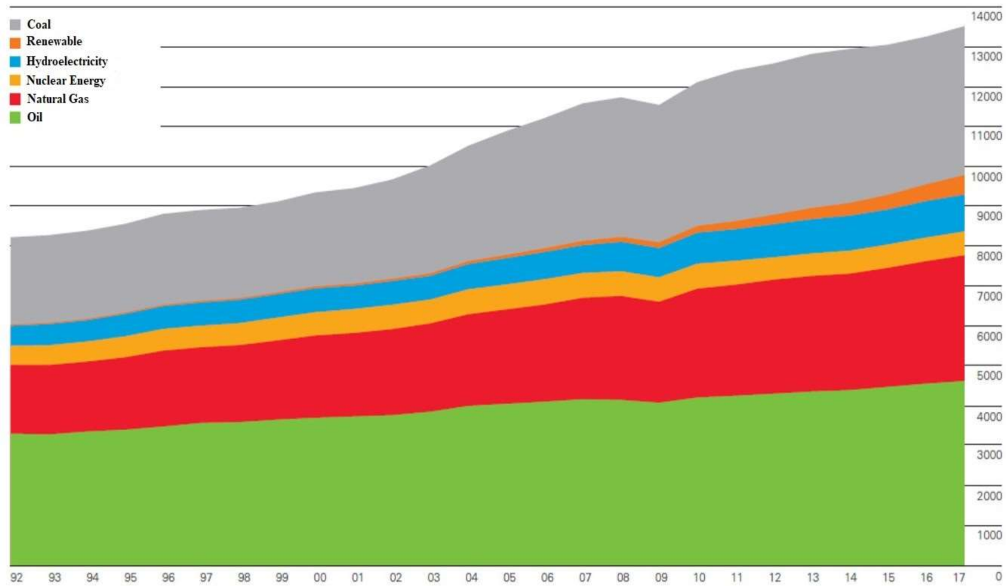

Figure 1-2- Source of Energy Consuming

A study published in a reputable journal emphasized the detrimental impact of IC engine emissions on human health. The diagram provided shows the elements of IC engine exhaust and the emissions it releases, including nitrogen oxides (NOx), particulate matter (PM), carbon monoxide (CO), and volatile organic compounds (VOCs). These emissions are associated with respiratory conditions such as asthma and chronic obstructive pulmonary disease (COPD), as well as cardiovascular issues like heart attacks and strokes. Efforts to mitigate these health risks have led to advancements in emission control technologies, including catalytic converters and cleaner fuel formulations. Additionally, the growing interest in electric vehicles and alternative propulsion systems aims to reduce the reliance on traditional IC engines, promoting a cleaner and healthier environment. Policymakers, researchers, and industry stakeholders need to work together to find a middle ground that considers energy efficiency, economic factors, and public health concerns when dealing with the issues linked to internal combustion engines [4].

1.4 Green House Gas Emission

Vehicles emit greenhouse gases, primarily carbon dioxide (CO2), which is a key factor contributing to climate change and the increase in worldwide temperatures. The Intergovernmental Panel on Climate Change (IPCC) regularly publishes assessment reports detailing human activities' impact on the climate, including transportation.

1.5 Brake and tire wear

Besides exhaust emissions, non-exhaust sources of pollution from vehicles, such as the wear and tear of brake systems and tires, contribute to the release of various pollutants. Here are some common pollutants and their effects on health.

1.5.1 Particulate Matter (PM)

Effect on Health: Inhalation of PM can lead to respiratory and cardiovascular problems, aggravate asthma, and cause other respiratory diseases. Fine particles can penetrate deep into the lungs and even enter the bloodstream.

1.5.2 Nitrogen Oxides (NO_x)

The impact on health: NOx can irritate the respiratory system, aid in the creation of ground-level ozone (a significant element of smog), and worsen respiratory ailments like asthma. Prolonged exposure might elevate the likelihood of respiratory infections.

1.5.3 Carbon Monoxide (CO)

The impact on health: Carbon monoxide disrupts the body's oxygen transportation process, resulting in symptoms like headaches, dizziness, nausea, and, at high levels, can be life-threatening.

1.5.4 Volatile Organic Compounds (VOCs)

The impact on health from volatile organic compounds (VOCs) includes the creation of ground-level ozone, leading to respiratory and eye irritation, and worsening pre-existing respiratory issues. Prolonged exposure may also be associated with specific types of cancer.

1.5.5 Sulfur Dioxide (SO_2)

Effect on Health: SO2 can irritate the respiratory system, particularly in individuals with asthma. Prolonged exposure may lead to respiratory diseases and cardiovascular issues.

1.5.6 Lead (Pb)

Effect on Health: While leaded gasoline is less common today, historic exposure to lead in exhaust emissions has been associated with developmental and neurological issues, especially in children.

1.5.7 Polycyclic Aromatic Hydrocarbons (PAHs)

Effect on Health: PAHs are known to cause cancer and have been associated with a higher likelihood of developing cancer, especially lung cancer. Additionally, they can lead to respiratory and cardiovascular problems.

1.5.8 Metals (e.g., Cadmium, Chromium, Nickel)

Effect on Health: Exposure to metals from brake and tire wear can have various health effects depending on the specific metal. Some may cause respiratory and cardiovascular issues, while others may be carcinogenic.

1.5.9 Noise Pollution

Effect on Health: While not a chemical pollutant, noise pollution from vehicles can contribute to stress, sleep disturbances, and hearing loss. Chronic exposure may lead to cardiovascular problems.

It is crucial to understand that the impact on health can differ depending on factors like the concentration of pollutants, how long one is exposed, individual vulnerability, and the general air quality. Taking steps to minimize and manage these pollutants is essential for both public health and environmental welfare [4].

1.6 Urban Air Quality

The concentration of pollutants due to numerous vehicles shown in Figure 1-3 is often higher in urban areas [5]. Initiatives aimed at mitigating environmental pollution caused by vehicular emissions, as depicted in Figure 1-4, encompass the advancement and acceptance of electric vehicles (EVs), enhancements in fuel efficiency, and advocacy for public transportation.

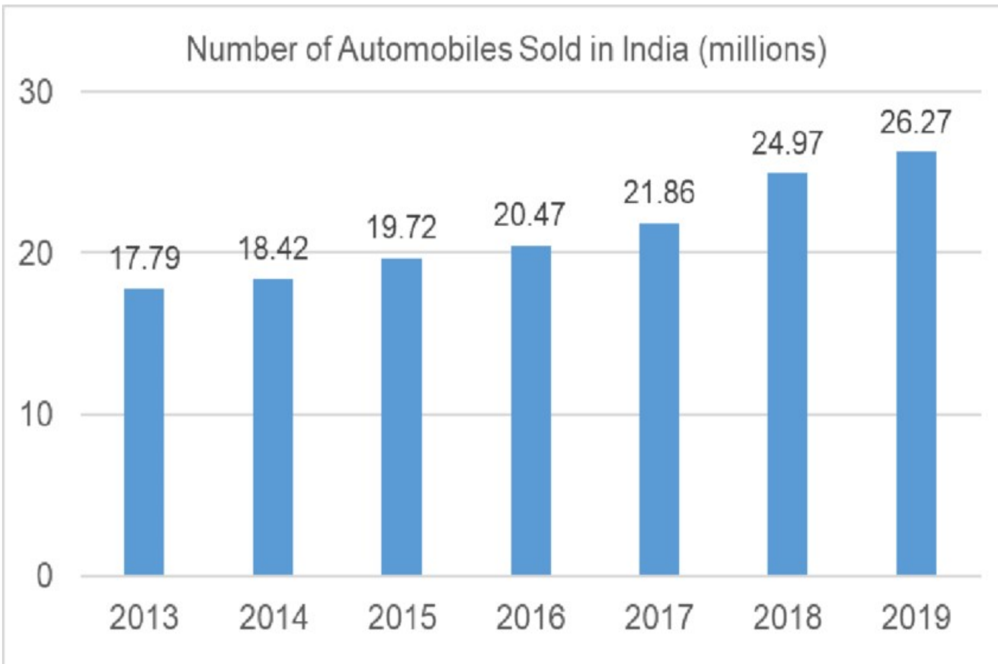

Figure 1-3- Source: Society of Indian Automobiles sold in India (in Millions)

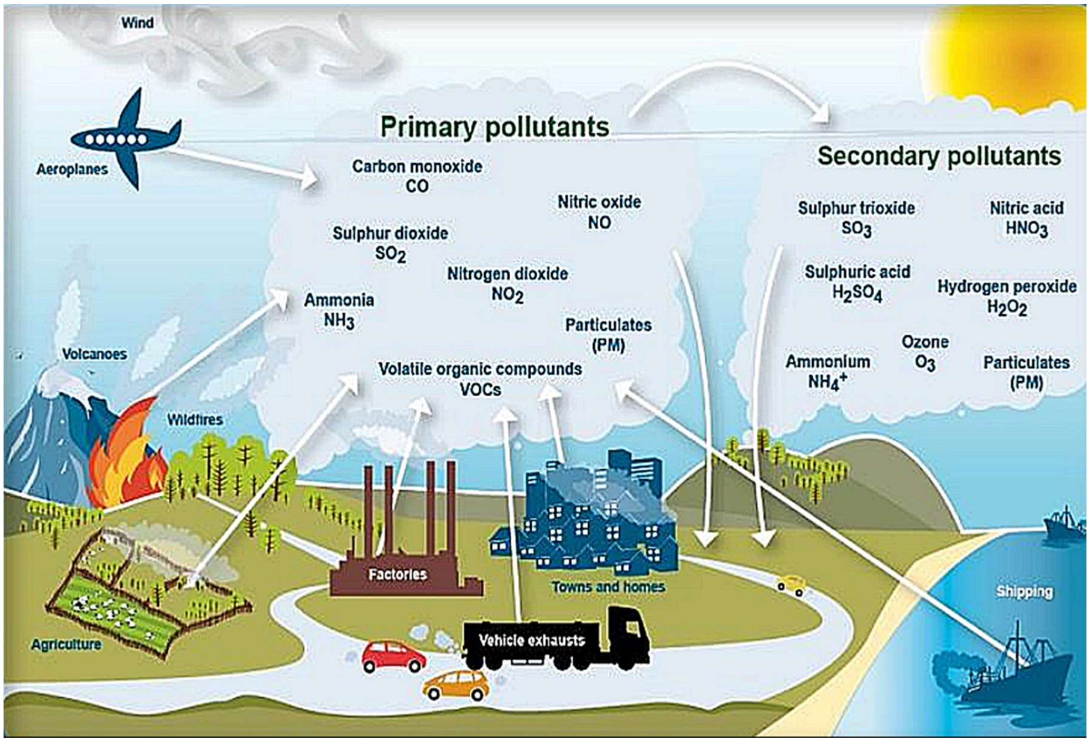

Figure 1-4-Toxic pollution-causing pollutants

1.7 E-mobility

The word "e-mobility" refers to the broad ideas and methods of using electric-powered technologies (e.g., Drivetrain). With the ability to charge outside, e-mobility transitions from using current fossil fuels, which release carbon emissions, to utilizing electrical power sources. Electromobility includes various types of vehicles, including fully electric cars, plug-in electric versions, hybrid models, and vehicles powered by hydrogen fuel cells. Driverless vehicles are also part of the electro-mobility landscape, with potential appearances on public roads as proposed by several governments between 2021 and 2022. The concept of e-mobility is sometimes integrated with other innovations like microcontrollers and sensors to enhance overall vehicle energy efficiency. Additionally, certain battery-operated electric vehicles incorporate solar energy, serving as an alternative charging method and contributing to prolonged battery life.

1.8 Historical Overview of EV

Early Concepts (19^{th} Century): The idea of electric vehicles has its origins in the 19th century, as pioneers such as Thomas Davenport and Thomas Parker engaged in trials involving carriages propelled by electricity. However, the limited energy storage capacity of early batteries hindered widespread adoption. After realizing the threat posed by the depletion of finite fossil resources and environmental problems, all nations around the globe are becoming more interested in exploring new energy alternatives. Reducing the quantity of emissions from conventional vehicles that are produced when fossil fuels are burned could be achieved by using coordinated electric vehicles for transportation. Although electric vehicles seem to be increasingly prevalent in contemporary times, their history holds surprising origins. Thomas Davenport crafted the inaugural non-rechargeable electric vehicle, resembling a tricycle, in 1834. The invention of lead acid batteries occurred in 1874, contributing to the development of electric vehicles. David Salomon achieved notable success in creating electric vehicles powered by rechargeable batteries. In 1884, the Electric Carriage and Waggon Company introduced the renowned "Electrobat," marking a significant milestone in the early history of electric vehicles [6].

1.9 Revival and Challenges (20th Century)

The late 20th century witnessed a renewed fascination with electric vehicles, prompted by apprehensions regarding air pollution and reliance on oil. During the 1990s, the automotive industry unveiled electric vehicle models like the General Motors EV1 and Toyota RAV4 EV. However, despite the initial excitement, issues such as restricted range and elevated expenses contributed to a waning interest in electric vehicles.

1.9.1 Modern Era (21st Century)

The automotive industry in the 21st century has undergone a significant transformation, particularly with the resurgence of interest in electric vehicles (EVs). This renewed emphasis can be attributed to several factors, including advancements in battery technology, increasing environmental awareness, and supportive policy measures. A key factor driving the growth of electric vehicles is the continuous enhancement of battery technology. In recent years, there have been substantial improvements in lithium-ion batteries, leading to increased efficiency, cost-effectiveness, and higher energy storage capacities. These advancements have addressed major concerns like limited range and long charging times, thereby enhancing the overall attractiveness of electric vehicles. The increased focus on the environment has been instrumental in the renewed popularity of electric vehicles. As worries regarding climate change and air quality have intensified, there is a greater acknowledgment of the environmental consequences associated with conventional internal combustion engine cars. Electric vehicles, being emissions-free, are now seen as a greener and more environmentally sustainable option, in line with international endeavors to minimize carbon emissions and address climate change. Government policies and global initiatives have significantly hastened the adoption of electric vehicles. Numerous nations have implemented various incentives, subsidies, and regulations aimed at promoting the growth and acceptance of electric vehicles. These strategies encompass tax benefits for purchasers of EVs, funding for charging infrastructure expansion, and more stringent emission standards for conventional automobiles. Such governmental backing has fostered a favorable environment for the expansion of the electric vehicle sector.

In this dynamic scenario, companies such as Tesla have played a pivotal role. Under the leadership of visionary entrepreneur Elon Musk, Tesla has been a frontrunner in the electric vehicle revolution. The introduction of innovative models like the Tesla Roadster and the Model S demonstrated the potential for high-performance electric vehicles, challenging the traditional notion that electric cars compromise on speed and luxury. Tesla's success not only showcased the market feasibility of electric vehicles but also motivated traditional automakers to increase their investments in electric vehicle research and development to stay competitive.

The automotive sector has undergone a diverse transformation in the 21st century, driven by technological advancements, environmental awareness, and favorable regulations. This convergence has led to a heightened emphasis on electric vehicles, fundamentally altering the trajectory of transportation.

1.9.2 Global Policy and Initiatives

The Indian government has taken proactive steps to promote a sustainable and environmentally friendly future, with a strong emphasis on electric vehicles (EVs). Key initiatives such as the Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME-I) and its follow-up, FAME-II, highlight the government's dedication to this cause. FAME-I, initiated in 2015, played a pivotal role in advancing India's electric mobility efforts by focusing on the growth, production, and adoption of electric and hybrid vehicles. This initiative aimed to minimize vehicle emissions and facilitate a shift towards cleaner and more sustainable transportation options. The policy included a range of measures, such as manufacturers' incentives, buyers' subsidies, and investments in charging infrastructure. Building upon the success and insights gained from FAME-I, the Government of India introduced FAME-II in 2019 to further accelerate the adoption of electric vehicles. This comprehensive policy aimed to address the challenges the EV ecosystem faces by providing a more robust framework. FAME-II continued to incentivize electric vehicle manufacturing, emphasizing electric two-wheelers, three-wheelers, and public transportation. Additionally, it placed a strong emphasis on charging infrastructure expansion to alleviate range anxiety and facilitate a seamless transition to electric mobility. Under FAME-II, financial incentives were extended to electric vehicle buyers, creating a more attractive proposition for individuals and businesses looking to invest in environmentally friendly transportation solutions. The policy also allocated funds for research and development in battery technologies, promoting indigenous innovation and reducing dependence on imported components. Furthermore, FAME-II emphasized the importance of promoting electric mobility in public transportation, with a focus on electric buses and shared mobility solutions. This approach aimed to not only reduce emissions but also create a visible impact by integrating electric vehicles into daily public transit.

In summary, the FAME-I and FAME-II initiatives of the Government of India exemplify a holistic approach towards fostering electric vehicle adoption. Through a combination of financial incentives, infrastructure development, and targeted support for manufacturers, these policies contribute significantly to global efforts in mitigating climate change and promoting sustainable transportation [7].

1.9.3 Advantages of EVs

In the context of India, the situation outlined raises significant concerns due to the country's vast population and the possible impacts of swift urbanization and industrial development. India is currently facing substantial air pollution challenges in numerous urban areas, leading to significant health hazards for its population. As of the present day, India is home to over 1.3 billion people, and it faces the challenge of accommodating a growing population while simultaneously addressing environmental issues. If the global population reaches 10 billion by 2050, as predicted, India's share in this growth will be substantial. The potential rise in the quantity of cars on streets, particularly if they persist in using internal combustion engines, represents a notable risk to air purity. Numerous urban areas in India are presently grappling with elevated levels of air contamination, with fine particulate pollution playing a crucial role in causing respiratory ailments and various health issues. The Air Research Board's findings in California, attributing thousands of deaths annually to fine particle pollution, highlight the urgency of addressing this issue. In India, where densely populated urban areas often lack adequate infrastructure and public transportation, the consequences of a surge in vehicle emissions could be devastating. To address the negative impact on air quality and public health, India should embrace sustainable transportation options. Introducing zero-emission vehicles fueled by renewable energy can offer a swift and efficient solution to lessen air pollution. This shift will not only diminish dependence on fossil fuels but also help decrease greenhouse gas emissions, aligning with international endeavors to address climate change.

In India's case, policy initiatives and incentives to promote electric vehicles, invest in renewable energy infrastructure, and improve public transportation systems are crucial. Additionally, raising awareness among the population about the environmental and health benefits of sustainable transportation is essential for successful implementation. By addressing the challenges posed by the potential increase in population and vehicle numbers through sustainable transportation, India can take significant steps towards creating healthier and more environmentally friendly urban environments [8].

1.9.4 Scope of EVs in India

With intentions to rise to the third rank by 2030, India's transport sector is currently the fifth largest in the world. Such a vast domestic market will require more transportation than the conventional fuel-intensive methods can provide. The Indian government is exploring alternative ways to provide economical, ecologically friendly, and effective transport services, lowering the country's reliance on foreign oil imports and their negative effects on public and environmental health. India would gain from the switch to electric vehicles in several ways, including the availability of trained labor in the skilled and industrial sectors and the country's wealth of renewable energy sources. 30% of private automobiles, 40% of buses, 70% of buses and trucks, and 80% of two- and three-wheelers might all be electrified by 2030. India is actively encouraging the widespread adoption of electric vehicles throughout the country by providing extra benefits to both customers and manufacturers at the national and local levels. It is crucial for a nation that heavily depends on coal for electricity generation to implement stringent measures to fulfill its future aspirations. The FAME II program, which addresses the reduction of oil, net energy, and net CO2 emissions over the life of two-, three-, and four-wheeled vehicles and buses as well as the operating costs linked to higher adoption levels by 2030, was assessed by NITI Aayog. An electric vehicle (EV) ecosystem is developing in India, where policies and programs are being created and put into place to support the early adoption of e-mobility solutions. One such tactic, FAME II [9], is positioned to accomplish its goal of increasing the use and manufacturing of EVs by building on the knowledge acquired from its predecessor[10].

1.10 Recent Research and Innovations

1.10.1 Battery Technology

Exploration in the field of battery technology has significantly contributed to improving the efficiency and travel distance of electric vehicles. Progress in lithium-ion batteries, solid-state batteries, and other innovative technologies seeks to tackle issues associated with energy density, charging durations, and overall longevity [11].

1.10.2 Vehicle-to-Grid (V2G) Integration

Scientists are presently researching how electric vehicles can be integrated into the electricity grid through Vehicle-to-Grid (V2G) technology. This innovation allows electric vehicles to not only receive power from the grid but also contribute surplus electricity back to it. This initiative promotes grid reliability and supports the integration of renewable energy sources [12]. In recent years, vehicle-to-grid (V2G) technology has gained traction due to its potential to optimize energy distribution and support grid stability, especially as the energy landscape shifts towards cleaner sources. This detailed review explores the concept of V2G, using surplus electricity from EVs to benefit both individual owners and the broader energy infrastructure. V2G is a technology enabling bidirectional power flow between electric vehicles (EVs) and the electrical grid. In this setup, EVs can charge during periods of low electricity demand and then feed surplus energy back to the grid during peak demand. This provides ancillary services such as peak shaving, voltage support, and frequency regulation, which are crucial to maintaining grid stability and efficiency.

The economic benefits for EV owners participating in V2G are potentially significant. Utility companies can offer compensation for surplus energy, transforming EVs into valuable energy assets. This not only provides a source of passive income for vehicle owners but also contributes to the economic feasibility of EV ownership.

1.10.2.1 *Technical Data in V2G Operations: Optimizing and Stabilizing the Grid:*

1.10.2.1.1 Battery Ratings and State-of-Charge (SoC):

Knowing the current SoC, battery capacity, and power output capability helps manage energy distribution effectively. Battery data, such as depth-of-discharge and charge/discharge cycles, helps prevent premature degradation, which is crucial in optimizing V2G systems without compromising battery health.

1.10.2.1.2 Capacity Aggregation:

By aggregating the power output of many EVs, V2G systems can provide sizable energy reserves. For instance, in California, it's estimated that if 10% of EVs were connected in V2G mode, they could offer up to 10 GW of power during peak demand.

1.10.2.2 ***Power Electronics and Grid Compatibility:***

1.10.2.2.1 Inverter and Power Electronics Specifications:

Bidirectional inverters that meet high-efficiency and grid-interactive standards are essential. Technical data on power conversion losses, harmonics, and efficiency ratings can optimize the bidirectional energy flow, limiting power losses and maintaining grid stability.

1.10.2.2.2 Voltage and Frequency Regulation:

EVs can help maintain grid voltage and frequency. V2G systems can adjust the voltage based on real-time data, reducing fluctuations that typically cause grid instability.

1.10.2.3 ***Grid Load Balancing and Renewable Integration:***

1.10.2.3.1 Demand Response and Peak Shaving:

V2G can offset demand peaks by feeding electricity back to the grid during high-demand periods. Real-time data on grid load and demand forecasts enable effective scheduling, which is critical for utilities aiming to manage peak demand.

1.10.2.3.2 Renewable Energy Balancing:

V2G can help balance intermittent renewables like solar and wind. Solar-powered EVs can be charged during the day and discharge surplus power during evening peaks, reducing the need for fossil-fuel-based peaking plants.

1.10.2.4 ***Policy, Economic Incentives, and Business Models:***

1.10.2.4.1 Net Metering Policies:

Under net metering, EV owners may be compensated at retail electricity rates for surplus electricity supplied to the grid. This system benefits EV owners financially, while utilities benefit from additional renewable energy supply.

1.10.2.4.2 Dynamic Pricing Models:

Through real-time energy pricing, V2G can dynamically adjust when EVs charge and discharge, capitalizing on low-cost periods to charge and high-cost periods to discharge. Utility companies could provide financial incentives for EV owners to supply power during peak times.

1.10.2.5 ***Technical Challenges in V2G Implementation:***

1.10.2.5.1 Battery Wear and Energy Loss:

While V2G is promising, frequent charging and discharging can shorten battery lifespan. To mitigate wear, high-quality battery management systems must monitor temperature, depth of discharge, and SoC.

1.10.2.5.2 Bidirectional Charger Standards and Harmonics Control:

Grid stability is sensitive to harmonics from power electronics in EVs. Technical standards like IEEE 1547 have evolved to regulate harmonics and support V2G, but harmonics management remains an area requiring robust solutions to minimize grid disturbances.

1.10.2.5.3 Interoperability and Infrastructure:

V2G requires interoperable communication between EVs, chargers, and the grid. Data standards like ISO 15118 enable smooth interactions, but widespread implementation is essential to ensure compatibility across vehicles, chargers, and utility systems.

1.10.2.5.4 Economic and Environmental Benefits of V2G:

With V2G, EV owners contribute directly to grid stability and earn financial benefits. Moreover, V2G can reduce dependency on fossil fuels during peak demand, lowering greenhouse gas emissions. In Tokyo, for example, V2G trials have demonstrated reduced energy costs and improved grid resilience, with EVs connected to the grid providing backup power for critical infrastructure.

While V2G technology holds immense promise, several obstacles remain, including a lack of standardized bidirectional chargers, the economic cost of frequent battery cycling, and the need for revised grid management policies to accommodate distributed energy resources. Addressing these challenges will require collaboration between stakeholders, government incentives, and continued research into advanced bidirectional charging and energy management technologies [13].

1.10.3 Autonomous Electric Vehicles

The ongoing research focuses on the convergence of electric and autonomous vehicle technologies. Combining self-driving features with electric vehicles has the potential to improve efficiency, decrease traffic incidents, and transform city transportation [14].

1.10.4 Circular Economy and Sustainable Materials

Researchers are currently examining the environmental effects of electric vehicles at every stage of their existence. Key areas of research include the creation of eco-friendly materials for production, the implementation of battery recycling methods, and the reduction of EVs' overall carbon emissions [15]. Incorporating the concept of a circular economy and sustainable materials into solar-powered electric vehicle (EV) systems aligns well with the global shift toward sustainable transportation. A circular economy focuses on minimizing waste, maximizing resource utilization, and keeping materials within a sustainable lifecycle. For solar-powered EVs, this approach addresses the entire lifecycle of components—from raw material extraction and production to usage, recycling, and disposal.

1.10.4.1 *Circular Economy in Solar-Powered EV Systems:*

Implementing circular economy principles in solar-powered EVs ensures that the production and use of EV components have minimal environmental impact. This model includes:

1.10.4.1.1 Materials Selection and Recycling:

Sustainable materials such as recycled aluminum, bio-based polymers, and renewable energy sources are used for battery and motor components. After batteries reach the end of their lifecycle, they are recycled to recover valuable elements like lithium, cobalt, and nickel, reducing reliance on raw mineral extraction and minimizing ecological damage.

1.10.4.1.2 Battery Second-Life Applications:

After their initial usage in EVs, batteries can be repurposed for secondary applications, such as energy storage in renewable power grids. This practice enhances the economic life of batteries and contributes to the stability of renewable energy systems by storing solar energy generated during peak times.

1.10.4.1.3 Design for Disassembly:

Solar-powered EV components can be designed with modular structures, enabling easy disassembly, repair, or upgrade of individual parts. This approach reduces waste, lowers long-term costs, and ensures that materials can be effectively reclaimed and recycled.

1.10.4.2 *Sustainable Materials in EV Systems:*

The shift to sustainable materials within EVs helps reduce carbon emissions and promotes environmental stewardship. Key materials and methods include:

1.10.4.2.1 Lightweight Materials:

Lightweight yet durable materials, like carbon fiber composites and high-strength steel, improve energy efficiency by reducing the EV's weight and extending range without sacrificing durability.

1.10.4.2.2 Bio-Based and Recyclable Polymers:

These are employed in vehicle interiors and battery casings, reducing reliance on petroleum-based plastics and minimizing the environmental impact during disposal or recycling.

1.10.4.2.3 Solar Panel Efficiency and Durability:

Solar-powered EVs integrate high-efficiency photovoltaic (PV) cells with longer lifespans and greater recyclability. Innovations in PV technology, like organic and perovskite solar cells, improve energy yield while using fewer resources and easier recycling at the end of life.

1.10.4.3 *Integrating Sustainability and Decarbonization:*

This research emphasizes the adoption of sustainable materials and circular economy principles in advancing the solar-powered EV sector. By implementing these principles, EV systems reduce dependency on fossil fuels, encourage the repurposing of components, and support a clean energy future. Sustainable practices in EV production and end-of-life management reduce emissions significantly, contributing to deep decarbonization. Integrating technologies such as Solar Thermal Chemical Looping

(STCL) and Chemical Looping Reforming (CLR) in energy systems supporting EV infrastructure further aids in CO2 capture and conversion, embodying a circular approach to carbon management.

This analysis underlines a holistic approach to solar-powered EVs, focusing on both technical advancements and sustainability, which are essential to meet the growing demand for eco-friendly transportation. Through circular economy principles, sustainable materials, and innovative decarbonization strategies, the study provides a pathway toward an efficient and environmentally sustainable EV ecosystem [16].

1.10.5 Battery-Swapping Techniques to Enhance Range for Electric Vehicles

Battery-swapping techniques represent a promising solution to enhance the range and convenience of electric vehicles (EVs), especially within the passenger transport sector. This evaluates the economic feasibility and impact of battery swapping (BS) on the adoption of EVs compared to traditional plug-in charging methods. By examining various EV modes—such as four-wheelers (4Ws), two-wheelers (2Ws), three-wheelers (3Ws), and buses—the study highlights how BS systems can provide cost-effective solutions for different types of passengers EVs, ultimately aiding the shift toward sustainable transportation [17].

1.10.5.1 *Distinct Business Models and Subscription Fees for Battery Swapping:*

One significant contribution of this study is formulating distinct business models across various passenger transport modes. Each model addresses subscription fees that take into account vehicle type, usage frequency, and operational needs, differentiating between private and commercial EV users. By analyzing the major cost factors—subscription fees, swapping infrastructure costs, and battery-related expenses—this study provides a foundation for Battery Swapping Station economics that can adapt to the unique needs of various countries or cities.

Results show that battery swapping is financially advantageous. For instance, incorporating government subsidies bridges the cost gap, making Battery Swapping financially viable. Subsidies not only lower the cost per kilometer for Battery Swapping EVs but also shorten payback periods, improve the internal rate of return, and increase net present value. This makes Battery Swapping Station an appealing alternative for energy operators, incentivizing investment in Battery Swapping Station infrastructure and enabling its scalability as a mainstream charging solution.

1.10.5.2 ***Increased Demand for Electric Vehicles and Solar Energy Consumption:*** Adopting Battery Swapping Stations increases EV service demand, as shown by a notable 6% rise in overall EV service demand. Further, subsidy-driven models show the potential to increase EV demand by 8% to 10% with 50% and 100% subsidy levels, respectively. This heightened demand also leads to an 8% rise in electricity consumption through Battery Swapping, a figure that grows to 11% and 13% under the same subsidy conditions. Solar-powered EV systems, when paired with BS, maximize the utilization of solar energy and distribute loads more evenly across the day, especially when Battery Swapping Station locations are optimized to complement peak solar generation times.

1.10.5.3 ***Environmental Impact and Policy Implications of Battery Swapping:*** Battery Swapping techniques offer an impactful reduction in CO_2 emissions, due to increased EV penetration, with reductions reaching up to 9% by 2070 and climbing to 12% and 14% with 50% and 100% subsidies, respectively. These findings indicate that Battery Swapping holds considerable potential as a sustainable solution for reducing carbon emissions in the transportation sector. Moreover, from a policy standpoint, equivalent subsidies for battery-swapping-based EVs as those provided to traditional EVs would further enhance the economic and environmental benefits of battery swapping, fostering a smoother transition toward a zero-emission future.

1.10.5.4 ***Overcoming Operational and Behavioral Challenges in Battery Swapping:*** Despite its potential, the battery-swapping model faces challenges such as user reluctance to swap batteries due to concerns over battery quality and wear. Addressing these issues may require standardizing battery quality and offering assurances regarding performance and lifespan. Additionally, implementing a queuing model tailored to the Battery Swapping Station could optimize daily and overall battery availability based on usage patterns, mitigating wait times and enhancing user experience.

It aims to contribute to a low-carbon economy by fostering renewable-driven EV adoption and enhancing energy resilience through solar PV-backed Battery Swapping systems, especially relevant for emerging EV markets like India [18].

1.11 Challenges for EVs

Several Challenges faced India in the adoption and promotion of Electric Vehicle [19].

1.11.1 Refueling of Electric Vehicle Points

The establishment of electric refueling stations is currently underway. Given that numerous places you visit lack charging infrastructure for electric vehicles, you may face the risk of being stranded should you run out of power on an extended trip.

1.11.2 Electricity has Cost

Electric vehicles might require a substantial amount of charging for optimal performance, potentially leading to an adverse effect on your monthly electricity expenses.

1.11.3 Limited Driving Speed and Distance Covered:

The limitations on speed and distance for electric vehicles are evident, with many of these cars needing frequent charging and having a range typically between 50 to 100 kilometers. As a result, long-distance journeys are currently impractical, although improvements in technology are expected to address this issue in the future.

1.11.4 Extended Charging Period

The constraints of electric vehicles are found in their limited velocity and distance capabilities. Many of these automobiles necessitate frequent recharging, typically covering distances between 50 to 100 kilometers. Currently, extended journeys are impractical with these vehicles; however, there is an expectation that this scenario will evolve in the future.

1.11.5 Absence of Sound as a Drawback

The absence of sound poses a disadvantage, as individuals generally prefer to be aware of noises originating from their surroundings. Consequently, silence can be perceived as a drawback. Despite their quiet nature, electric vehicles have the potential to contribute to accidents.

1.11.6 Not suitable in areas facing significant electricity deficiencies.

Due to their reliance on electricity for recharging, electric vehicles are unsuitable for deployment in regions experiencing severe power shortages. The heightened demand for electricity would further impede their daily energy needs.

1.11.7 Battery Replacement

Almost all electric vehicles need to have their batteries changed every three to ten years, depending on the kind and usage of the battery.

1.12 Electric Motor Technologies

The heart of any electric vehicle lies in its propulsion system. Various types of electric motors are shown in Figure 1-5

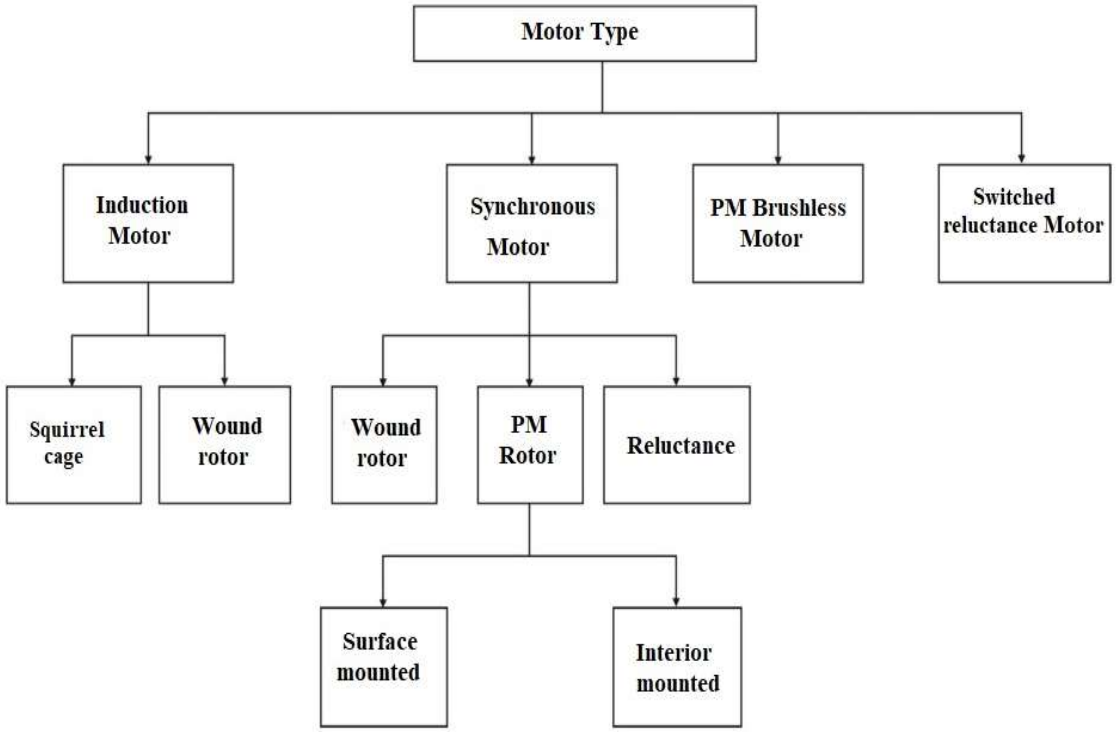

Figure 1-5-Type of electric motors

This thesis thoroughly explores the performance characteristics of different electric motor technologies, including Induction Motors (IMs) and Brushless DC (BLDC) Motors. A comprehensive evaluation, taking into account torque density, efficiency, and cost-effectiveness, serves as the foundation for suggesting the most suitable motor choices for various types of vehicles and usage situations. Two prevalent electric motor varieties employed in electric vehicle (EV) propulsion systems include induction motors (IMs) and brushless DC motors (BLDCs). The primary objective of this introduction is to highlight the advantages of utilizing induction motors in electric vehicle applications compared to brushless DC motors.

1.12.1 BLDC Motor

Brushless DC (BLDC) motors are named for their lack of a commutator and brush system, distinguishing them from permanent magnet DC motors. BLDC motors use electronic commutation instead of traditional mechanical methods, thus avoiding the necessity for frequent upkeep, unlike conventional DC motors. These motors boast excellent traction properties, featuring both high initial torque and efficiency. BLDC motors seamlessly integrate with high-power density design techniques, making them well-suited for various applications. Given their superior traction characteristics, BLDC motors stand out as the preferred choice for electric vehicle propulsion systems [20].

1.12.2 Induction Motor

In the realm of electric vehicles, choosing a three-phase induction motor over a single-phase model offers several advantages, including increased power output, improved efficiency, and smoother operation. The prevalence of three-phase motors in industrial and automotive domains renders them more cost-effective and accessible for electric vehicle manufacturers. Unlike DC series motors with substantial starting torque, induction motors operate at a fixed voltage and frequency, a feature modifiable through control strategies like FOC or v/f approaches. These strategies facilitate the motor's initiation with full torque, making it well-suited for traction applications. Squirrel cage induction motors, known for their extended lifespan, demand minimal maintenance and boast up to 90.2% efficiency in design and 27 Kg approximately [21]. Despite being a high-speed, long-range electric vehicle option, they surpass BLDC motors in terms of reliability and robustness. In industrial settings, three-phase induction motors are ubiquitous, offering consistent speed across various loads, cost-effective rotor structures, easy maintenance, and high waveform reliability when coupled with inverters. However, their application in high-power scenarios faces challenges such as the presence of high-power converter devices, torque ripple causing mechanical vibrations, and increased noise, resulting in smaller conductor sizes and lower power converter device ratings. Nevertheless, their capability to withstand faults, especially critical and reliable applications, justifies the increased complexity of multi-phase drives in high-power contexts like electric vehicle applications [22].

- Because IM does not have a collector or brushes, it requires minimal maintenance.
- For the identical nominal power, IM is less expensive than DC motors.
- For a given nominal power, the weight of an IM is lower than that of a DC motor.

- When it comes to working in unusual environmental conditions, IM motors are more reliable than DC motors.
- IM can be produced with a nominal voltage of up to 25 KV.
- IM can be produced with greater power and rotate at a speed of 50,000 revolutions per minute[23].

1.13 Advantages of Induction Motors in Electric Vehicle Propulsion:

1.13.1 Simplicity and Robustness

Induction motors are known for their simple construction, which translates to lower manufacturing costs and increased reliability. Their robust design allows for reduced maintenance requirements, making them an attractive option for electric vehicle manufacturers.

1.13.2 High Torque Density

Induction motors exhibit high torque density, providing strong acceleration and better performance in stop-and-go traffic conditions. This characteristic makes them well-suited for urban driving scenarios, where frequent acceleration and deceleration are common [24].

Induction motors (IMs) are widely utilized in electric vehicles (EVs) due to their ability to deliver high torque density, which contributes to strong acceleration and reliable performance, particularly in stop-and-go traffic conditions. This feature stems from specific design and operational characteristics that make IMs well-suited to urban driving environments where frequent starts, stops, and rapid accelerations are common.

1.13.2.1 *Torque Density and Magnetic Field Interaction:*

1.13.2.1.1 Design of Rotor and Stator:

Induction motors have a unique design. The stator generates a rotating magnetic field that induces currents in the rotor. The interaction between the stator's magnetic field and the induced currents in the rotor creates torque. By carefully designing the rotor's bars and stator's coils to maximize magnetic coupling, IMs achieve high torque density, a critical factor for accelerating from low speeds.

1.13.2.1.2 Synchronous Speed and Slip:

The difference between the synchronous speed (the speed of the rotating magnetic field) and the rotor speed, known as slip, allows induction motors to generate high torque at low speeds, especially useful in stop-and-go scenarios. Technical data from various studies highlight that typical IMs maintain a slip ratio between 3% to 5% in standard driving conditions, enabling substantial low-end torque, particularly advantageous during acceleration from a standstill.

1.13.2.2 *Enhanced Acceleration Through High Starting Torque:*

1.13.2.2.1 Torque-Speed Characteristic:

Induction motors exhibit a characteristic torque-speed curve that allows for substantial torque at lower speeds, which is ideal for initial acceleration in EVs. This torque, known as starting torque, is critical for providing the immediate power needed to initiate vehicle movement from rest, common in urban traffic. The design of the rotor bars, often made of copper or aluminum, is crucial here, as these materials optimize current flow, improving efficiency and resulting in higher starting torque.

1.13.2.2.2 Impact of Rotor Design:

Induction motors in EVs are frequently optimized with squirrel cage rotors, enhancing starting torque without excessive current draw. This rotor design ensures that the motor can provide high torque while maintaining efficient operation, a key factor in both acceleration and smooth performance in stop-and-go conditions.

1.13.2.3 *Operational Efficiency in Stop-and-Go Traffic:*

1.13.2.3.1 Thermal Management and Efficiency:

One of the main challenges in stop-and-go driving is maintaining efficiency while avoiding overheating[25], especially during frequent starts and stops that produce substantial thermal buildup. Advanced cooling techniques in induction motors, such as liquid or air cooling, help manage temperature, allowing sustained high torque output without thermal degradation. This ensures that the motor can consistently perform even under demanding traffic conditions, extending both motor life and EV performance [26].

1.13.2.3.2 Inverter and Control System Synchronization:

Induction motors for EV applications are coupled with inverters and controllers that optimize torque output. Pulse Width Modulation (PWM) control, for example, adjusts the frequency and amplitude of the AC supply, providing smooth torque delivery without sudden jolts. The ability to quickly and precisely control torque is particularly beneficial in stop-and-go traffic, as it allows the motor to respond promptly to acceleration demands without wasting energy.

1.13.2.4 ***Advantages of High Torque Density in Urban Conditions:***

1.13.2.4.1 Reduced Wear on Components:

High torque density allows induction motors to deliver the required torque without excessively large motor sizes or weights. This compactness contributes to less strain on transmission and suspension components, reducing overall wear and maintenance costs. Data from EV drivetrain studies suggest that high torque density can increase overall drivetrain longevity by up to 20%, especially in urban driving scenarios requiring frequent acceleration.

1.13.2.4.2 Battery Efficiency and Range:

High torque density contributes to optimized battery usage, as it reduces the amount of time the motor needs to reach desired speeds. In EVs, this is particularly useful for preserving battery life, as quick torque availability minimizes prolonged energy demand. By achieving higher torque with a lower current draw, induction motors improve battery efficiency, indirectly extending range—an asset in traffic-laden environments.

1.13.2.5 ***Technical Data Examples from Experimental Studies:***

1.13.2.5.1 Torque per Ampere Ratio:

Experimental data often measures the torque-to-current ratio (Nm/A), a key indicator of an induction motor's efficiency in torque generation. In high-performance EVs, typical values range from 0.8 to 1.2 Nm/A, depending on motor size and design, with values on the higher end indicating better efficiency in torque production. This high ratio is a fundamental factor in rapid acceleration capabilities in urban settings.

1.13.2.5.2 Rotor Induction and Slip Ratio:

Data from studies show that at lower speeds (e.g., <1000 RPM), slip ratios increase slightly to allow for high torque production, with some designs achieving up to 20 Nm of torque at low speeds under controlled slip conditions. This enables responsive acceleration from a standstill, ideal for traffic conditions.

1.13.2.5.3 Thermal Data and Durability:

Thermal tests on induction motors in stop-and-go cycles reveal that motors designed with efficient cooling can maintain temperatures below 150°C, reducing the risk of overheating and allowing for continued high torque output during frequent acceleration and braking cycles.

Induction motors' ability to provide high torque density, manage thermal loads efficiently, and adapt to inverter controls makes them highly effective for EV applications, especially in stop-and-go traffic. The precise control over torque delivery and consistent thermal management under demanding conditions enhance the motor's longevity and performance, positioning IMs as a top choice for urban electric mobility solutions. These technical advantages underline the viability of induction motors in modern EVs, contributing to improved acceleration, reduced battery strain, and overall operational efficiency in urban driving contexts [13].

1.13.3 Regenerative Braking Efficiency

The inherent regenerative braking capability of induction motors allows for efficient energy recovery during deceleration, contributing to improved overall energy efficiency in electric vehicles. This feature enhances the range and efficiency of the vehicle [27].

1.13.4 Cost-Effectiveness

Induction motors are typically more economical to manufacture compared to BLDC motors because of their simpler design and lack of permanent magnets. This cost efficiency plays a role in making electric vehicles more accessible to consumers by lowering their overall cost [28].

1.13.5 Wide Operation Range

Induction motors exhibit efficient performance across a broad spectrum of speeds and loads, eliminating the necessity for intricate control systems. This versatility proves especially beneficial in practical driving scenarios, where the motor encounters fluctuating demands [29].

1.13.6 Battery Systems and Energy Storage

The efficiency and range of electric vehicles heavily depend on the energy storage system. An in-depth analysis is conducted on recent advancements in battery technology, including solid-state batteries and advanced lithium-ion chemistries. The study thoroughly assesses the effects of these breakthroughs on energy density, charging durations, and overall lifecycle performance. Emphasis is placed on the pivotal equilibrium between energy capacity and weight throughout the evaluation.

1.13.7 Control Strategies for Enhance Performance

The implementation of sophisticated control strategies is pivotal in maximizing the performance of electric vehicles. This research investigates the latest developments in motor control algorithms, regenerative braking systems, and adaptive power management. Emphasis is placed on achieving seamless integration between the vehicle's electric powertrain and other subsystems, ensuring optimal efficiency under varying driving conditions [30].

1.13.8 Sustainable Integration with the Power Grid

As the prevalence of electric vehicles rises, it becomes imperative to assess their influence on the power grid. This research explores techniques for smoothly integrating electric vehicles, including smart charging strategies, the adoption of vehicle-to-grid (V2G) systems, and the potential impact of renewable energy sources on powering these vehicles. The objective is to formulate a comprehensive strategy that not only amplifies the ecological advantages of electric transportation but also safeguards grid stability and dependability [31].

1.13.9 Human-Machine Interaction and User Experience

Beyond the technical aspects, this research investigates the human-machine interaction and user experience in electric vehicles. The integration of advanced driver-assistance systems, user-friendly interfaces, and the impact of electric vehicle adoption on driving behavior are examined to provide insights into the broader societal acceptance of electric mobility [32].

1.13.10 Environment Impact Assessment

A comprehensive examination of the entire life cycle is carried out to evaluate the holistic environmental repercussions of electric vehicles. This analysis encompasses various aspects including manufacturing, energy origins, and the disposal process at the end of the vehicle's life. The objective is to furnish an all-encompassing comprehension of the ecological footprint associated with electric mobility, steering forthcoming advancements toward heightened sustainability.

In summary, this dissertation adds value to the ongoing conversation surrounding electric vehicles by conducting a detailed analysis of recent studies and advancements. Its discoveries are intended to educate policymakers, industry participants, and scholars about the critical factors for enhancing electric vehicle technologies and promoting a sustainable and effective transportation landscape [33].

1.14 Solar can be an added advantage in electrified vehicles to charge the EV's Battery.

At the interface between Earth's atmosphere and space, approximately 1.73×10^{14} kilowatts of solar radiation infiltrate the atmosphere. Due to the phenomena of scattering, absorption, and reflection, a portion of this radiation reaches the Earth's surface. Approximately 18 to 20 percent of the sun's energy is taken in by the Earth's atmosphere. The interaction of the atmosphere, clouds, and Earth's surface causes about 35 percent of this energy to be reflected in space. Direct solar energy reaching the Earth's surface follows an uninterrupted, straight path. The solar constant, denoting the solar radiation measured at right angles outside the Earth's atmosphere, is quantified at 1367 watts per square meter. Photovoltaic (PV) technology allows for the direct transformation of solar energy into electricity. At the core of a photovoltaic system lies the solar cell, which is essential for this conversion process. Photovoltaic cells use semiconductors such as silicon (Si), gallium (Ga), cadmium (Cd), arsenic (As), germanium (Ge), and so on. The photoelectric effect causes electrons at the interface of two different semiconductor materials to liberate energy when solar light strikes them [34]. Solar-powered vehicles offer a hopeful direction in sustainable transportation, seeking to utilize solar energy to drive vehicles and store this energy in the electric vehicle's battery. This approach aims to decrease reliance on conventional fossil fuels, thereby lessening the environmental impact. Typically, these vehicles incorporate photovoltaic (PV) cells into their design to transform sunlight into electrical energy. The generated electricity can be directly employed to propel the vehicle or stored in batteries for future use. A key benefit of solar-powered vehicles lies in their capacity to function with minimal or no emissions, thereby playing a pivotal role in fostering a cleaner and more sustainable transportation sector. However, limited energy conversion efficiency, the intermittent nature of sunlight, and the need for lightweight and efficient energy storage solutions have been areas of active research.

1.15 Description of the problem

Nevertheless, incorporating solar PV technology into electric vehicles is considered a practical measure for reducing carbon emissions within the road transportation sector. The most important consideration is the area that can be used to directly combine a photovoltaic panel with an electric vehicle rooftop. The light-electric vehicle is the ideal option for integrating PV technology with the electric vehicle. The other benefits of an electric vehicle include its lightweight, affordability, and big overhead space. The upper space can serve as a solar PV panel that could potentially boost the driving range of electric vehicles and extend the lifespan of their batteries. PV-based induction motor-powered electric vehicle's PV output power is studied for varying irradiation levels. A prime mover induction motor which is a robust, reliable, low-maintenance induction motor can be utilized as the propulsion system for an electric vehicle. The reliability robustness low maintenance characteristics may be an added advantage for the Indian market as a good solar-powered Induction motor electric vehicle.

1.16 Motivation

The main issue with automobiles using internal combustion engines worldwide is pollution. The pollutants released into the air, water, and land by internal combustion engine vehicles are directly related to global warming, emissions of greenhouse gases, and ozone layer depletion. ICE vehicles are powered by traditional energy sources like fossil fuels, which have a finite supply and cannot be converted. Because ICE vehicles have low conversion efficiencies, they use more non-renewable energy resources and release more pollutants from combustion into the atmosphere. The principal energy supply that keeps humans alive in the modern period is conventional energy. Around the world, 74% of the fuel consumed by people is derived from three primary sources of conventional energy: coal, oil, and natural gas. A mismatch exists between the world's energy supply and demand since traditional energy sources are running out daily and are also multiplying at a rapid pace. Due to the escalating energy demand, conventional resources are inadequate, necessitating additional energy to sustain current human development. Solar energy is recognized as a highly promising renewable resource, offering a viable solution to meet both present and future energy requirements. By using photovoltaic (PV) panels, solar energy has the only capability to produce electricity. Solar PV technology has a broad range of power output capacities, ranging from milliwatts to gigawatts. The meritorious qualities of solar PV technology are its non-polluting nature and pure environment. Therefore, a viable step towards decarbonizing the transportation industry would be an electric vehicle that makes use of an electric propulsion system. Furthermore, as the majority of vehicle parking is done outside, solar PV technology may be utilized for electric vehicle propelling applications as well as a standalone charging option on the roof of the electric vehicle.

1.17 Thesis Contribution

The study specified and answered research questions. The following contributions are included in it:

Induction motors are superior to other motors when it comes to propulsion for electric vehicles, as demonstrated by a thorough review of the literature that includes statistical research and design publications.

1. The various contemporary designs, technologies, and classification approaches presented in conferences, research papers, and other publications have undergone thorough scrutiny and analysis for this thesis.

2. The analysis of the BLDC and Induction motors' performances in the suggested system. The literature has been thoroughly reviewed.

3. A PV-based IM-driven EV system design created with MATLAB/Simulink must have a motor that is durable, affordable, and dependable for use in EV propulsion applications.

1.18 Research Problem

The chapter also contains an overview of the reasons behind the research as well as the particular problems and goals that the study set out to address. An illustrated depiction of the research aims and techniques is provided. Consequently, the organization and publications of the thesis contributed to a thorough understanding.

1. Too short Battery life
2. Limited availability of charging station
3. Driving limitations for the long run
4. Speed limitation
5. Reliability and robustness of the motors according to the rural and urban road
6. Maintenance and fewer skilled person availability
7. Awareness of subsidies provided by the Government
8. Cost of Photovoltaic hindrance to reaching people
9. Due to the environmental change, the solar-based vehicle may be affected and a high-quality MPPT can change the scene.

10. Most vehicles are used to and fro office work so challenges faced by charging stations can be overcome if economical quality charging systems are available at home and office.
11. Awareness of policies and subsidies of government.

1.19 Research Gap

1.19.1 Electric Vehicles (EVs)

Research Gap: While significant advancements have been made in enhancing the energy density and lifespan of electric vehicle batteries, there is still a research gap in understanding and addressing the environmental impact and sustainable disposal of lithium-ion batteries, which are commonly used in electric vehicles. The life cycle analysis, including extraction of raw materials, manufacturing processes, and end-of-life disposal methods, requires more attention to ensure the overall environmental sustainability of electric vehicles.

1.19.2 Solar Charging for Electric Vehicles

Research Gap: The integration of solar panels for charging electric vehicle batteries has gained attention for its potential to reduce dependency on the grid. However, there is a research gap in developing efficient and cost-effective energy storage solutions to address the intermittency and variability of solar power. Investigating and optimizing energy storage technologies, such as advanced batteries or hybrid energy storage systems, would contribute to a more reliable and stable solar-charging infrastructure for electric vehicles.

1.19.3 Induction Motor in Electric Vehicles

Research Gap: Although Brushless DC (BLDC) motors are widely used in electric vehicles for propulsion due to their efficiency and reliability, the application of induction motors remains an underexplored area. A research gap exists in comprehensively studying the performance, efficiency, and potential benefits of using induction motors in electric vehicles for different applications. This includes investigating the control strategies, thermal management, and overall system optimization when induction motors are employed as an alternative to BLDC motors for propulsion in electric vehicles.

1.20 The objective of the proposed research work

Taking into account all relevant factors, the researcher has the following objectives.

(a) Design of a photovoltaic-based induction motor-driven electric vehicle systems

(b) Performance evaluation of BLDC and Induction motor-based electric vehicle

(c) Performance evaluation of induction motor-operated Electric vehicle applying Simulation methodology.

1.21 Proposed Research Methodology

An electric vehicle is the most demanding type of vehicle to take the place of an internal combustion engine type vehicle which not only saves the environment by not extracting fossil fuel from nature but is a zero-emission vehicle (ZEV). Different kinds of electric motors are utilized in electric vehicles, and they have some drawbacks such as limitations in speed, range, reliability, and maintenance. Additionally, the transition to electric vehicles could significantly impact the power grid and energy consumption.

(a) A study of the existing practices for various types of designs of induction motors is driven which is powered by solar energy, and electric vehicles, and critical investigation will be carried out through a review of the works of literature.

(b) Evaluate the performance analysis of induction motors compared parameters with other available motor parameters for electric vehicles while reviewing existing literature.

(c) By applying MATLAB/Simulink software performance evaluations of induction motor-operated Electric vehicle systems, after implementation consider relevant system performance.

Methodologies adopted in this research work are taken into steps shown in Figure 1-6 and the instrument used in this research is explained in Table 1-1 whereas Flow chart Figure 1-7 shows the procedure adopted for the proposed Methodology applied in the research work.

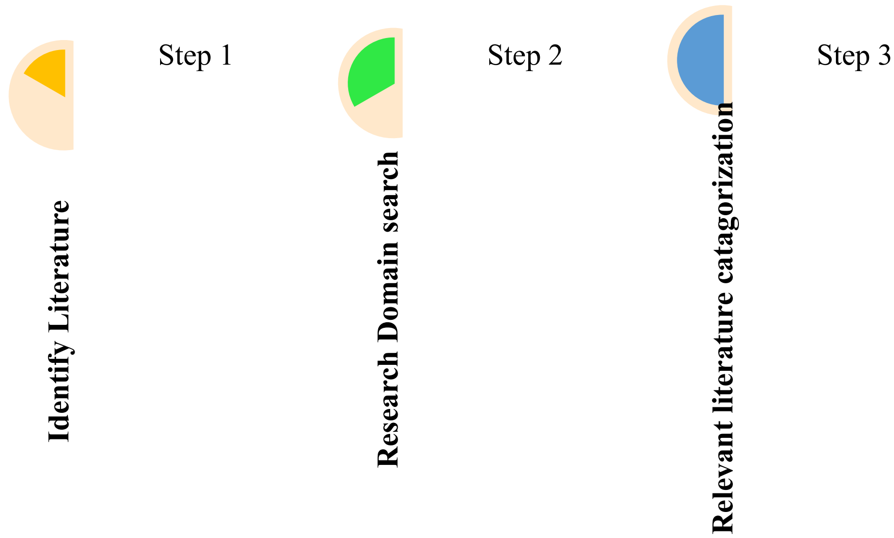

Figure 1-6-Methodology to follow research work

Table 1-1- Analysis undertaken entire research and instruments used in LPU

Objective	Analysis undertaken	Instruments/processes/ software to be used	In-house Availability (Yes/No)	Organization /Institute (where facility available
Objective 1	Design of a photovoltaic-based induction motor-driven electric vehicle systems	MATLAB 64-bit processor, 4 GB RAM/ relevant Research article	Yes	LPU, Punjab
Objective 2	Performance evaluation of BLDC and Induction motor-based electric vehicle	MATLAB 64-bit processor, 4 GB RAM/ relevant Research article	Yes	LPU, Punjab

Objective 3	Performance evaluation of induction motor-operated Electric vehicle applying Simulation methodology.	MATLAB 64-bit processor, 4 GB RAM/ relevant Research article	Yes	LPU, Punjab

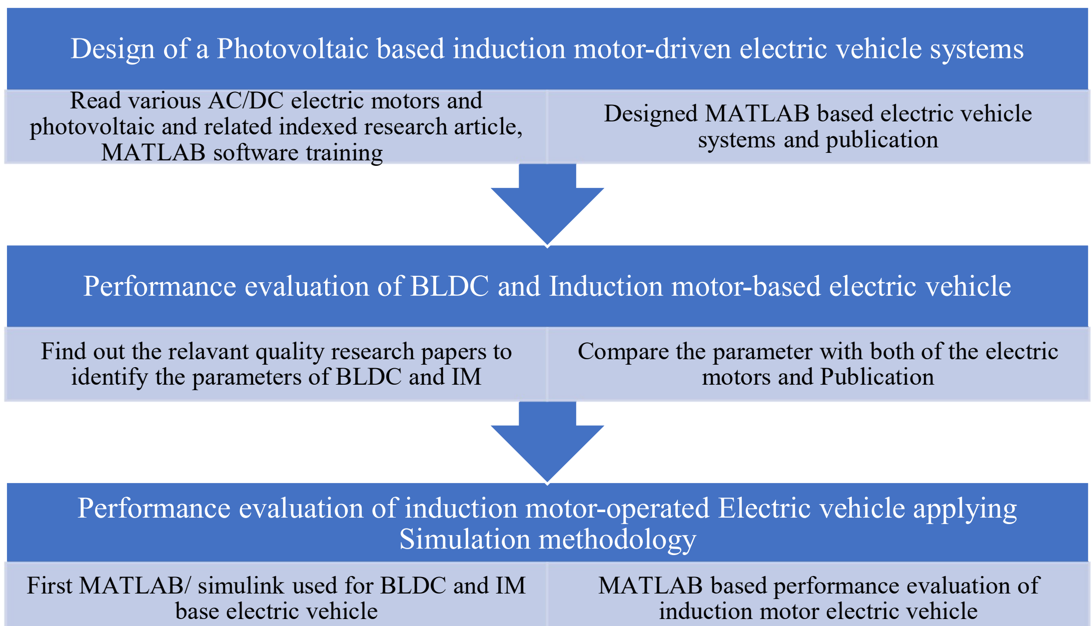

Figure 1-7-Proposed Methodology Flow Chart

1.22 Structuring the thesis:

The structuring of the thesis is in the following manner and shown in Figure 1-8

Chapter 1

With an emphasis on the Introduction part of current research and innovation, the **chapter first** primarily covers the evolution and history of electric vehicles. The benefits of induction motors for applications involving electric propulsion. When used as a stand-alone source of energy for charging electric vehicles, solar energy is a renewable resource with advantages. The research's motivation and goals are outlined.

Chapter 2

In **chapter two**, an examination of the performance of both the induction motor and brushless DC motor is conducted through a comprehensive literature survey. This chapter encompasses a thorough review of current research papers providing a comprehensive overview of the relevant studies.

Chapter 3

In **Chapter Three**, the practical design of PV-based induction motor-driven electric vehicle systems is thoroughly described. Additionally, this chapter uses the MATLAB/Simulink methodology to address real-world design problems. The simulation results demonstrate that the proposed electric vehicle utilizing an induction motor and solar energy outperforms other electric vehicle variants, showcasing superior performance and efficiency.

Chapter 4

In the **fourth chapter**, different approaches to explaining the operation of brushless DC motors powered electric vehicles, as well as practical issues and unit commitment issues, are examined. This chapter delves deeply into the theoretical and mathematical requirements needed to solve a variety of optimization issues, including limited and unconstrained ones. The new work technique presented in this chapter aims to achieve the suggested research objectives.

Chapter 5

Chapter Five assessed the effectiveness of an electric vehicle propelled by an induction motor.

Chapter 6

In the **Sixth chapter** Performance evaluation of induction motor-operated Electric vehicle applying Simulation methodology.

Chapter 7

The **Seventh chapter** summarizes the significant conclusions of the research work carried out preparing the current thesis, and it concludes with future scope and opportunity in this research.

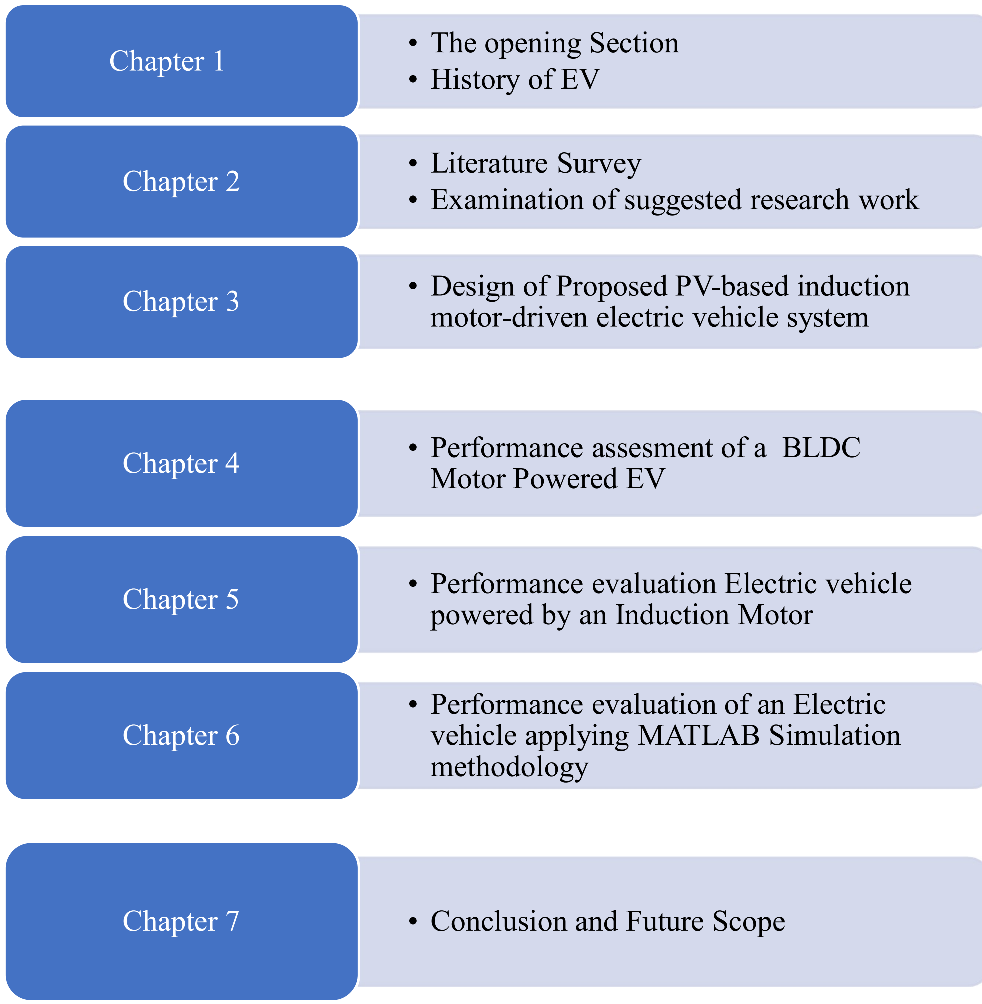

Figure 1-8-Organization of the full thesis

1.23 Chapter Summary

This introduction chapter delves into the growing importance of Electric Vehicles (EVs) as a sustainable alternative to traditional Internal Combustion Engine (ICE) vehicles. Different IEEE standards for electric vehicles were discussed in Chapter 2 as shown in Table 2-5. In this Chapter a brief discussion is imputed on the research work carried out in the successive chapters. It highlights the detrimental effects of ICE vehicles, such as their contribution to outdoor air pollution, greenhouse gas emissions, and particulate matter from brake and tire wear, emphasizing the need for cleaner solutions to improve urban air quality. The discussion includes a historical overview of EVs, global policy frameworks, and initiatives fostering the adoption of e-mobility. It identifies the advantages of EVs, such as reduced emissions and enhanced energy efficiency, alongside their scope in India—a country with significant untapped potential in EV adoption. Recent advancements in solar energy systems and their integration into EVs as charging solutions further enhance the sustainability aspect.

Key areas of focus include:

- The comparison of electric motor technologies such as Brushless DC Motors (BLDC) and Induction Motors (IM), analyzing their performance for EV propulsion.

- The advantages of induction motors, including their durability, cost-effectiveness, and robustness in electric vehicle systems.

- Research on photovoltaic (PV)-based systems, which leverage solar energy to charge EV batteries, offering a green energy solution.

The chapter identifies the research gaps, particularly the performance evaluation of BLDC and induction motor-driven EV systems using simulation methodologies, and lays the groundwork for a photovoltaic-based induction motor-driven EV system design. It also provides an outline of the proposed research methodology, contributing to the understanding and optimization of EV systems.

1.24 Key Observations

1.24.1.1 *Need for Transition to EVs:*

ICE vehicles significantly contribute to environmental degradation. EVs, coupled with renewable energy sources like solar, offer a cleaner, more sustainable transportation solution.

1.24.1.2 *E-mobility Advancements:*

Historical and recent developments highlight the role of policy, innovation, and global initiatives in accelerating EV adoption.

1.24.1.3 *Motor Technologies:*

- Induction Motors are recognized for their reliability, cost-effectiveness, and robustness, making them ideal for EV propulsion.

- BLDC Motors excels in efficiency and torque control, but they are more expensive.

1.24.1.4 *Solar Integration:*

Utilizing solar PV systems to charge EV batteries enhances sustainability and reduces dependency on conventional energy sources.

1.24.1.5 *Challenges and Research Gaps:*

Despite their advantages, EVs face challenges, including high initial costs, limited charging infrastructure, and energy management. Additionally, a detailed performance evaluation of various motor technologies in EV systems is lacking in existing literature.

1.25 Chapter Conclusion

The introduction chapter establishes the importance of EVs in mitigating environmental issues and transitioning to cleaner transportation alternatives. It highlights the key challenges, including the need for energy-efficient motor technologies, cost reduction, and infrastructure development. The proposed research aims to bridge these gaps by focusing on:

1. Designing a photovoltaic-based induction motor-driven EV system, utilizing solar energy to enhance battery charging and reduce reliance on the grid.

2. Conducting a comprehensive performance evaluation of BLDC and induction motors for EV applications using simulation methodologies.

3. Exploring innovative designs to improve motor performance, system efficiency, and energy utilization in EV systems.

This chapter sets the foundation for the proposed methodology, which integrates renewable energy sources, motor optimization, and simulation-based performance analysis to address current research gaps and contribute to the advancement of EV technology.

2 Chapter 2

2.1 Literature Survey

One significant way to reduce reliance on fossil fuels is to electrify the transportation sector. Since our nation's energy supplies are steady, reducing greenhouse gas emissions is not likely to happen quickly. Electric vehicles are considered a favorable choice when considering the transportation sector. Coordinating the use of electric vehicles for transportation could effectively decrease emissions generated from burning fossil fuels for energy production. The fundamental requirement for the smooth operation of daily activities is electrical energy. The modern civilized world has experienced remarkable progress, resulting in a substantial rise in the need for energy to fulfill these requirements. Fossil fuels are the primary resource utilized by the power industry to generate vast amounts of electricity, despite the convenience of this method, it has the drawback of releasing emissions harmful to the environment. Hence, it is essential to thoughtfully evaluate the adoption of alternative energy sources to ensure their continuous accessibility. The prevailing energy consumption pattern, solely reliant on fossil fuels, poses a risk of rapid depletion, emphasizing the necessity for exploring and adopting non-conventional energy sources for long-term sustainability. The adoption of renewable energy sources has led to a decrease in the energy required to meet demand. Solar and wind power have become key players in global energy production. Up till now, the solar power industry in India has experienced the fastest growth among all renewable power sectors. In October 2021, 45.7 GW of solar power was installed nationwide in India. This study includes the examination of solar energy [35]. Climate affects both temperature and solar radiation in this research project. As a result, summer and winter have different temperatures and amounts of solar radiation shown in Figures 2-1 and Figure 2-2. Here, the sun radiations for both summer and winter are taken into consideration. Several Indian cities have already begun implementing BEVs.

To meet the demands of the market, a heightened interest could emerge through the enhanced capability to charge and discharge Battery Electric Vehicles (BEVs). India boasts flourishing manufacturing sectors, creating a heightened requirement for transportation. Consequently, a promising opportunity arises for the establishment of domestic Electric Vehicle (EV) companies in India, fueled by the escalating demand for electric vehicles. The manifold issues stemming from the consumption of fossil fuels prompt a critical need for intervention. Electrifying the transportation sector stands out as a pivotal strategy to alleviate dependence on fossil fuels. This necessitates a transformation of the transportation infrastructure and the implementation of rigorous efficiency assessments for clean technology, leveraging low-carbon energy sources. According to data from the National Electric Mobility Mission Plan (NEMMP) 2020, incorporating 400,000 electric vehicles could prevent the emission of 4 million metric tons of carbon dioxide and conserve 120 million barrels of oil. Forecasts by the Centre for Science and Environment suggest that by 2030, electric vehicles may constitute 60% to 80% of public transit fleets in many cities, based on estimates between 2025 and 2030. Electric vehicles (EVs) have garnered significant attention as an eco-conscious mode of transportation. The choice of motor technology is crucial in determining the overall functionality of EVs, with the effectiveness and reliability of electric motors being key elements that impact the propulsion system of these vehicles. The integration of photovoltaic (PV) systems into electric vehicles (EVs) holds great potential for promoting sustainable transportation. This literature review aims to provide a comprehensive overview of recent research on electric vehicles utilizing photovoltaic technology. It also intends to examine advancements in evaluating the efficiency of induction motors and brushless DC motors for powering electric vehicles simultaneously.

The objective of this research is to conduct a thorough evaluation of the operational efficiency of both induction motors (IM) and brushless DC motors (BLDC) within the realm of electric vehicle propulsion. The emphasis will be placed on identifying particular situations where induction motors may demonstrate superiority and specific performance metrics will be highlighted for a detailed analysis. The goal is to offer a comprehensive comparison of IM and BLDC performance in electric vehicle applications while focusing on distinct performance criteria.

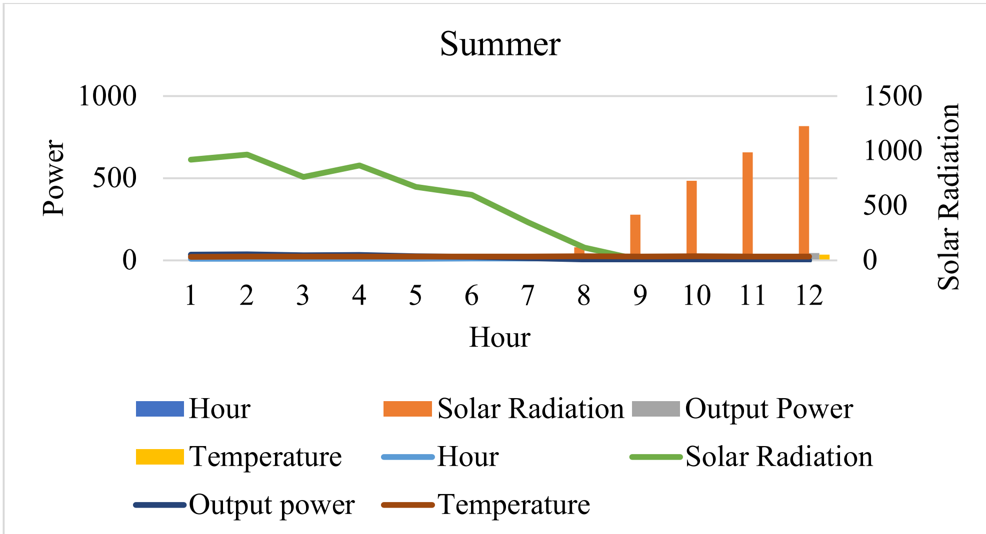

Figure 2-1-Summer solar radiation impacts power.

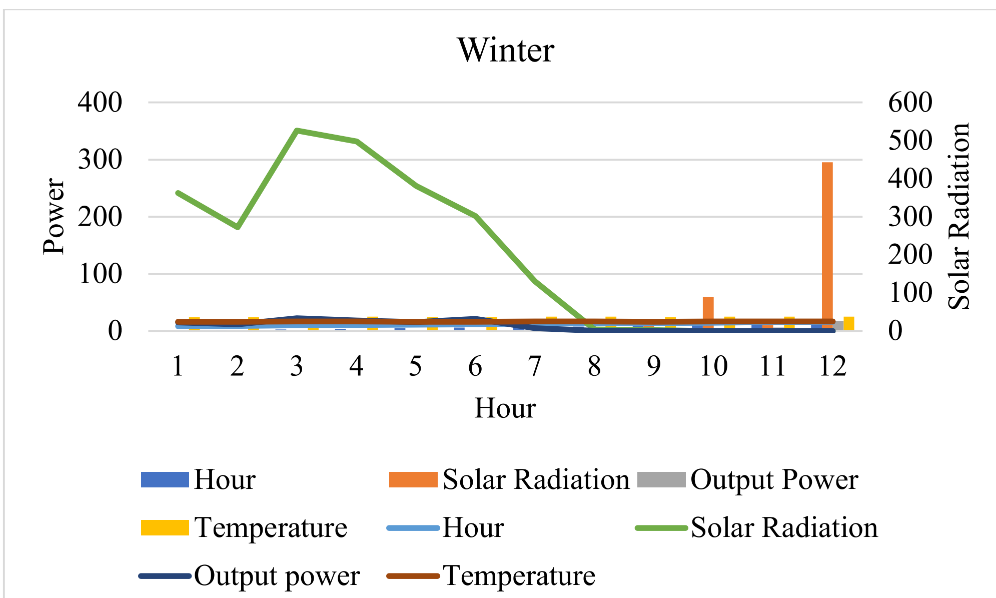

Figure 2-2-Winter Solar Radiation vs Power

2.2 Performance Evaluation of Electric Vehicle Propulsion Motors

2.2.1 Comparative Analysis of Brushless and Induction Motors in Electric Vehicles

Current research focuses on conducting a comparative analysis between induction motors and brushless DC motors for electric vehicle propulsion. This evaluation considers several factors such as efficiency, torque response, and thermal regulation [36] [37].

2.2.2 Advantages of Brushless Motors

Research suggests that brushless motors provide specific benefits such as increased efficiency, reduced maintenance needs, and higher power density [38]. Brushless motors are recognized for their accurate regulation and quick response, rendering them appropriate for use in scenarios involving fluctuating loads.

2.2.3 Advantages of Induction Motors

Conversely, induction motors have been favored for their robustness, reliability, and cost-effectiveness in electric vehicle applications [39].

Induction motors do not require permanent magnets, reducing concerns related to material scarcity and cost.

2.2.4 Performance Metrics

Research comparing the effectiveness, torque properties, and general performance of brushless and induction motors in electric vehicles has produced varied findings as presented in Table 2-1. Some research suggests that induction motors may exhibit superior torque performance at certain operating conditions [2]. Others highlight the efficiency gains achieved by advanced brushless motor designs [40].

Table 2-1-Performance metrics for BLDC and Induction Motor

Parameter	Description
Motor Type	- Brushless Motor (e.g., Permanent Magnet Synchronous Motor - PMSM)
	- Induction Motor (e.g., Asynchronous Motor)
Efficiency	- Brushless Motors tend to have higher efficiency due to reduced losses in the absence of brushes.
	- Induction Motors may have slightly lower efficiency due to losses in rotor windings and rotor losses.
Torque Characteristics	- Brushless Motors often exhibit smoother torque characteristics, providing precise control over a wide range of speeds.
	- Induction Motors may show superior torque performance at lower speeds, making them suitable for certain applications.
Power Density	- Brushless Motors typically have higher power density, allowing for more compact designs with high power output.
	- Induction Motors may have lower power density, leading to larger physical sizes for equivalent power outputs.
Response Time	- Brushless Motors generally have faster response times due to the absence of rotor windings, enabling quicker changes in speed.
	- Induction motors may have slightly slower response times due to the rotor's inertia and the nature of the rotor winding.
Control Complexity	- Brushless Motors require more complex electronic control systems (such as sensor feedback) for precise operation.
	- Induction Motors may have simpler control systems, especially in scalar control mode, making them cost-effective in certain cases.

Parameter	Description
Maintenance	- Brushless Motors generally have lower maintenance requirements as there are no brushes to wear out.
	- Induction Motors may require periodic maintenance of brushes and rotor windings.
Thermal Management	- Brushless Motors often have better thermal management, allowing for higher continuous power output without overheating.
	- Induction Motors may experience more significant thermal challenges, particularly during high-load and low-speed conditions.

2.2.5 Challenges and Considerations faced during performance evaluation

When writing about challenges faced, here are some challenges, along with potential ways to address them [19].

Literature Review Challenges

Data Collection and Analysis Challenges

Insufficient or unreliable data

Technical Challenges

2.2.6 Efficiency of Energy

Research suggests that the energy efficiency of electric vehicles is a critical consideration for their widespread adoption. Some studies indicate that brushless motors, due to their design and control characteristics, can achieve higher energy efficiency in certain driving conditions [41]. It's important to highlight that the performance of both types of motors is affected by factors like load characteristics and operational environments. Figure 2-3 demonstrates how the efficiency of the IM drive is related to the load percentage. The graph shows that energy efficiency increases when the IM operates at its peak performance level. Comparing the outcomes of the controller tuned with established tuning rules to those achieved with the suggested rules reveals a more commendable performance with the proposed approach.

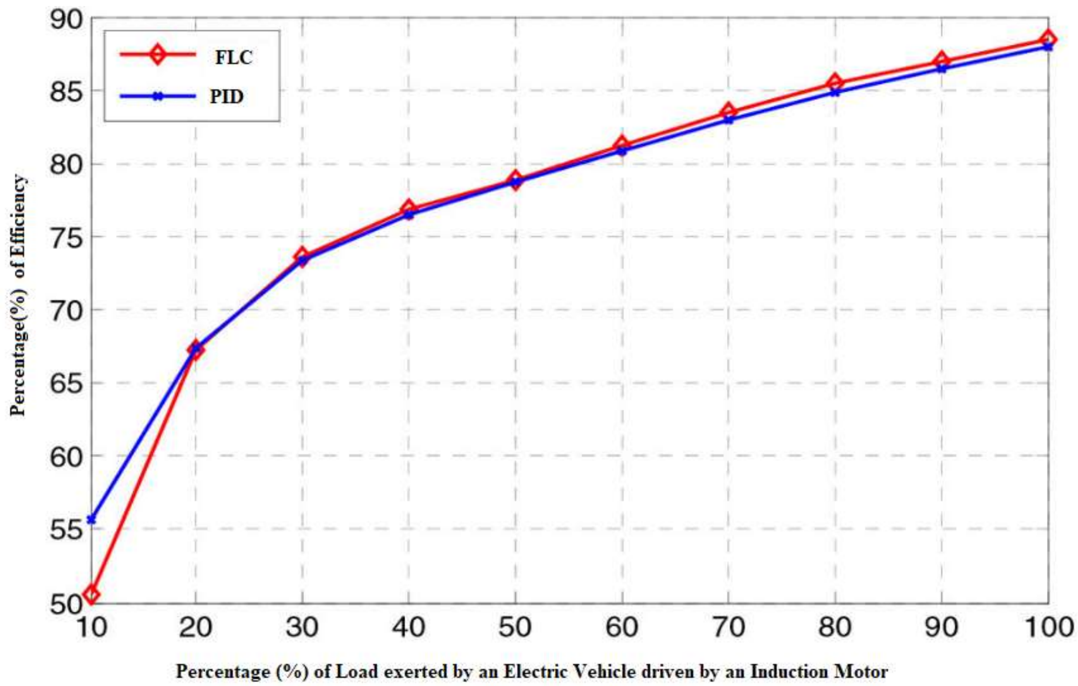

Figure 2-3 Efficiency of IM-EV: PID vs FLC [42]

2.2.7 Temperature Regulation and Cooling Systems

Thermal management is a critical aspect of electric vehicle motor systems. Induction motors, known for their robustness, often exhibit better thermal performance in high-load scenarios. Research has explored advanced cooling techniques for brushless motors to address thermal challenges, emphasizing the importance of effective cooling strategies for both motor types in enhancing overall vehicle efficiency [43].

Attaining the ideal thermal comfort inside the cabin involves controlling different factors such as temperature, humidity, and airflow to keep them within the preferred comfort zone. It's important to recognize that the cabin's thermal management requirements can differ between summer and winter, as indicated in Table 2-2.

Table 2-2 Cabin temperature management requirements

Season	Cabin Temperature (℃)	Relative Humidity (%)	Airflow Rate (m/s)	Fresh Air Volume (m^3/h)	Thermal Load (kW)
Summer	24~ 28	40~ 65	0.3~ 28	20~ 25	3.0~ 9.3
Winter	18~ 20	>30	0.2~ 0.3	15~ 20	1.5~ 6.0

2.2.8 Reliability and Maintenance

Reliability and maintenance requirements are crucial considerations for electric vehicle manufacturers. While induction motors are often lauded for their robustness and minimal maintenance needs, recent studies have focused on improving the reliability of brushless motors. Advanced sensor technologies and fault diagnosis systems have been explored to enhance the reliability of brushless motor systems in electric vehicles [44].

2.2.9 Cost Considerations

Cost is a significant factor influencing the choice of motor technology in electric vehicles. Induction motors, being less dependent on rare earth materials, are often perceived as more cost-effective. However, research has focused on cost-reduction strategies for brushless motors, exploring innovative manufacturing processes and material choices to make them more competitive in terms of overall cost [45].

2.3 Advances in Motor Control Algorithms[46]

The effectiveness and functionality of brushless and induction motors depend significantly on the control algorithms utilized. Recent studies have explored sophisticated control techniques like predictive control and artificial intelligence-driven algorithms to enhance the efficiency of these motors in electric vehicles [47]. Motor control algorithms are crucial components in the field of robotics, automation, and mechatronics. These algorithms are responsible for controlling the movement and behavior of motors, ensuring precise and efficient operation. Here are some common motor control strategies with the Mathematical Data in Table 2-3.

Table 2-3-Control Strategies and Mathematical Data

Application Area	**Control Strategy**	**Key Mathematical/Technical Data**
Process Industry	Model Predictive Control (MPC)	-Optimization objectives (e.g., minimize cost, maximize efficiency) -System dynamics and constraints modeling -Prediction horizon and control horizon Real-time optimization algorithms
Robotics and Automation	Predictive Control for Robotics	-Trajectory planning and optimization -Dynamic modeling of robotic systems -Integration with vision systems for real-time feedback -Adaptive control strategies for changing environments
Energy Management	Predictive Control in Smart Grids	- Predicting loads and demand, incorporating renewable energy sources, managing grid stability and congestion, and optimizing

		battery and energy storage are crucial aspects of energy management.
Automotive Industry	Model Predictive Control in Vehicles	-Vehicle dynamics and control -Trajectory planning for autonomous vehicles -Collision avoidance and safety considerations -Fuel efficiency and emission optimization
Healthcare Systems	Predictive Control in Patient Treatment	-Pharmacokinetic and pharmacodynamic modeling -Dosage optimization for personalized medicine -Real-time patient monitoring and adaptive control Minimizing side effects and optimizing treatment outcomes
Supply Chain Management	Predictive Analytics for Inventory Control	-Demand forecasting and supply chain modeling -Inventory optimization and order fulfillment -Real-time tracking and logistics optimization -Risk management strategies for supply chain disruptions
Environmental Monitoring	AI-Based Algorithms for Pollution Control	-Sensor data processing and pattern recognition

		-Adaptive control for minimizing environmental impact -Integration with data from satellite imaging and remote sensing

2.3.1 Proportional-Integral-Derivative (PID) Control in Motor Management Applications:

The Proportional Integral Derivative (PID) control method is an algorithm widely used in engineering applications to achieve precise control over dynamic systems and classic controller method type shown in the block diagram shown in Figure 2-4, especially in motor management where it is essential to regulate position, velocity, and torque. By incorporating proportional, integral, and derivative components, PID control provides a balanced approach that enhances system stability while ensuring prompt responsiveness to changes, making it ideal for motor control in applications where precision and adaptability are required[48].

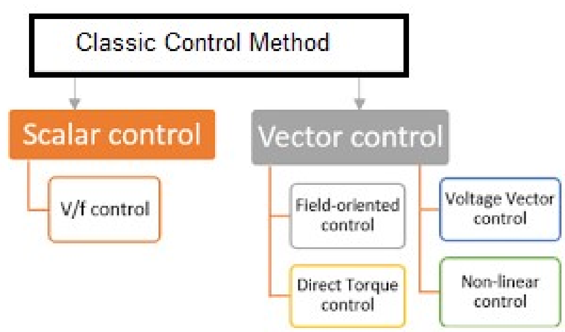

Figure 2-4-Block Diagram of Classic Controller

2.3.1.1 *PID Control Components and Their Functions:*

2.3.1.1.1 Proportional (P) Component:

The proportional component generates a control output proportional to the error, which is the difference between the desired set point and the current process variable. The proportional gain K_p, determines the control output's sensitivity to error; higher K_p values improve responsiveness but may lead to instability if too high[41]. Mathematically, this term is expressed as:

$$P_{output} = K_p \times error \tag{2-1}$$

2.3.1.1.2 Integral (I) Component:

The integral component addresses accumulating past errors by summing them over time, effectively eliminating residual steady-state error. The integral gain, K_i , dictates the accumulation rate of the integral action. If set too high, K_i may, lead to oscillations or overshoot, while low values result in slower response times. The integral action is mathematically represented as:

$$I_{output} = K_i \times \int_0^t error\, dt \tag{2-2}$$

2.3.1.1.3 Derivative (D) Component:

The derivative component predicts future error trends by considering the rate of change of the error, offering a dampening effect that reduces overshoot and improves system stability. The derivative gain, K_d determines the control response's sensitivity to the rate of error change. Excessively high K_d values can lead to system instability due to amplified noise, while low values reduce the dampening effect. The derivative term is expressed as:

$$D_{output} = K_d \times \frac{d(error)}{dt} \tag{2-3}$$

The overall PID controller output, which is the sum of these three components, can be formulated as:

$$\text{Control output} = K_p \times error + K_i \int_0^t error\, dt + K_d \times \frac{d_{error}}{dt} \tag{2-4}$$

2.3.1.2 *Tuning PID Parameters for Motor Control:*

Tuning the PID parameters K_p, K_i and K_d is crucial to achieving optimal performance in motor control applications. A well-tuned PID controller ensures that the system reaches the desired setpoint quickly, with minimal overshoot and without excessive oscillations [49]. Standard tuning methods include:

2.3.1.2.1 Ziegler-Nichols Method:

This empirical approach involves setting $K_i$and K_d to zero, increasing K_p until sustained oscillations occur, and then using predefined formulas to determine the optimal values of K_p, $K_i$and K_d.

2.3.1.2.2 Cohen-Coon Method:

Suitable for first-order systems with time delays, this method uses system-specific data, such as time constant and delay, to calculate PID parameters.

2.3.1.2.3 Automatic Tuning:

Many modern PID controllers come equipped with self-tuning capabilities that automatically adjust parameters based on real-time feedback, allowing for adaptive control in dynamic environments.

2.3.1.3 *Application of PID Control in Motor Management:*

In motor management applications, PID control can be utilized for:

2.3.1.3.1 Position Control:

By adjusting the motor's position to reach a specified setpoint, PID controllers provide precise positioning necessary for robotic arms, CNC machines, and actuators [39].

2.3.1.3.2 Velocity Control:

In scenarios where speed regulation is crucial (e.g., conveyor belts, fan control), PID controllers adjust the motor's speed to meet the desired rate with minimal error, accounting for load changes and external disturbances.

2.3.1.3.3 Torque Control:

For applications requiring torque control, such as electric vehicles, PID controllers regulate the torque output of motors, maintaining stability while responding dynamically to load variations.

2.3.1.4 *Achieving Stability and Agility with PID Control:*

PID controllers achieve a balance between stability and agility through the combined actions of the P, I, and D components. The proportional term provides an immediate response to error, the integral term eliminates persistent errors, and the derivative term stabilizes the system against sudden changes, preventing overshoot. By fine-tuning these components, PID controllers maintain stability without compromising the agility needed to respond to rapid changes in setpoints or disturbances[50].

2.3.1.5 *Benefits and Limitations in Motor Control Applications:*

The PID control method offers various benefits, such as:

(a) Ease of Implementation:

Due to its straightforward algorithmic structure, PID controllers are simple to implement in both analog and digital systems.

(b) Broad Applicability:

PID controllers are versatile and suitable for controlling position, velocity, and torque across diverse motor types.

(c) High Accuracy:

Well-tuned PID controllers provide high accuracy and minimal steady-state error. However, limitations include susceptibility to noise (particularly in the derivative component) and potential difficulty in tuning for systems with complex dynamics or non-linear behavior[25].

The PID control method is widely adopted in motor management due to its flexibility, adaptability, and effectiveness in ensuring precise control. By appropriately tuning the proportional, integral, and derivative gains, PID control enables effective regulation of position, velocity, and torque in motor-driven systems. This combination of simplicity and effectiveness makes PID control an invaluable tool in motor management applications where both stability and agility are critical.

2.3.2 Field-Oriented Control (FOC) or Vector Control:

Field-Oriented Control (FOC), also known as Vector Control, is an advanced method used to regulate AC motors, particularly induction and synchronous motors, by decoupling the control of torque and flux. The technique leverages mathematical transformations to manipulate motor parameters, converting complex alternating current (AC) signals into a simplified, steady-state representation. This decoupling allows for more precise and efficient control over the motor's output characteristics[41][44].

2.3.2.1 *Mathematical Transformations:*

2.3.2.1.1 Clark Transformation:

First, the three-phase stator currents (i.e., I_a I_b and I_c) are transformed into two-phase currents I_α and I_β in a stationary coordinate system using the Clark transformation.

2.3.2.1.2 Park Transformation:

The stationary two-phase system is then converted into a rotating reference frame using the Park transformation. In this rotating reference frame, the motor currents are expressed as two components, I_d (direct axis, aligned with the rotor flux) and I_q (quadrature axis, perpendicular to the rotor flux).

2.3.2.1.3 Control of I_d and I_q Components:

With the direct and quadrature components defined, I_d and I_q can be independently controlled. The I_d component regulates the rotor's magnetic flux, while I_q is responsible for torque production. By controlling I_d and I_q independently, FOC enables a linear relationship between motor torque and current, similar to the behavior of a DC motor.

2.3.2.2 *PWM Modulation and Inverter Control:*

- Following the transformations, control signals are sent to the inverter's pulse-width modulation (PWM) unit, which adjusts the switching patterns to achieve the desired current outputs for each phase. By continually monitoring the position of the rotor flux and updating the control inputs accordingly, the FOC system maintains optimal performance and responds dynamically to changing load demands[51].

2.3.2.2.1 Advantages of FOC in AC Motors:

Field-oriented control offers several advantages for motor control, making it a preferred choice in applications demanding high dynamic performance, accuracy, and efficiency:

2.3.2.2.2 Decoupled Torque and Flux Control:

FOC enables independent control over torque and flux, enhancing response time and precision.

2.3.2.2.3 High Efficiency and Speed Range:

The linear relationship between torque and current provides improved efficiency across a wide speed range, enabling more effective control, especially at low speeds.

2.3.2.2.4 Smooth and Precise Performance:

This method minimizes oscillations and delivers smoother motion, even under varying load conditions, which is essential for applications requiring high accuracy.

2.3.2.3 *Applications of FOC:*

Due to these advantages, FOC has become widely adopted in sectors that rely on precise motor control. Its typical applications include:

2.3.2.3.1 Electric Vehicle (EV) Drives:

In EVs, FOC provides high efficiency and responsiveness, crucial for vehicle acceleration, regenerative braking, and overall energy efficiency. FOC is also effective for traction control, ensuring stable and reliable motor performance across various driving conditions.

2.3.2.3.2 Industrial Automation:

Many industrial systems use FOC to optimize AC motors, particularly where variable-speed drives are essential for processes requiring precise torque and speed control, such as in conveyor systems, hoists, and CNC machines.

2.3.2.3.3 Robotics:

FOC is instrumental in robotic arms and actuators, providing smooth, high-precision control that enhances robotic motion and accuracy, essential for tasks requiring dexterity and fine positioning.

2.3.2.4 *Technical Data Summary for FOC Implementation:*

A few technical points provide further insight into FOC implementation:

2.3.2.4.1 Controller Types:

Proportional-integral (PI) controllers are commonly used to regulate the I_d and I_q components[52].

2.3.2.4.2 Sampling Frequency:

High sampling rates (typically between 10-20 kHz) are required to ensure real-time tracking and control.

2.3.2.4.3 Inverter and PWM Requirements:

A PWM inverter with high switching frequencies enables precise adjustments of voltage and current, critical for maintaining desired I_d and I_q values.

In summary, Field-Oriented Control is a robust and efficient control method, achieving precise and independent control over motor performance. Its capacity to separate torque and flux makes it invaluable in applications where dynamic response and accuracy are key, such as in EV drives, industrial automation, and robotics. By enhancing AC motor capabilities, FOC supports advanced applications in modern, energy-efficient systems.

2.3.3 Model Predictive Control (MPC)

Model Predictive Control (MPC) is an advanced control strategy employed in various fields, ranging from robotics to complex industrial processes. MPC uses a mathematical model of the system to predict and optimize control actions over a specified future time horizon. This predictive capability, combined with the integration of system constraints, makes MPC highly suitable for systems with nonlinearities, delays, and time-varying dynamics, often encountered in electric motor control, robotic systems, and other demanding environments[53].

2.3.3.1 *How MPC Works: Core Concepts and Mechanisms:*

2.3.3.1.1 System Model and Prediction Horizon:

- MPC relies on an internal dynamic model of the system to forecast future states based on current and past control inputs. The model is typically represented as a discrete-time state-space or transfer function model, which captures the behavior of the system over time[54].

- A critical component of MPC is the prediction horizon—the time frame within which MPC simulates and predicts system responses. A longer horizon can lead to better control precision but increases computational demand.

2.3.3.1.2 Cost Function Optimization:

- MPC continuously optimizes a cost function, which quantifies the error between predicted outputs and desired reference values over the prediction horizon. The cost function often includes terms for tracking errors, control effort, and other system-specific performance metrics.

- Minimizing the cost function ensures that the controller delivers the desired performance while respecting system constraints, balancing the trade-off between control accuracy and stability.

2.3.3.2 *System Constraints Handling:*

- MPC incorporates hard and soft constraints on states and inputs, enabling the controller to respect physical and operational limitations such as motor torque limits, maximum voltage or current, and position bounds.

- By embedding these constraints into the optimization process, MPC ensures safe and feasible control actions, essential for systems where constraint violation could lead to instability or hardware damage.

2.3.3.3 *Optimization Process:*

- At each time step, MPC solves an optimization problem that minimizes the cost function over the prediction horizon. The receding horizon approach is applied, where only the first control action from the optimized sequence is implemented before the entire process is repeated.

- This real-time optimization allows MPC to adapt to changing conditions and disturbances, making it robust in dynamic environments where accurate control is critical.

2.3.3.4 *Technical Data on MPC for Electric Motor Control Applications:*

2.3.3.4.1 Dynamic Model Representation:

For electric motors, an MPC approach would typically employ a state-space model that represents the motor's current, speed, and torque as state variables[55]. These dynamics can include nonlinear elements, like saturation effects, which make traditional control challenging.

2.3.3.4.2 Prediction Horizon and Sampling:

Typical prediction horizons for motor control applications might range from 10-30 milliseconds, with sampling rates in the range of 1 kHz or higher to ensure smooth and rapid response to load changes and disturbances.

2.3.3.4.3 Constraints:

In electric motor control, common constraints include maximum allowable current to prevent overheating, voltage limits to avoid damage to electrical components, and torque limits to protect mechanical structures.

2.3.3.4.4 Optimization Metrics:

The cost function in MPC for motor applications often combines terms for speed tracking (to ensure the motor follows the desired speed profile), torque ripple minimization (to reduce mechanical stress and noise), and power consumption optimization (for energy efficiency)[56].

2.3.3.5 *Benefits of MPC in Systems with Nonlinear Elements:*

2.3.3.5.1 Enhanced Stability and Precision:

MPC's predictive capabilities and real-time optimization ensure high-precision control, particularly valuable in nonlinear systems where simple control techniques fall short.

2.3.3.5.2 Flexibility with Nonlinear and Time-Variant Dynamics:

By incorporating a dynamic model, MPC handles nonlinear behaviors, such as load-dependent torque characteristics or magnetic saturation in motors, and can adapt to time-varying parameters.

2.3.3.5.3 Efficient Constraint Management:

The ability to incorporate physical constraints directly into the control formulation ensures that the control actions respect system limitations, enhancing the operational safety and longevity of the controlled equipment.

2.3.3.6 *Applications in Robotics and Industrial Operations:*

In robotics and advanced industrial systems, MPC excels due to its predictive control and handling of complex dynamics. Specific applications include:

2.3.3.6.1 Robotics:

MPC is used for trajectory tracking, path planning, and collision avoidance, providing real-time adaptability to environmental changes and dynamic obstacles.

2.3.3.6.2 Industrial Automation:

For processes such as chemical batch reactions or precision machining, MPC ensures optimal performance by dynamically adjusting control inputs to meet quality standards while respecting equipment constraints.

2.3.3.6.3 Electric Motor-Driven Applications:

MPC is increasingly applied in motor-driven systems where control precision, efficiency, and responsiveness are paramount, such as in electric vehicles, robotic actuators, and conveyor systems in manufacturing.

The high computational demand of MPC, particularly for systems with long prediction horizons or complex constraints, can limit its use in applications where processing power is restricted. Advances in computational efficiency, model reduction techniques, and hardware acceleration (e.g., using GPUs) are broadening MPC's feasibility for embedded applications. As predictive models continue to improve, MPC is expected to gain traction in emerging fields like autonomous systems and smart grids, where it can enhance control strategies in uncertain and highly dynamic environments.

2.3.4 Sliding Mode Control (SMC):

Sliding Mode Control (SMC) is a robust, nonlinear control method widely recognized for its effectiveness in dealing with systems that exhibit uncertainties or disturbances. This control technique establishes a sliding surface in the state space, which is a predefined manifold where the system dynamics are enforced to evolve. By using a discontinuous control signal, SMC drives the system states toward this surface and maintains them there, effectively transforming a high-dimensional control problem into a lower-dimensional one, and simplifying system behavior[25].

2.3.4.1 ***Sliding Surface Design:***

The sliding surface in SMC is defined by a specific equation, typically as a linear combination of system states. For a system with a state vector x the sliding surface S_x can often be defined as:

$$S_x = C_x \tag{2-5}$$

where C is a constant matrix that determines the characteristics of the surface. The sliding surface represents the desired behavior, guiding the system trajectory towards equilibrium. Once the system reaches this surface, the motion is constrained, reducing the system's effective order. This property allows SMC to manage high-order, complex systems by focusing on behavior along the sliding manifold.

2.3.4.2 ***Control Law and Switching Mechanism:***

The key feature of SMC is its use of a discontinuous control law that switches the system states across the sliding surface, effectively 'sliding' the states along this surface. The control law u_t generally has two components:

$$u_t = u_{eq}(t) + u_{sw}(t) \tag{2-6}$$

2.3.4.2.1 Equivalent Control $u_{eq}(\mathrm{t})$:

This term compensates for the nominal dynamics, keeping the system on the sliding surface.

2.3.4.2.2 Switching Control$u_{sw}(t)$:

This term enforces the sliding mode, typically designed as:

$$u_{sw}(t) = -K\, sin\, (S(x)) \tag{2-7}$$

where K is a positive gain and (S(x)) indicates a switching function. The switching action ensures robustness by stabilizing the system against model uncertainties and external disturbances.

2.3.4.3 ***Robustness and Chattering:***

A prominent strength of SMC lies in its robustness to disturbances and modeling inaccuracies. Once on the sliding surface, the system is unaffected by certain disturbances, as long as they satisfy the matched condition—meaning the disturbance lies within the span of the input matrix. However, the high-frequency switching introduced by $u_{sw}(t)$ can lead to a phenomenon called chattering, where rapid control oscillations occur near the sliding surface, potentially causing wear in mechanical systems or unwanted dynamics in electrical circuits.

To mitigate chattering, methods such as boundary layer design and higher-order SMC are often employed:

2.3.4.3.1 Boundary Layer Approach:

By introducing a boundary layer around the sliding surface, the sign function is replaced with a continuous approximation, reducing chattering at the cost of slightly less precision.

2.3.4.3.2 Higher-Order SMC:

In this approach, derivatives of the sliding variable are used, creating smoother control signals and further reducing chattering.

2.3.4.4 *Applications of SMC:*

SMC's robustness makes it suitable for various applications, particularly in systems with uncertain dynamics, such as:

2.3.4.4.1 Mechanical Systems:

SMC is frequently applied in robotics, where model uncertainties and external forces (like friction or payload variations) impact performance. SMC helps ensure precise tracking even when these uncertainties are present.

2.3.4.4.2 Electric Drives and Power Systems:

In high-performance control of electric drives, SMC offers fast response and robustness against parameter variations. Applications in permanent magnet synchronous motors (PMSMs) and induction motor drives are popular due to SMC's stability and resistance to load disturbances.

2.3.4.4.3 Aerospace Systems:

SMC is suitable for controlling spacecraft and UAVs, where it can counteract aerodynamic uncertainties and environmental disturbances.

2.3.4.4.4 Automotive Systems:

Advanced vehicle stability control and anti-lock braking systems use SMC to ensure robustness and performance under varying road conditions.

2.3.4.5 *Implementation and Practical Considerations:*

To implement SMC effectively, system parameters and control gains must be carefully selected. Gains should be high enough to enforce the sliding condition but optimized to prevent excessive chattering. Implementing boundary layers can make SMC more practical in physical systems, where actuation limits and system constraints are present. Controller tuning can also benefit from adaptive or fuzzy logic techniques, allowing the SMC controller to adjust parameters in real-time based on operating conditions.

Sliding Mode Control remains a valuable tool in modern control engineering due to its robustness in the face of model uncertainties and external disturbances. While it requires careful design to address chattering, advances in SMC techniques—such as higher-order SMC and boundary layer methods—have broadened their applicability in various engineering fields.

2.3.5 Fuzzy Logic Control:

2.3.5.1 *Linguistic Variables:*

Unlike numerical variables, linguistic variables in FLC describe qualitative aspects of a system's behavior, such as "high," "medium," or "low." These variables are defined by fuzzy sets that assign a degree of membership to each value within a range, representing how well a given input belongs to a particular set.

2.3.5.2 *Membership Functions:*

Membership functions define how each input value corresponds to a linguistic variable. Commonly used types include triangular, trapezoidal, and Gaussian functions. For instance, in a temperature control system, the fuzzy sets "Cold," "Warm," and "Hot" could be defined by overlapping membership functions, where "Cold" might cover temperatures between 0°C and 20°C, "Warm" from 15°C to 30°C, and "Hot" above 25°C. This overlap is crucial as it allows the system to handle inputs with ambiguity by blending the boundaries of each linguistic term.

2.3.5.3 *Fuzzy Rules:*

Fuzzy logic controllers utilize "if-then" rules to create control actions based on the relationship between input and output variables. These rules are created from human expertise or observed system behavior. A typical rule might state, "If the temperature is high and the humidity is low, then set the fan speed to high." This rule-based approach is more flexible than strict mathematical models, making it easier to adapt and fine-tune the system according to practical needs.

2.3.5.4 *Structure of a Fuzzy Logic Controller:*

A fuzzy logic controller has three main components:

2.3.5.4.1 Fuzzification:

In this initial step, input data is converted into degrees of membership across relevant linguistic variables. For instance, if the input temperature is 22°C, fuzzification might determine that it belongs 30% to the "Cold" category, 70% to "Warm," and 0% to "Hot." This is the process of translating crisp values into fuzzy sets.

2.3.5.4.2 Inference Engine:

The inference engine is responsible for applying fuzzy rules to the fuzzified inputs. Using methods such as Mamdani or Sugeno inference, the engine processes each rule to determine the system's output behavior. For instance, the rule "If the temperature is warm, then set cooling to medium" would activate and influence the output proportionally.

2.3.5.4.3 Defuzzification:

The output of the inference engine is a fuzzy set, which must be converted back to a crisp value. This step, known as defuzzification, translates the fuzzy output to a specific action or control signal. Techniques like the centroid method are often employed, which calculates the center of gravity of the fuzzy set, resulting in a single numerical output.

2.3.5.5 *Technical Application of Fuzzy Logic Control:*

2.3.5.5.1 Automotive Systems:

In vehicles, fuzzy logic controllers handle various control tasks such as automatic transmission, antilock braking systems (ABS), and cruise control. For example, in an ABS, a fuzzy controller can evaluate the braking force needed under different road conditions by processing inputs like wheel speed and slip rate, and then modulating the braking pressure to prevent skidding. Traditional controllers would struggle with the same level of adaptability without a precise model.

2.3.5.5.2 Household Appliances:

Fuzzy logic has widespread application in appliances where simple, adaptable controls are preferred. In washing machines, for instance, fuzzy controllers optimize the wash cycle by analyzing load weight, soil level, and fabric type. Fuzzy rules then adjust the water level, detergent concentration, and agitation speed for efficient cleaning without user intervention.

2.3.5.5.3 Industrial Processes:

Fuzzy controllers excel in managing complex industrial processes, such as chemical mixing, where precise models are impractical due to varying conditions. In such cases, a fuzzy controller can interpret sensor readings (e.g., pH, temperature, flow rate) and adjust inputs accordingly, ensuring stable operation and product quality.

2.3.5.6 *Advantages of Fuzzy Logic Controllers:*

2.3.5.6.1 Adaptability and Robustness:

Fuzzy controllers handle nonlinearities and uncertainties well, which makes them robust against parameter variations and noise. They can be adjusted or “trained” based on expert knowledge or observed performance, rather than requiring exact model-based adjustments.

2.3.5.6.2 Human-Like Reasoning:

By using linguistic terms and rules, fuzzy controllers can closely approximate human decision-making processes, making them ideal for applications that require intuitive control, such as user interfaces in electronics.

2.3.5.6.3 Simplification of Complex Systems:

In systems where it’s challenging to derive mathematical models, fuzzy logic provides an effective alternative, reducing computational demands and making it easier to design and implement controllers.

2.3.5.7 *Challenges and Limitations:*

2.3.5.7.1 Rule Explosion:

In complex systems with multiple inputs and outputs, the number of rules required can increase exponentially, leading to a “rule explosion.” This makes it necessary to use optimization techniques (e.g., genetic algorithms) to simplify rule bases.

2.3.5.7.2 Difficulty in Defining Membership Functions:

The design of membership functions requires expert input and can be subjective. Incorrect or overly generalized membership functions may affect control accuracy, necessitating iterative tuning or adaptive methods.

In summary, fuzzy logic control provides an effective solution for applications requiring flexible, human-like decision-making capabilities. It allows systems to operate reliably in the presence of uncertainty, adapting to varied conditions without needing precise mathematical models. As a result, FLC remains valuable across fields from automotive to household appliances, especially in scenarios where classical control approaches are infeasible or overly complex.

2.3.6 Description and Mechanism of Adaptive Control:

Adaptive control algorithms rely on feedback from the system's response to determine the necessary parameter adjustments. The underlying principle involves continuously monitoring the system’s output and comparing it to a desired reference or setpoint. If deviations arise, the adaptive control algorithm modifies the controller parameters to minimize these deviations, thus stabilizing the system and achieving optimal performance.

The adaptation process typically includes two main components:

2.3.6.1 *Identification Mechanism:*

This component estimates the current parameters or states of the system based on input-output data.

2.3.6.2 *Control Law Adjustment:*

Based on the identified parameters, the control law adjusts the controller parameters in real time to achieve the desired response.

The adaptive control framework commonly uses either direct or indirect approaches:

2.3.6.2.1 Direct Adaptive Control:

In this approach, the controller parameters are adjusted without explicitly identifying the system's parameters.

2.3.6.2.2 Indirect Adaptive Control:

This approach involves identifying the system parameters first and then calculating the controller parameters based on this model.

The control strategy's adaptability allows it to manage systems with time-varying characteristics, modeling uncertainties, and nonlinear behaviors, providing robustness that fixed controllers cannot offer.

2.3.6.3 ***Mathematical Foundation of Adaptive Control:***

Adaptive control strategies often rely on mathematical models, including:

2.3.6.3.1 Model Reference Adaptive Control (MRAC):

MRAC ensures the system follows a reference model's behavior by continuously adjusting the controller parameters. For instance, using a Lyapunov function-based stability criterion, MRAC minimizes the error between the model and the actual system, guaranteeing stability under varying parameters.

2.3.6.3.2 Self-Tuning Regulators (STR):

STR utilizes recursive estimation techniques, such as least squares or Kalman filters, to identify the system parameters in real time and then update the control law accordingly. STR is widely used for stochastic systems or systems with noise, as it provides robust performance.

In each adaptive control method, parameter estimation algorithms, such as gradient descent or least squares estimation, are used to update controller gains or coefficients. For instance, a gradient descent algorithm minimizes a cost function based on the error, adjusting controller parameters to reduce the deviation over time.

2.3.6.4 *Application of Adaptive Control in Systems with Uncertain or Varying Conditions:*

Adaptive control is particularly valuable in fields where system parameters change unpredictably or are challenging to model accurately. Applications include:

2.3.6.4.1 Aerospace Engineering:

Aircraft dynamics are affected by factors like altitude, temperature, and structural loads, which can change drastically during a flight. Adaptive control helps adjust the autopilot and flight control systems in real-time, maintaining stability across varying conditions.

2.3.6.4.2 Robotics:

In industrial robotics, adaptive control manages changes in load and joint friction. Adaptive algorithms allow robots to modify movement speed and force, ensuring precision even with varying payloads or unforeseen environmental changes.

2.3.6.4.3 Automotive Systems:

Adaptive cruise control and anti-lock braking systems use adaptive control to respond to changes in road friction, vehicle load, and other dynamic factors, improving safety and comfort.

2.3.6.4.4 Process Control in Manufacturing:

Adaptive control is employed in chemical and manufacturing processes where external disturbances, raw material variations, or environmental factors affect production. Adaptive controllers ensure consistent output by adjusting parameters to compensate for these disturbances.

2.3.6.5 *Technical Data and Performance Metrics for Adaptive Control:*

Technical data for evaluating adaptive control systems often includes metrics such as:

2.3.6.5.1 Parameter Convergence Speed:

The speed at which the controller parameters reach a stable value after a change in system characteristics. This is critical for systems with high-frequency disturbances.

2.3.6.5.2 Tracking Error:

The deviation between the actual system output and the desired reference output. A low tracking error indicates effective adaptation.

2.3.6.5.3 System Stability:

Adaptive controllers need to ensure that parameter updates do not destabilize the system. Stability can be confirmed using Lyapunov's stability criterion.

2.3.6.5.4 Robustness Against Noise:

Adaptive control systems often operate in environments with sensor noise or measurement disturbances, so robustness metrics help evaluate the controller's ability to filter out noise.

For instance, an adaptive control system applied in an autonomous vehicle might be tested under varying road conditions, loads, and speeds. Data on real-time tracking error, parameter adaptation time, and stability across scenarios help verify the effectiveness of the adaptive control approach.

2.3.6.6 *Advantages and Challenges of Adaptive Control:*

2.3.6.6.1 Advantages:

- Adaptive controllers adjust to unpredictable changes, making systems more resilient to parameter variations and disturbances.

- Adaptive control is effective for nonlinear systems that fixed-parameter controllers struggle to manage.

- By optimizing the response to dynamic conditions, adaptive control can reduce wear and tear on mechanical components.

2.3.6.6.2 Challenges:

-The development of adaptive control algorithms requires a deep understanding of system dynamics, which can be computationally intensive and complex.

- Ensuring stability under all conditions is challenging, especially when system parameters vary rapidly.

- Adaptive control depends on accurate, real-time data, which can be challenging to obtain in certain environments.

Adaptive control provides a powerful solution for systems with unpredictable or time-varying characteristics, maintaining performance by updating controller parameters in real-time. Its applications span aerospace, robotics, automotive, and industrial processes, where system resilience and performance are paramount. With advancements in computational power and sensor technology, adaptive control is becoming increasingly accessible and applicable, driving innovation in various fields where stability and adaptability are essential.

2.3.7 Brushless DC Motor (BLDC) Commutation Algorithms:

Description: BLDC motors require specific commutation algorithms to control the switching of power electronics devices. Common methods include trapezoidal commutation and sinusoidal commutation.

Application: Used in applications like electric vehicles, drones, and computer cooling systems.

Algorithms like these can be applied using different programming languages and are frequently incorporated into microcontrollers or digital signal processors for real-time motor control. The selection of the algorithm is determined by the particular needs and attributes of the motor control system.

2.3.8 Dynamic Response and Torque Ripple

The dynamic response and torque ripple of motors are crucial factors affecting the overall performance of electric vehicles as shown in Table 2-4. Research has compared the dynamic response characteristics and torque ripple of induction motors and brushless DC motors under different operating conditions, shedding light on their suitability for applications with varying load profiles [57].

Table 2-4- Overall performance, Dynamic response of EV

Motor Type	Dynamic Response	Torque Ripple	Operating Conditions	Research Article References
Induction Motors	- Comparatively lower dynamic response due to rotor inertia.	- Moderate torque ripple attributed to inherent motor design.	- Varying load conditions, such as sudden accelerations and decelerations.	[58]
Brushless DC Motors	- Rapid dynamic response due to low rotor inertia and precise control.	- Low torque ripple, especially in sensor-based control systems.	- Diverse load profiles, including constant and fluctuating loads.	[59]
Comparison/Conclusion	- Brushless DC motors offer a superior dynamic response, making them suitable for applications requiring quick and precise adjustments.	- Both motor types exhibit manageable torque ripple, but BLDC motors can achieve lower ripple levels.	- The choice depends on the specific application requirements and desired performance characteristics.	[41]

2.3.9 Regenerative Braking Performance

Regenerative braking plays a crucial role in electric vehicles by enabling energy recovery. Research has explored and contrasted the regenerative braking capabilities of induction motors and brushless DC motors, examining aspects like braking efficiency, energy recuperation, and control methodologies [20].

In summary, regenerative braking is an essential aspect of electric vehicles, playing a significant role in recovering energy and enhancing overall efficiency. Research has thoroughly investigated and compared the regenerative braking capabilities of two major motor types: induction motors and brushless DC motors. These studies have examined different factors such as braking efficiency, energy recuperation, and control methods to improve the performance of regenerative braking systems. The research conducted by authors such as [60] has shed light on the nuances of regenerative braking in induction motors shown in Figure 2-4, offering insights into the intricacies of their performance and potential areas of improvement. Additionally, works like [61] have delved into the regenerative braking capabilities of brushless DC motors, providing a comparative analysis with induction motors and highlighting their respective advantages and limitations. Through these studies, the electric vehicle industry gains a comprehensive understanding of the factors influencing regenerative braking, paving the way for advancements in technology and control strategies. The results of this study make a significant contribution to improving regenerative braking systems and lay the groundwork for future advancements in electric vehicle technology and the efficient use of sustainable energy. As the field continues to evolve, the integration of regenerative braking technologies will likely become even more sophisticated, enhancing the overall efficiency and sustainability of electric vehicles.

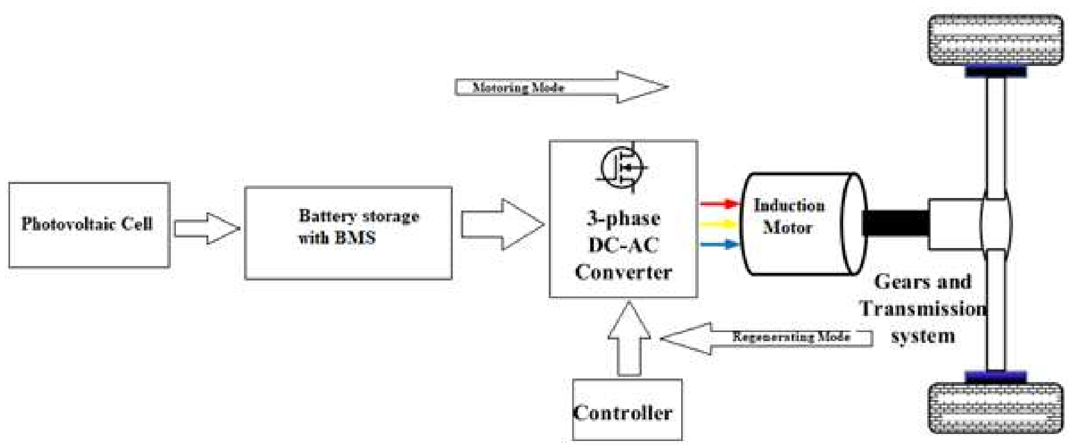

Figure 2-5-Induction Motor: Regeneration and Motoring Mode

2.3.10 Efficiency at Partial Load Conditions

Electric vehicles often operate under partial load conditions as shown in Table 2-5 during real-world driving scenarios. Studies have investigated the effectiveness of induction motors and brushless DC motors under partial load conditions, offering valuable insights into how these motors perform relative to each other in practical driving scenarios [24].

Table 2-5-Partial Load Efficiency: BLDC vs IM [62]

Aspect	Induction Motors	Brushless DC Motors
Efficiency at Partial Load Condition	Research indicates varying efficiency levels at partial loads, with a potential decrease in efficiency compared to full load conditions.	Studies suggest relatively better efficiency at partial loads, potentially outperforming induction motors in these scenarios.
Real-world Driving Scenarios	Performance in real-world driving conditions might exhibit fluctuations, and the efficiency may be influenced by factors such as acceleration, deceleration, and speed variations.	Brushless DC motors show promise in providing consistent and efficient performance in real-world driving scenarios, especially under partial load conditions.
Energy Consumption	Induction motors consume more energy under partial loads, reducing efficiency.	Brushless DC motors improve energy efficiency, extending electric vehicle range.
Temperature and Thermal Management	Operating under partial load conditions may lead to increased heating in induction motors, requiring effective thermal management systems.	Brushless DC motors, in some cases, exhibit better thermal performance under partial loads, reducing the need for extensive thermal management and enhancing overall reliability.

Regenerative Braking	Research suggests that induction motors may encounter challenges in maintaining high regenerative braking efficiency at partial loads.	Brushless DC motors show promise in achieving effective regenerative braking at partial loads, contributing to enhanced energy recovery during deceleration.

2.4 Temperature and Thermal Performance

Effective temperature control is essential for ensuring the durability and extended lifespan of electric vehicle motors. Research has delved into the thermal efficiency of both induction motors and brushless DC motors, examining variables like temperature increase, cooling techniques, and their influence on motor effectiveness [63]. Research on temperature management in electric vehicle (EV) motors highlights its crucial role in ensuring reliability and longevity. Studies have delved into the thermal performance of both induction motors and brushless DC (BLDC) motors, examining various factors that influence their temperature behavior. Some key findings include:

2.4.1 Temperature Rise

- Investigations have focused on understanding the temperature rise within electric vehicle motors during operation. Elevated temperatures can negatively impact motor components, leading to accelerated wear and potential failure.

- Researchers have measured and analyzed the temperature rise in different operating conditions to identify optimal temperature ranges for motor performance and longevity.

2.4.2 Cooling Strategies

- Various cooling strategies have been explored to mitigate excessive heat generation in EV motors. Common methods include air cooling, liquid cooling, and hybrid cooling systems.

- Studies compare the effectiveness of different cooling approaches in maintaining an optimal temperature range for motor components. This includes assessing the heat dissipation capabilities of cooling systems under varying loads and driving conditions [63].

2.4.3 Impact on Motor Efficiency

- Effective control of temperature significantly influences the performance of electric vehicle motors. Elevated temperatures can cause heightened resistance in motor windings and related parts, leading to energy wastage and diminished overall effectiveness [60].

- Researchers have investigated the correlation between motor temperature, efficiency, and energy consumption to develop strategies that optimize temperature conditions for improved motor performance. Thermal Modeling and Simulation: Mathematical modeling and simulation methods are utilized to forecast and examine the thermal performance of electric vehicle (EV) motors. These techniques include finite element analysis (FEA) and computational fluid dynamics (CFD) simulations. These models assist researchers and engineers in comprehending how various design factors and operating conditions impact motor thermal performance, thus aiding in the development of more efficient and reliable cooling systems. When it comes to material selection, the choice of materials for motor components like stators and rotors is crucial for effective temperature management. Studies have investigated advanced materials with improved thermal conductivity and heat resistance to enhance the overall thermal efficiency of EV motors.

In the end, observations are research on temperature regulation in EV motors is comprehensive, encompassing temperature rise analysis, assessment of cooling strategies, understanding the effects on motor efficiency, employing thermal modeling techniques, and exploring advanced materials. These findings contribute significantly to the advancement of robust and efficient electric propulsion systems in the automotive industry.

2.4.4 Power Density and Compactness

The power density and compactness of motors are essential for electric vehicles, especially in constrained spaces. Research has focused on evaluating the power density and compactness of induction motors and brushless DC motors, exploring design considerations and material choices [64]. The study involved a comprehensive analysis of key performance metrics, including efficiency, torque characteristics, and thermal management. A series of simulation studies and experimental tests were conducted to assess the motors' behavior under various operating conditions.

The research involved extensive experimentation and simulation studies to evaluate the performance of both motor types across various driving scenarios. Key parameters such as efficiency, torque response, and thermal characteristics were thoroughly analyzed. The statement highlights the significance of power density and compactness in motors for electric vehicles, particularly in situations where space is limited. Research efforts have been directed towards assessing these two crucial factors in both induction motors and brushless DC motors. The inquiry entails a comprehensive examination of different design factors and material options aimed at improving the efficiency of these motors within the realm of electric vehicles.

2.4.5 Importance of Power Density and Compactness

- Power density pertains to the quantity of power generated by a motor about its size or weight. In the context of electric vehicles, enhancing power density is essential to attaining superior performance while maintaining optimal size and weight.

- Compactness is vital for electric vehicles operating in constrained spaces, such as compact cars or urban environments. Motors with smaller footprints contribute to increased flexibility in vehicle design and placement [12].

2.4.6 Focus on Induction Motors

- Induction motors are widely used in electric vehicles, and research has aimed to enhance their power density and compactness.

- Studies may involve optimizing the winding configurations, magnetic circuit design, and cooling systems to achieve higher power density without sacrificing efficiency.

2.4.7 Exploration of Brushless DC Motors

- Brushless DC motors are known for their efficiency and reliability in electric vehicles. Researchers have delved into improving their power density and compactness.

- The investigation may include advancements in magnet materials, stator and rotor design, and control algorithms to maximize the motor's performance within the given spatial constraints.

2.4.8 Design Considerations

- Researchers are likely examining various design aspects, such as the arrangement of coils, type of cooling systems, and integration with other vehicle components, to optimize the overall design for enhanced power density and compactness.

2.4.9 Material Choices

- Selecting appropriate materials is crucial for attaining the desired power density and compactness. Researchers may explore advanced materials for motor components to improve efficiency, reduce weight, and enhance overall performance.

In summary, the research in this field emphasizes the need for motors with high power density and compactness in electric vehicles, considering the specific challenges posed by constrained spaces. The exploration spans both induction motors and brushless DC motors, with a focus on design considerations and material choices to push the boundaries of motor performance in the context of electric mobility [65]. The study found that induction motors exhibited better thermal management capabilities during continuous operation at high speeds, making them more suitable for highway driving conditions. The ability to dissipate heat effectively contributed to sustained performance without compromising efficiency [66].

2.5 Recent Advances in Electric Vehicles: Photovoltaic-Based Electric Vehicles

2.5.1 PV Integration Strategies

Recent research has explored various strategies for integrating photovoltaic systems into electric vehicles, including solar roof panels, body-integrated solar cells, and innovative charging solutions [67].

2.5.2 Energy Harvesting Efficiency

Studies have investigated the efficiency of energy harvesting from photovoltaic systems on electric vehicles, considering factors such as solar cell efficiency, placement optimization, and real-world driving conditions [68]. This thesis compiles a wide range of relevant scholarly reviewed and research articles published in the reputed journal until the year 2024. The results and final insights from pertinent research endeavors are documented in Table 2-6 presented here.

Table 2-6- Reviewed article findings support research

Sl. No.	Detail of the journal/ Book / Book chapter/ website link	Year of Publication	Indexing of journal (Scopus/ SCI indexed)	Main findings or conclusion relevant to the proposed research work	Remark

1	F. F. Ahmad, O. Rejeb, A. Kadir Hamid, M. Bettayeb, and C. Ghenai, "Performance analysis and planning of Self-Sufficient solar PV-Powered electric vehicle charging station in dusty conditions for sustainable transport," *Transp. Res. Interdiscip. Perspect.*, vol. 27, no. August, p. 101214, 2024, doi: 10.1016/j.trip.2024.101214.	2024	SCI	Solar-powered off-grid EV station meets demand but underperform due to dust.	[69]
2	D. Hao *et al.*, "Solar energy harvesting technologies for PV self-powered applications: A comprehensive review," *Renew. Energy*, vol. 188, no. February, pp. 678–697, 2022, doi: 10.1016/j.renene.2022.02.066	2023	SCI	The observation reveals that the power attains its peak value at 1880 W when the photovoltaic (PV) panel operates without the MPPT algorithm, with the PV panel's power reaching 275 W under these conditions.	[68]

3	M. Errouha, S. Motahhir, Q. Combe, and A. Derouich, “Intelligent control of induction motor for photovoltaic water pumping system,” *SN Appl. Sci.*, vol. 3, no. 9, 2021, doi: 10.1007/s42452-021-04757-4	2023	SCI	The utilization of solar photovoltaic (SPV) panels has witnessed a surge, propelled by significant advancements in semiconductor technology and the subsequent decrease in costs.	[70]
4	H. Fakour *et al.*, “Evaluation of solar photovoltaic carport canopy with electric vehicle charging potential,” *Sci. Rep.*, vol. 13, no. 1, pp. 1–13, 2023, doi: 10.1038/s41598-023-29223-6	2023	SCI	A case study's findings revealed a possible solar energy yield of 140 MWh/year, which could power over 3000 vehicles for a full hour each month.	[53]

5	A. Srivastava, M. Manas, and R. K. Dubey, “Electric vehicle integration’s impacts on power quality in distribution network and associated mitigation measures: a review,” *J. Eng. Appl. Sci.*, vol. 70, no. 1, pp. 1–29, 2023, doi: 10.1186/s44147-023-00193-w.	2023	SCI	Electric vehicles in distribution networks may cause voltage imbalance and failures.	[71]
6	N. V. Martyushev, B. V. Malozyomov, S. N. Sorokova, E. A. Efremenkov, and M. Qi, “Mathematical Modeling the Performance of an Electric Vehicle Considering Various Driving Cycles,” *Mathematics*, vol. 11, no. 11, 2023, doi: 10.3390/math11112586	2023	SCI	Regular braking, especially in urban traffic conditions, contributes significantly to replenishing the battery with electrical energy.	[72]

7	M. Ibrahim, V. Rjabtšikov, and R. Gilbert, “Overview of Digital Twin Platforms for EV Applications,” *Sensors*, vol. 23, no. 3, 2023, doi: 10.3390/s23031414	2023	SCI	Many manufacturers commonly employ Digital Twin Platforms in Electric Vehicle (EV) applications. These platforms offer a virtual depiction or sophisticated simulation of a tangible object in real time.	[73]
8	S. Powell, G. V. Cezar, L. Min, I. M. L. Azevedo, and R. Rajagopal, “adoption,” vol. 7, no. October, 2022, doi: 10.1038/s41560-022-01105-7	2022	SCI	Renewable energy like solar energy can help to lower the load of the grid in the daytime.	[74]
9	T. Selmi, A. Khadhraoui, and A. Cherif, “Fuel cell–based electric vehicles technologies and challenges,” *Environ. Sci. Pollut. Res.*, vol. 29, no. 52, pp. 78121–78131, 2022, doi: 10.1007/s11356-022-23171-w	2022	SCI	Power electronics and alternative sources of energy to charge the EV battery becoming the right choice	[75]

10	A. I. S. Juhaniya, A. A. Ibrahim, M. A. A. Mohd Zainuri, M. A. Zulkifley, and M. A. Remli, "Optimal Stator and Rotor Slots Design of Induction Motors for Electric Vehicles Using Opposition-Based Jellyfish Search Optimization," *Machines*, vol. 10, no. 12, 2022, doi: 10.3390/machines10121217.	2022	SCI	Induction Motor is becoming the choice of motor for EVs	[76]
11	A. . de Souza, D.F.; Salotti, F.A.M.; Sauer, I.L.; Tatizawa, H.; de Almeida, A.T.; Kanashiro, "A Performance Evaluation of Three-Phase Induction Electric Motors between 1945 and 2020," *Energies*, vol. 15, no. 6, pp. 1–31, 2022, doi: 10.3390/en15062002	2022	SCI	The Squirrel Cage Induction Motor was found suitable for EVs in terms of robustness, reliability, and durability.	[21]

12	M. Aishwarya and R. M. Brisilla, “Design of Energy-Efficient Induction motor using ANSYS software,” *Results Eng.*, vol. 16, no. June, p. 100616, 2022, doi: 10.1016/j.rineng.2022.100616	2022	SCI	The induction motor is preferred for its adaptable motor control, use of cost-effective materials, and effective ventilation and cooling mechanisms. In particular, the Squirrel Cage Induction Motor (SCIM) is known for its compact design and efficient use of economical materials.	[77]
13	Y. Wu and E. Kontou, “Designing electric vehicle incentives to meet emission reduction targets,” *Transp. Res. Part D*, vol. 107, no. May, p. 103320, 2022, doi: 10.1016/j.trd.2022.103320	2022	SCI	monetary incentive scheme and more charging stations can be more beneficial to zero-emission and attract EV consumers.	[78]

14	L. Maybury, P. Corcoran, and L. Cipcigan, "Mathematical modeling of electric vehicle adoption: A systematic literature review," *Transp. Res. Part D Transp. Environ.*, vol. 107, no. May, p. 103278, 2022, doi: 10.1016/j.trd.2022.103278	2022	SCI	To enhance the energy efficiency, lifespan, and overall driving distance of electric vehicles (EVs), it is crucial to incorporate various energy sources, leading to reduced battery energy usage and improved durability.	[79]
15	P. O. Babalola and O. E. Atiba, "Solar powered cars - a review," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1107, no. 1, p. 012058, 2021, doi: 10.1088/1757-899x/1107/1/012058	2021	Scopus	Solar Power may be an alternative source to charge the battery of EVs.	[80]

16	A. Glowacz, "Thermographic fault diagnosis of ventilation in BLDC motors," *Sensors*, vol. 21, no. 21, Nov. 2021, doi: 10.3390/s21217245	2021	SCI	The investigation into identifying faults in three-phase induction motors used the SMOFS-20-EXPANDED technique along with LDA, NBC, and CT. The overall success rate of recognition reached 94.99 percent. Particularly noteworthy is the 100 percent. Accuracy was achieved when analyzing genuine thermal images of the three-phase induction motor.	[81]
17	H. B. Marulasiddappa and V. Pushparajesh, "Review on different control techniques for induction motor drive in electric vehicle," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1055, no. 1, p. 012142, 2021, doi: 10.1088/1757-899x/1055/1/012142	2021	SCI	The induction motor, being devoid of a commutator, is exceptionally dependable, and robust, and requires minimal maintenance, making it well-suited for Electric Vehicle (EV) applications.	[82]

18	J. Jimenez-Gonzalez, F. Gonzalez-Montañez, V. M. Jimenez-Mondragon, J. U. Liceaga-Castro, R. Escarela-Perez, and J. C. Olivares-Galvan, "Parameter identification of bldc motor using electromechanical tests and recursive least-squares algorithm: Experimental validation," *Actuators*, vol. 10, no. 7, 2021, doi: 10.3390/act10070143	2021	SCI	The identification of mechanical parameters through a no-load test was performed, demonstrating favorable results when compared to alternative motors.	[83]

19	B. S. I. and H. A. Alam Tahjib, Humaiya Tanzin, S M Imrat Rahman, "Development of a Solar Powered Electric Vehicle based on Tadpole Design," in *2021 2nd International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST)*, 2021, pp. 206–210. doi: 10.1109/ICREST51555.2021.9331052	2021	Scopus	Tadpole a solar-based three-wheel (Two front and one rear) vehicle design and performance evaluated by simulating PROTEUS software and has been validated using Lotus Shark Software.	[50]
20	J. A. Sanguesa, V. Torres-sanz, P. Garrido, F. J. Martinez, and J. M. Marquez-barja, "smart cities A Review on Electric Vehicles : Technologies and Challenges," pp. 372–404, 2021, [Online]. Available: https://doi.org/10.3390/smartcities4010022	2021	SCI	EVs are more comfortable than IC base vehicles due to the absence of noise; and vibration. Graphene can be a short charging method for the battery.	[84]

21	M. H. Mobarak, S. Member, R. N. Kleiman, and J. Bauman, "Solar-Charged Electric Vehicles : A Comprehensive Analysis of Grid, Driver, and Environmental Benefits," vol. 7782, no. c, 2020, doi: 10.1109/TTE.2020.2996363	2021	IEEE Xplore	Using economical thin-film solar cells on electric vehicle surfaces boosts efficiency by 20%, enhancing mileage and energy usage.	[85]
22	R. S. Sundararajan and M. T. Iqbal, "Dynamic Modelling of a Solar Energy System with Vehicle to Home Option for Newfoundland Conditions," *Eur. J. Eng. Technol. Res.*, vol. 6, no. 5, pp. 16–23, 2021, doi: 10.24018/ejers.2021.6.5.2497	2021	Scopus	The process of simulating and designing Vehicle-to-Home (V2H) and Vehicle-to-Grid (V2G) systems was carried out using HOMER and MATLAB Simulink.	[55]

23	B. S. R. Vinay Anand, Himanshu Sharma, “ENHANCING ELECTRIC VEHICLE EFFICIENCY WITH INDUCTION MOTORS AND OPTIMIZED SOLAR POWER INTEGRATION,” *China Pet. Process. Petrochemical Technol.*, vol. 24, no. 1, pp. 263–292, 2024, doi: 10.5281/zenodo.7778371	2021	Scopus	The Induction Motor outperforms the PM Machine at 4400-6000 rpm, offering 6kW continuous power and 87% peak efficiency.	[86]

24	B. S. and K. S. Kamal Singh, Anjanee Kumar Mishra, "Solar powered battery charging scheme for light electric vehicles (LEVs)," *Int. J. Emerg. Electr. Power Syst.*, vol. 22, no. 1, pp. 101–111, 2021, doi: 10.1515/ijeeps-2020-0200	2021	Scopus	The drawback of Battery Electric Vehicles (BEVs) is primarily associated with the lifespan of their batteries. Quick charging can cause corrosion, reducing the overall durability of the battery. The charging performance of a Light Electric Vehicle is evaluated using a half-effect current sensor (LA55-P). A small inductor (0.1 mH) can be strategically positioned close to the battery terminal to improve charging effectiveness and minimize variations.	[87]

25	S. Goel, R. Sharma, and A. Kumar, "A review on barrier and challenges of electric vehicle in India and vehicle to grid optimisation," vol. 4, no. January, 2021, doi: 10.1016/j.treng.2021.100057	2021	SCI	-Research gaps exist in EV technology, particularly in charging infrastructure, driving range, expertise, and consumer awareness of economic benefits. -Electric vehicle adoption depends on incentivizing policies and expanded charging infrastructure to promote widespread utilization and acceptance.	[88]
26	I. E. Atawi, E. Hendawi, and S. A. Zaid, "Analysis and Design of a Standalone Electric Vehicle Charging Station Supplied by Photovoltaic Energy," *processes*, vol. 9, p. 1246, 2021, doi: 10.3390/pr9071246	2021	SCI	Charging stations face grid overload and cost challenges with fast charging. A stand-alone charging station is a good support for the utility grid. The energy storage battery can overcome the charging and discharge at the time of solar variation.	[89]

27	W. Cai, X. Wu, M. Zhou, Y. Liang, and Y. Wang, "Review and Development of Electric Motor Systems and Electric Powertrains for New Energy Vehicles," *Automot. Innov.*, vol. 4, no. 1, pp. 3–22, 2021, doi: 10.1007/s42154-021-00139-z.	2021	SCI	The squirrel cage induction motor (IM) finds extensive application in electric vehicles (EVs). Its uncomplicated yet robust design, cost-effectiveness, superior reliability, minimal noise, negligible torque fluctuation, and the absence of maintenance requirements make it a popular choice. Additionally, it can achieve high speeds, reaching up to 15,000 revolutions per minute (rpm).	[90]
28	D. Gope and S. K. Goel, "Design optimization of permanent magnet synchronous motor using Taguchi method and experimental validation," *Int. J. Emerg. Electr. Power Syst.*, vol. 22, no. 1, pp. 9–20, 2021, doi: 10.1515/ijeeps-2020-0169	2021	Scopus	Rotor size can be optimized by using the Taguchi method	[91]

29	M. Nour, J. P. Chaves-Ávila, G. Magdy, and Á. Sánchez-Miralles, "Review of positive and negative impacts of electric vehicles charging on electric power systems," *Energies*, vol. 13, no. 18, 2020, doi: 10.3390/en13184675	2020	Scopus	Solar charging, Wireless charging, and battery swapping may be the future potential of EV charging systems.	[92]
30	Balint Hartmann, "Comparing various solar irradiance categorization methods e A critique on robustness lint Hartmann," vol. 154, 2020, doi: 10.1016/j.renene.2020.03.055	2020	SCI	Classifying solar irradiance is simple but lacks robustness, making it suitable for static computations	[93]
31	I. Miri, A. Fotouhi, and N. Ewin, "Electric vehicle energy consumption modeling and estimation—A case study," *Int. J. Energy Res.*, vol. 45, no. 1, pp. 501–520, 2021, doi: 10.1002/er.5700	2020	SCI	A MATLAB model evaluates inverter effectiveness, EV range, battery efficiencies, auxiliary power, motor-inverter efficiency, and regenerative braking strategy.	[94]

32	P. Ashkrof, G. Homem de Almeida Correia, and B. van Arem, “Analysis of the effect of charging needs on battery electric vehicle drivers’ route choice behavior: A case study in the Netherlands,” *Transp. Res. Part D Transp. Environ.*, vol. 78, no. December 2019, p. 102206, 2020, doi: 10.1016/j.trd.2019.102206.	2020	SCI	Driver's route and charging preferences depend on route, vehicle, and socio-economic factors.	[95]
33	P. Das, P. Mathuria, R. Bhakar, J. Mathur, and A. Kanudia, “Flexibility requirement for large-scale renewable energy integration in Indian power system : Technology, policy and modeling options,” *Energy Strategy. Rev.*, vol. 29, no. April, p. 100482, 2020, doi: 10.1016/j.esr.2020.100482	2020	SCI	India has announced its commitment to increasing its renewable energy (RE) capacity to 175 gigawatts by 2022.	[96]

34	A. E. Aliasand and F. T. Josh, "Selection of Motor foran Electric Vehicle: A Review," *Mater. Today Proc.*, vol. 24, pp. 1804–1815, 2020, doi: 10.1016/j.matpr.2020.03.605	2020	Scopus	1. Motor control techniques: (a) Sensorless, (b) MRAS, (c) FOC, (d) FEM, (e) Fault-tolerant, (f) Flux weakening. 2. The most generally utilized motor drive in the EV is the induction motor drive which is cost-effective too	[97]
35	C. R. K. J and M. A. Majid, "Renewable energy for sustainable development in India : current status, future prospects, challenges, employment, and investment opportunities," vol. 1, pp. 1–36, 2020, [Online]. Available: https://doi.org/10.1186/s13705-019-0232-1	2020	SCI	India is a major coal importer, with 90% of its solar cells sourced from China, Taiwan, and Malaysia.	[98]

36	R. S. and S. B. S. K. Panigrahi, P. R. Satpathy, “Design and Realisation of a Low-Cost Solar PV Incorporated Electric Vehicle for Parking Premises,” in *International Conference on Computational Intelligence for Smart Power System and Sustainable Energy (CISPSSE)*, 2020, pp. 29–32. doi: 10.1109/CISPSSE49931.2020.9212259	2020	Scopus	The charge station design has been developed and validated using MATLAB/Simulink. Solar energy is stored in the battery, which fulfills two functions: it powers electric vehicle (EV) charging and supports household energy requirements.	[99]

37	S.-M. Tudoroiu, R.-E.; Zaheeruddin, M.; Tudoroiu, N.; Radu, "SOC Estimation of a Rechargeable Li-Ion Battery Used in Fuel-Cell Hybrid Electric Vehicles — Comparative Study of Accuracy and Robustness Performance Based on Statistical Criteria. Part I : Equivalent Models," *batteries*, vol. 6, p. 42, 2020, doi: 10.3390/batteries6030042	2020	Scopus	1. Maximum power P_{max}= VNI (V-voltage, N- no. of cell, I- maximum charging current allowed per cell) 2. Polymer electrolyte membranes are widely used in fuel cell vehicles.	[48]

38	H. A. R. Oladepo Olatunde, Mohammad Yusri Hassan, Md Pauzi Abdullah, "Hybrid photovoltaic/small-hydropower microgrid in smart distribution network with grid isolated electric vehicle charging system.," *J. Energy Storage*, vol. 31, no. April, p. 101673, 2020, doi: 10.1016/j.est.2020.101673.	2020	Scopus	Electric vehicles achieve a low-carbon emission transportation	[100]

39	N. V. Bharadwaj, P. Chandrasekhar, and M. Sivakumar, "Induction motor design analysis for electric vehicle application," *AIP Conf. Proc.*, vol. 2269, no. October, pp. 10–14, 2020, doi: 10.1063/5.0019486	2020	Scopus	1. More efficient is Induction. Motors that are longer and have a larger diameter. 2. Squirrel cage IM is most suitable commercially for EV 3. Winding the bar proves to be more efficient than traditional stranded windings. 4. Various forms of losses can be experienced in (IM). 5. Induction motor design for EVs optimizes efficiency, torque, and power factor through advanced materials and structural improvements.	[101]
40	W. Brahim and W. Achmad, "Case study : Solar electric vehicles in India. Case study : Solar electric vehicles in India .," 2020, doi: 10.1088/1757-899X/937/1/012033	2020	SCI	PV rooftop or its charging method of implementation in the vehicle can be a better option to take the place of IC engine-based conventional vehicles and eco-friendly and sustainable systems.	[102]

41	A. Sierra Rodriguez, T. de Santana, I. MacGill, N. J. Ekins-Daukes, and A. Reinders, "A feasibility study of solar PV-powered electric cars using an interdisciplinary modeling approach for the electricity balance, CO2 emissions, and economic aspects: The cases of The Netherlands, Norway, Brazil, and Australia," *Prog. Photovoltaics Res. Appl.*, vol. 28, no. 6, pp. 517–532, 2020, doi: 10.1002/pip.3202.	2020	SCI	Solar photovoltaic (PV) powered electric vehicles offer a promising alternative to conventional grid charging methods for electric vehicles. When compared to internal combustion engine (ICE) vehicles, they present a viable technological solution and are increasingly becoming more financially attractive for reducing emissions in the transportation sector in many countries.	[103]

42	K. S. and M. S. B. Jyothi, P. Bhavana, "IOP Conference Series : Materials Science and Engineering Analysis of Z-Source Inverter fed Asynchronous Motor for Electric Vehicle Applications Analysis of Z-Source Inverter fed Asynchronous Motor for Electric Vehicle Applications," 2020. doi: 10.1088/1757-899X/993/1/012087	2020	Scopus	(a) A proposed system involves an inverter with an impedance source to power an asynchronous motor. (b) The performance of an asynchronous motor for electric vehicles has been simulated using MATLAB. (c) The advantages of controlling and managing the performance of an Induction Motor (IM) are noteworthy, and the design of converters for control purposes is straightforward.	[51]
43	X. Sun, Z. Li, X. Wang, and C. Li, "Technology development of electric vehicles: A review," *Energies*, vol. 13, no. 1, pp. 1–29, 2019, doi: 10.3390/en13010090	2019	SCI	Due to Mature technology, and low prices, an Induction Motor is a reasonable choice for EV applications.	[104]

44	L. I. Farfan-Cabrera, "Tribology of electric vehicles: A review of critical components, current state, and future improvement trends," *Tribol. Int.*, vol. 138, no. April, pp. 473–486, 2019, doi: 10.1016/j.triboint.2019.06.029	2019	Scopus	In the field of transportation, there are many tribological factors associated with electric vehicles, and they present significant efficiency challenges. These challenges are especially noticeable in critical tribological components of electric vehicles, including the electric motor, transmission, steering system, tires, wheel bearings, rolling bearing friction, gears, and other related areas.	[105]
45	M. Waseem, A. F. Sherwani, and M. Suhaib, "Integration of solar energy in electrical, hybrid, autonomous vehicles: a technological review," *SN Appl. Sci.*, vol. 1, no. 11, 2019, doi: 10.1007/s42452-019-1458-4	2019	Scopus	The majority of scholarly works propose that opting for supercapacitors and polymer fuel cells represents the optimal solution for storing energy in electric vehicles.	[106]

46	F. F. Marco Pasetti, Stefano Rinaldi, “Assessment of electric vehicle charging costs in presence of distributed photovoltaic generation and variable electricity tariffs,” *Energies*, vol. 12, no. 3, 2019, doi: 10.3390/en12030499	2019	SCI	The primary obstacle encountered by PPEV is achieving optimal speed, which is challenging even in ideal circumstances. Additional challenges include cost considerations and the need for quick recharging times.	[107]

2.6 Significance of the research

Technologies for producing power from renewable sources have developed due to a variety of variables, the most notable of which is solar energy. Among these are the facts that the usage of traditional energy sources in the transportation sector has been proven to be both restricted and a major contributing element to environmental pollution. However, as India's population grows, so too will its energy needs, which will raise the country's potential to generate electricity. Furthermore, based on India's current energy generation scenario, a hike in capacity will result in a rise in electricity costs because of pollution control costs. India has a great deal of potential for renewable energy that may be used for all kinds of electrical applications, according to recognized facts.

This study aims to explore the potential of induction motors as the primary propulsion system for electric vehicles and to investigate the use of solar photovoltaic (PV) systems for charging the batteries of these vehicles. This study focuses on the use of solar photovoltaics (PV), which decreases reliance on fossil fuels for grid electricity and charging station operations. Additionally, solar charging extends the battery life of electric vehicle batteries. Additionally, an induction motor improves the electric vehicle's overall performance, including its speed and range, with less maintenance needed. Enhancing electric vehicle performance and advancing the Indian government's goal of reaching as many consumers as possible are the results of this research.

2.6.1 Chapter Summary

The literature survey conducted for this research extensively reviews the advancements, challenges, and considerations associated with the performance evaluation of electric vehicle (EV) propulsion motors, focusing on Brushless DC Motors (BLDC) and Induction Motors (IM). Key areas of analysis include performance metrics, energy efficiency, temperature regulation, dynamic response, and cost-effectiveness, all of which are critical for developing high-performing propulsion systems in EVs. Furthermore, recent advances in motor control algorithms such as Proportional-Integral-Derivative (PID) Control, Field-Oriented Control (FOC), and Model Predictive Control (MPC) are explored for their potential to enhance torque stability, minimize torque ripple, and optimize regenerative braking. Special attention is given to emerging trends in photovoltaic (PV)-based electric vehicles and their design considerations, including power density, compactness, and the integration of cooling strategies.

2.6.2 Key Observations

2.6.2.1 *Performance Metrics for EV Propulsion Motors:*

- Efficiency, torque ripple, and reliability are identified as primary performance indicators.

- BLDC motors exhibit high efficiency and compactness but face challenges in managing torque ripple and commutation complexity.

- Induction motors provide robust performance and cost advantages but suffer from lower efficiency under partial load conditions.

2.6.2.2 *Energy Efficiency and Cooling Systems:*

- Maintaining efficiency under varying load and thermal conditions remains a challenge.

- Effective cooling systems, including liquid cooling and forced air cooling, are vital for enhancing motor lifespan and thermal stability.

2.6.2.3 *Motor Control Algorithms:*

- Advanced algorithms like FOC and MPC show promise in reducing torque ripple and improving dynamic response.

- Regenerative braking performance is a critical feature where advanced control strategies improve energy recovery.

2.6.2.4 *Challenges in Performance Evaluation:*

- Issues like temperature regulation, dynamic load conditions, and partial-load efficiency require innovative approaches.

- Cost considerations, particularly for integrating advanced control systems and cooling mechanisms, remain a limiting factor for commercial deployment.

2.6.2.5 *Recent Advances in EV Propulsion:*

- Integration of photovoltaic systems for on-board charging presents new opportunities but introduces design complexities.

- Innovations in power density and compactness directly impact motor performance and overall vehicle efficiency.

2.6.2.6 *Reviewed Articles' Relevance:*

- Studies emphasize the importance of balancing motor efficiency with reliability and maintenance costs.

- Advances in cooling strategies and thermal management are key to achieving higher performance.

2.6.3 Chapter Conclusion

The literature survey underscores the critical role of BLDC and Induction Motors in electric vehicle propulsion, highlighting their unique strengths and limitations. It reveals that the selection of an appropriate propulsion motor depends on factors such as energy efficiency, cost, reliability, and thermal performance. Advances in motor control algorithms and cooling strategies are pivotal for overcoming challenges such as torque ripple, thermal regulation, and partial-load efficiency.

Additionally, the exploration of photovoltaic-based electric vehicles introduces novel avenues for enhancing energy efficiency and sustainability. However, design considerations, such as optimizing power density and compactness, remain vital to achieving practical implementation. By addressing the identified gaps, this research aims to contribute innovative solutions for the efficient and reliable performance of electric vehicle propulsion systems, paving the way for the next generation of sustainable transportation technologies.

3 Designing a photovoltaic-based induction motor-driven electric vehicle system

3.1 Selection of location

The research site was selected based on the researcher's workplace, although considerations such as the biodiversity and climate of western UP, with its abundance of sunny days, were also taken into account for observing the Solar Power induction-driven Electric Vehicle in terms of solar radiation and ensuring the accuracy of research findings to design a Photovoltaic induction motor-driven electric vehicle system we took the location with a latitude of 27.4739 degrees North longitudinal 77.6720 degrees East altitude 186m at Western UP of Mathura district. Analyzing solar radiation is essential because it plays a vital role in converting solar energy into electric power. It is subsequently used to drive electric vehicles equipped with solar-powered induction motors.

Say an Electric Vehicle runs in the Mathura District of UP from Goverdhan Chauraha to a Township of distance nearly 10 km which includes a slope and plain. At the smooth and slope road horizontal radiation can be given by (The output of the solar module will get reduced than actual)

$$S_{horizontal}=S_{incident}*Sin\ \theta_{road} \tag{3-1}$$

$$S_{module}=S_{incidence}*Sin(\ \theta_{road}+\gamma) \tag{3-2}$$

When θ_{road} is used to indicate the angle of elevation and γ is used to represent the tilt angle measured from the horizontal slope angle. The angle of elevation or gradient angle of the road θ_{road} is the angle between the road surface and the horizontal ground. This angle of elevation affects the vehicle's motion by introducing gradient resistance, which the motor must overcome. The steeper the road, the more power is required to drive the vehicle uphill. It depends on the road design and can change frequently, especially in hilly or mountainous regions.

$$\theta_{road}\ = 90-\phi+\alpha \tag{3-3}$$

(Where ϕ shown as latitude and α shown as declination angle)

$$A = 22.45\, Sin\, [\, 360/366\, (285 + d)] \quad (3\text{-}4)$$

Here, 'd' represents the specific day.

Hence

$$S_{module} = (S_{horizontal} * Sin\, (\, \theta_{road} + \gamma))/Sin\, \theta_{road} \quad (3\text{-}5)$$

Here, θ_{road} Represents the elevation angle, while γ denotes the tilt, indicating the inclination of the module relative to the horizontal surface.

$$\theta_{road} = 90 - \phi + \alpha \quad (3\text{-}6)$$

Where ϕ is latitude and α is declination angle

3.1.1 Projection Diagram of mini-EV

A projection diagram of an electric vehicle typically refers to a visual representation or schematic illustration that highlights key components and features of the electric vehicle from different viewpoints. It provides a simplified and technical overview of the vehicle's internal structure and systems. Figure 3-1 describes the typical components and features that are included in a projection diagram of electric vehicle forces exerted, at the Projection Positioning Circuit Satellite Map for the location with the latitude of 27.4739 degrees North longitudinal 77.6720-degree East altitude 186m at Western UP of Mathura district have taken into consideration for performing research work.

3.1.1.1 *Forces exerted by the electric Vehicle:*

The following types of force are exerted by Electric Vehicles when running either slope or plain surface

Force of Rolling Resistance (F_{rr})

Force of Aerodynamic Drag (F_{aero})

Force of Hill Climbing (F_{hc})

Force of Acceleration (F_{xl})

The force acting against the tire's movement called rolling resistance force, occurs as the tire moves across the road surface.

$$F_{Rolling} = \mu_R \times W \qquad (3\text{-}7)$$

Here

μ_R = Coefficient of force of rolling resistance

W = The rickshaw weight in kg

3.1.1.1.1 Force of Aerodynamic Drag (F_{Drag}):

Aerodynamic drag refers to the air resistance that slows down a vehicle's movement as it moves through the air.

$$F_{Drag} = 1/2 \times C_d \times A \times \rho \times (V)^2 \qquad (3\text{-}8)$$

Here,

C_d = The coefficient of force of drag of the vehicle

A = front area (sq. ft)

ρ = Constant (air mass density)

V = The vehicle's speed

3.1.1.1.2 Force of Acceleration (F_{acce}):

The acceleration force is the propulsion that assists a vehicle in reaching a predetermined velocity starting from a stationary position within a defined period. This relationship is directly influenced by the vehicle's mass and is regulated by Newton's second law of motion,

$$F_{acce} = mass\ of\ vehicle \times\ acceleration \qquad (3\text{-}9)$$

The total tractive force represents the cumulative force needed from the power system to move the vehicle to its desired speed. It includes the sum of all previously mentioned forces, thereby guaranteeing,

$$FD = F_{Rolling} + F_{Drag} + F_{acce} \quad (3\text{-}10)$$

Consequently, the motor must supply the necessary power to maintain the current velocity and acceleration,

$$PT = FD \times V \quad (3\text{-}11)$$

In this context, PT represents the motor's maximum power, FD signifies the driving force, and V denotes the maximum permissible speed of the rickshaw.

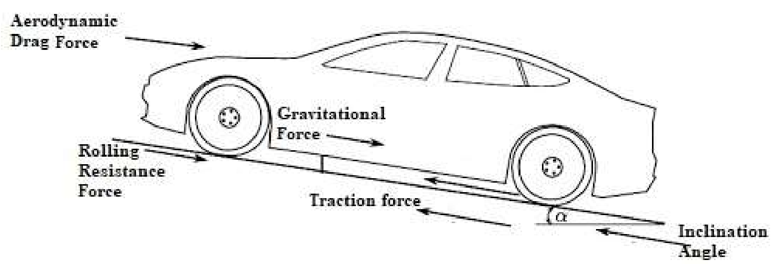

Figure 3-1-Diagram of forces on Electric Vehicle

3.2 Mathematical Modelling for Solar Power Induction Motor-Driven Electric Vehicle

Mathematical modeling of a solar-powered electric vehicle system involves creating equations and relationships that describe the various components and processes involved in converting solar energy into electric power to drive a vehicle.

3.2.1 Solar Panels

A rooftop solar panel system for electric vehicles utilizes photovoltaic cells to transform sunlight into electrical energy, facilitating environmentally friendly and sustainable transportation. These panels are constructed with several layers, including a semiconductor top layer like silicon, where sunlight triggers the release of electrons from photons, resulting in the generation of electric current.

The solar panels installed on the vehicle consist of either monocrystalline or polycrystalline silicon cells, which are specifically selected for their ability to efficiently convert sunlight into electricity. These cells are interconnected to create modules that are then incorporated into the vehicle's rooftop. A charge controller is employed to manage the voltage and current output from the solar panels, ensuring optimal charging and safeguarding the vehicle's battery. The electricity generated by the solar panels is stored in a high-capacity onboard battery pack. This stored energy complements the grid-charged battery, extending the vehicle's driving range and reducing its dependence on external charging stations. Integrating solar panels into the vehicle promotes sustainability, decreases carbon emissions, and enhances the overall effectiveness of electric transportation systems.

Solar panels transform sunlight into electrical energy. The expression below can be utilized to represent the generated power from these panels:

$$P_{panel}=A_{panel}*G*\eta_{panel} \tag{3-12}$$

where P_{panel} is the power solar panel output, A_{panel} is the area of the panel, G is the solar irradiance (incoming solar power per unit area), and η_{panel} is the efficiency of the panel.

The solar irradiance G can be further expressed as:

$$G=G_0*Cos\ \theta_{sun} \tag{3-13}$$

where G_0 is the solar constant (approximately 1361 W/m²), θ_{sun} Shows the angle of incidence of sunlight on the panels. The angle of incidence of sunlight on solar panels θ_{sun} is the angle between the incoming sunlight and the perpendicular (normal) to the panel surface. This angle determines the intensity of sunlight on the panels, with maximum energy generation occurring when sunlight hits the panels perpendicularly (i.e., $\theta_{sun}=0^0$). It varies based on the time of day, season, panel tilt, and geographic location.

3.2.2 Battery Storage

Solar panels generate electric power that can be stored in a battery for later use. This happens when solar-powered induction motor-driven Electric vehicles are parked in open-air areas.

3.2.3 State of Charge (SOC) of the Battery in Electric Vehicles

The State of Charge (SOC) of a battery in electric vehicles (EVs) is a critical parameter that indicates the battery's remaining capacity, expressed as a percentage of its full capacity. Understanding SOC is essential for efficient battery management, extending battery life, and ensuring the optimal performance of the EV. Here's a detailed explanation and description of SOC:

3.2.3.1 *Range Estimation:*

SOC helps in estimating the remaining driving range of the EV, enabling drivers to plan their trips and avoid running out of charge.

3.2.3.2 *Battery Health Management:*

Monitoring SOC is crucial for maintaining battery health and longevity, as it helps avoid deep discharges and overcharges that can degrade the battery.

3.2.3.3 *Energy Efficiency:*

Accurate SOC measurement allows for efficient energy management and usage, optimizing the performance of the EV.

3.2.3.4 *Charging Control:*

SOC is used to control the charging process, ensuring that the battery is charged to the appropriate level and preventing overcharging.

3.2.4 Methods of SOC Estimation

3.2.4.1 *Coulomb Counting (Ah Counting):*

This method involves measuring the current flow into and out of the battery over time. By integrating the current concerning time, the change in charge is calculated. The SOC is then estimated based on the initial SOC and the net charge added or removed.

$$SOC(t) = SOC(t_0) + \frac{1}{C_{nom}} \int_{t_0}^{t} I(t)\, dt \qquad (3\text{-}14)$$

where $Cnom$ is the nominal capacity of the battery, and $\mathrm{I(t)}$ is the current time t.

3.2.4.2 *Open Circuit Voltage (OCV) Method:*

This method estimates SOC based on the relationship between the battery's open circuit voltage and its SOC. The OCV-SOC relationship is typically obtained through empirical testing and calibration.

3.2.4.3 *Model-Based Estimation:*

This approach uses mathematical models of the battery's electrochemical behavior to estimate SOC. These models can incorporate factors like temperature, aging, and discharge rates to provide a more accurate SOC estimation.

3.2.4.4 *Kalman Filter:*

The Kalman filter is an advanced algorithm that combines coulomb counting with model-based estimation to improve SOC accuracy. It uses a series of measurements over time to produce estimates of unknown variables (like SOC) by minimizing the mean of the squared error.

3.2.4.5 *Machine Learning Techniques:*

Recently, machine learning algorithms have been employed to estimate SOC by analyzing patterns in battery data and learning the complex relationships between various parameters affecting SOC.

3.2.5 Factors Affecting SOC Accuracy

3.2.5.1 *Temperature:*

Battery performance and SOC estimation can be significantly affected by temperature variations.

3.2.5.2 *Battery Aging:*

As batteries age, their capacity and internal resistance change, affecting SOC estimation.

3.2.5.3 *Current Measurement Accuracy:*

Accurate current measurement is crucial for precise SOC estimation, especially in coulomb counting.

3.2.5.4 *Initial SOC:*

Accurate initial SOC is essential for methods like coulomb counting to provide reliable estimates.

3.2.5.5 *Dynamic Operating Conditions:*

Rapid changes in load or driving conditions can impact SOC estimation accuracy.

3.2.6 SOC Management Strategies

3.2.6.1 *Battery Management System (BMS):*

A BMS continuously monitors and manages SOC, ensuring the battery operates within safe limits and optimizing its performance.

3.2.6.2 *Thermal Management:*

Maintaining optimal battery temperature helps in achieving accurate SOC estimation and prolongs battery life.

3.2.6.3 *Regular Calibration:*

Periodic calibration of SOC estimation methods ensures accuracy, accounting for changes in battery behavior over time.

3.2.6.4 *User Feedback:*

Providing drivers with SOC information and charging recommendations helps in maintaining optimal battery usage and extending its lifespan.

3.2.7 State-of-Charge (SOC)

SOC represents the current charge level of a battery relative to its maximum capacity. It is typically expressed as a percentage, where 100% indicates a fully charged battery and 0% indicates a completely discharged battery.

This energy storage device can be characterized through a state-of-charge (SOC) model, illustrating the energy capacity over time:

$$\frac{d_{soc}}{dt} = (P_{panel} - P_{load}) / C_{battery} \tag{3-15}$$

where $\frac{d_{soc}}{dt}$ is the rate of change of the state of charge, P_{panel} is the generated power by the solar panel, P_{load} is the consumed power by the vehicle and other loads, and $C_{battery}$ is the battery capacity.

The State of Charge (SOC) is a fundamental parameter in the management of electric vehicle batteries. Accurate SOC estimation and management are essential for ensuring the efficient operation, safety, and longevity of the battery. Various methods, from simple coulomb counting to advanced machine learning techniques, are employed to estimate SOC, each with its advantages and limitations. Effective SOC management strategies, including the use of a Battery Management System (BMS), are crucial for the optimal performance of electric vehicles.

3.2.8 Electric Motor and Drive System

The electric motor converts the stored electrical energy from the battery into mechanical energy, propelling the vehicle in a forward direction. The electric motor's output can be represented as below the power it provides:

$$P_{motor} = P_{load} + P_{aux} \tag{3-16}$$

Here P_{load} is the power required to overcome vehicle resistance and accelerate, and P_{aux} is the power consumed by auxiliary systems (e.g., air conditioning).

3.2.9 The Behaviour of Vehicle Motion

The behavior of a vehicle's motion can be explained using core principles of physics, like Newton's second law, which correlates the vehicle's acceleration with the total force applied to it.:

$$F_{net} = m * a \tag{3-17}$$

where F_{net} is the acting net force exerted by the vehicle, m depicts the vehicle mass, and a shown as acceleration.

3.2.10 Estimation of Motor

The amount of power generated by the motor is determined by the specific performance characteristics desired for the vehicle, such as acceleration, maximum speed, and ability to navigate slopes. These performance criteria differ based on the type of vehicle and its intended use. One conventional approach involves calculating the power needed to overcome the various resistances encountered by the vehicle at a given speed, which encompasses factors like aerodynamic drag, rolling resistance, and uphill resistance.

Estimate the power required, equation shown as:

$$P_{load} = F_{resistance} * V \tag{3-18}$$

where P_{load} is the power required to overcome resistance, $F_{resistance}$ represents the resistance force, and V represents the speed of the vehicle.

$$F_{resistance} = m * g \tag{3-19}$$

Say the Vehicle's velocity is 30Km/hr; the mass of the vehicle is represented by m=550lbs and g=9.81m/sec

then from

$$P_{load} = F_{resistance} * V \tag{3-20}$$

3.2.11 Powertrain

The primary element of the drivetrain is the induction motor, a widely used electric motor in electric vehicles (EVs). Operating on the principle of electromagnetic induction, this motor converts electrical energy from the battery into mechanical energy to drive the wheels. Details about the induction motor can be referenced in Table 3-1, and its characteristics are valued for their reliability, simple design, and impressive efficiency.

Table 3-1-Power Train Specification

Motor Type	**3-Phase Induction Motor**
Weight of Vehicle (W)	550 lbs (230 Kg approx.)
Tire Radius (R)	0.75 ft
Frontal Area (A_f)	18.19 sq. ft.
Density of air (ρ)	0.07645 lb/cub. ft.
The angle of inclination on plain (θ)	0 degree
Gear ratio	5
Rolling Coefficient (C_{rr})	0.018
Inertia Coefficient (Ci)	1.06
Drag Coefficient (Cd)	0.15
Capacity in watt	3764.825W =3.6kW
Voltage in Volt	220 V
Current in Ampere	15A

3.2.11.1 ***Sizing of Induction Motor:***

The motor's sizing must account for the forces acting on the EV, such as rolling resistance, gradient resistance, aerodynamic drag, and acceleration resistance, as well as the desired performance parameters (e.g., top speed, acceleration, and terrain).

Power Demand

To assess the required motor power, we need to calculate the total power demand based on:

- Vehicle weight: 230 kg (Approx.)

- Desired top speed, acceleration, and terrain slope.

- Resistive forces acting on the vehicle.

$$P_{required} = \left(F_{rolling} + F_{aero} + F_{gradient} + F_{acceleration}\right) * v \quad (3\text{-}21)$$

Here:

- $F_{rolling}$: Rolling resistance

- F_{aero}: Aerodynamic drag

- $F_{gradient}$: Gradient resistance

- $F_{acceleration}$: Acceleration resistance

- v: Speed (m/s)

Breakdown of Resistive Forces

- Rolling Resistance:

$$F_{rolling} = C_{rr} * m * g \quad (3\text{-}22)$$

Assuming C_{rr}= 0.01 (typical for EV tires):

$$F_{rolling} = 0.01 * 230 * 9.81 = 22.57N \quad (3\text{-}23)$$

$$Aerodynamic\ Drag\ Force\ (F_{aero}) = \frac{1}{2} Density\ of\ air\ (\rho) * Drag\ Coefficient\ (Cd) * Frontal\ Area(A_f) * v^2 \quad (3\text{-}24)$$

Assuming:

- $Density\ of\ air\ (\rho)$= 1.225 kg/m³

- $Drag\ Coefficient\ (Cd)$= 0.3

- $Frontal\ Area(A_f)$= 0.6 m²

- Speed (v) = 10 m/s (36 km/h):

$Aerodynamic\ Drag\ Force\ (F_{aero}) = \frac{1}{2} * 1.225 * \ 0.3 * \ 0.6 * 10^2 = 11.03N$

(3-25)

- Gradient Resistance:

$$F_{gradient} = m * g * sin\,\theta \qquad (3\text{-}26)$$

For a flat road (θ = 0), $F_{gradient}$= 0. For a 5% gradient (sin(θ)≈ 0.05):

$$F_{gradient} = 230 * 9.81 * 0.05 = 112.88\ N \qquad (3\text{-}27)$$

- Acceleration Resistance:

$$F_{accceleration} = m * a \qquad (3\text{-}28)$$

Assuming $a = 1\,m/s^2$

$$F_{accceleration} = 230 * 1 \qquad (3\text{-}29)$$

Total Force and Power Requirement

Summing up forces for a 5% gradient and acceleration at 10 m/s (36 km/h):

$$F_{Total} = 22.57 + 11.03 + 112.88 + 230 = 376.48N \qquad (3\text{-}30)$$

The required power at this speed:

$$P_{required} = F_{Total} * v = 376.48 * 10 = 3{,}764.8W = 3.76kW \quad (3\text{-}31)$$

3.3 Estimation of Battery

The operation of the drivetrain hinges on the battery pack as its primary source of energy. This pack stores electrical power and then transfers it to the motor through power electronics. The range and performance of the electric vehicle (EV) are significantly affected by the capacity and voltage of the battery pack. The Depth of Discharge (DoD), as shown in Figure 3-3, indicates the proportion of the total stored energy that has been used. Mathematically, DoD is defined as the ratio of the discharged capacity to the total capacity, typically represented as a percentage. An important aspect to consider when discussing DoD is its impact on battery lifespan, as batteries typically endure a limited number of charge-discharge cycles before experiencing a notable capacity decline.

3.3.1 Battery Capacity

The size of the battery is calculated based on the distance the vehicle needs to cover on a single charge, known as the range, and the power it consumes. This range signifies the maximum distance the vehicle can travel without recharging. An equation can be used to estimate the battery capacity:

$$C_{batt} = (P_{load} * R_{range}) \,/\, (DOD * \eta_{battery}) \quad (3\text{-}32)$$

where $C_{battery}$ is the required battery capacity, P_{load} represents power required by the vehicle, R_{range} is the desired range, DOD represents the depth of discharge (typically a fraction of the total battery capacity), whereas $\eta_{battery}$ represents the efficiency of the battery. Let's say a vehicle runs to and fro from office to home and vice-versa then the total energy given by

$$C_{batt} = (P_{load} * R_{range}) \quad (3\text{-}33)$$

$$= 0.75 * 50/(40km/hr) = 0.937watt \text{ or } 1\ Kw \quad (3\text{-}34)$$

Normally efficiency of an Induction Motor is >90% so let's say 95% is the efficiency

$$C_{\ battery} = 1KW/0.95 = 1{,}052\ W \qquad (3\text{-}35)$$

$$Capacity\ of\ Battery = 1/(0.95 * 0.8 * 60) = 1/45.6 = 21Ah \qquad (3\text{-}36)$$

Therefore, based on the aforementioned computation, the recorded voltage is 48 volts. To meet the system's needs, a combination of two batteries with a capacity of 24 volts and 30 ampere-hours each is deemed necessary.

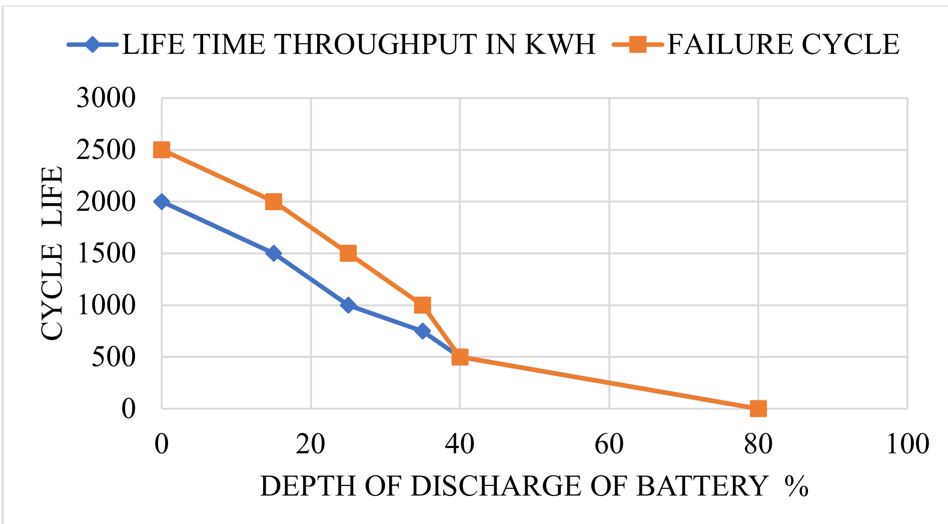

Figure 3-2-Depth of Discharge of Battery

3.3.2 Charging and Discharging of Electric Vehicle Batteries: Detailed Explanation with Mathematical Data

Electric vehicle (EV) batteries undergo charging and discharging cycles as they store and provide energy for propulsion. Understanding these processes mathematically is crucial for optimizing battery performance, ensuring safety, and extending battery life. Here is a detailed explanation:

3.3.2.1 *Battery Basics:*

3.3.2.1.1 Battery Capacity:

The capacity of a battery is measured in ampere-hours (Ah) or watt-hours (Wh) and represents the total amount of energy the battery can store.

3.3.2.1.2 Nominal Voltage (V_{nom}):

The typical voltage at which the battery operates is used for calculating energy capacity.

Energy Capacity(E):

$$E = C_{nom} \times V_{nom} \tag{3-37}$$

here C_{nom} shows the nominal capacity in Ah and V_{nom} Shows the nominal voltage value.

3.3.3 Charging Process

3.3.3.1 *Charging Current (I_{ch}):*

The current is applied to charge the battery.

3.3.3.2 *Charging Voltage (V_{ch}):*

The voltage applied during charging.

3.3.3.3 *Charging Time (t_{ch}):*

The time required to charge the battery from an initial state of charge SOC_i to a final state of charge SOC_f

3.3.3.4 *Constant Current (CC) Charging:*

In CC charging, the battery is charged at a constant current until a specific voltage is reached.

$$I_{ch} = Constant \tag{3-38}$$

The SOC increases linearly with time in this phase:

$$SOC\ (t)\ SOC_i + \frac{I_{ch} \times t}{C_{nom}} \tag{3-39}$$

3.3.3.5 *Constant Voltage (CV) Charging:*

Once the battery reaches a specified voltage, the charger switches to constant voltage mode, and the current decreases exponentially as the battery approaches full charge.

The current during CV charging can be approximated as:

$$I_{ch}(t) = I_0 \, e^{\frac{-t}{\tau}} \tag{3-40}$$

Here I_0 is the initial current at the start of the CV phase and τ is a time constant. The total charging time is the sum of the times for the CC and CV phases.

3.3.4 Discharging Process

3.3.4.1 *Discharging Current (I_{dis}):*

The current is drawn from the battery during discharge.

3.3.4.2 *Discharging Voltage (V_{dis}):*

The voltage of the battery during discharge typically decreases with the SOC.

3.3.4.3 *Discharging Time (t_{dis}):*

The time required to discharge the battery from an initial SOC_i to a final SOC_f

3.3.4.4 *Constant Power (CP) Discharge:*

In CP discharge, the power drawn from the battery remains constant.

$$P = V_{dis} \times I_{dis} = Const. \tag{3-41}$$

The current varies inversely with the voltage:

$$I_{dis}(t) = \frac{P}{V_{dis}(t)} \tag{3-42}$$

3.3.4.5 *Constant Current (CC) Discharge:*

In CC discharge, the battery is discharged at a constant current.

$$I_{dis} = Constant \tag{3-43}$$

The SOC decreases linearly with time in this phase:

$$SOC(t) = SOC_i - \frac{I_{dis} \times t}{C_{nom}} \tag{3-44}$$

3.3.5 Efficiency and Losses

3.3.5.1 *Coulombic Efficiency (η_{coul}):*

The ratio of the charge extracted from the battery to the charge put into the battery.

$$(\eta_{coul}) = \frac{Dicharge\ Capacity}{Charge\ Capacity} \tag{3-45}$$

3.3.5.2 *Energy Efficiency (η_{energy}):*

The ratio of the energy output during discharge to the energy input during charging.

$$\eta_{energy} = \frac{E_{dis}}{E_{ch}} \tag{3-46}$$

The charging and discharging processes of EV batteries involve complex interactions of current, voltage, time, and temperature. Mathematical modeling of these processes helps in optimizing battery management, ensuring efficient and safe operation, and prolonging battery life. Understanding these models is crucial for the development and deployment of effective Battery Management Systems (BMS) in electric vehicles.

3.4 Specification of battery used in photovoltaic-based IM-driven electric vehicle systems (Mini EV)

The passage describes the block model of a battery created using MATLAB, essential for supplying power to operate a motor. Additionally, it explains that when a solar panel is installed on the vehicle, energy is stored in the battery. Table 3-2 provides details about the battery subsystem, as illustrated in Figure 3-3.

Table 3-2-Battery model for PV-based IM-driven Mini EV

Type of Battery	**Li-ion**
Voltage capacity	48 V
The capacity of current in Ah	35 Ah
Full charge Max. voltage	50 V
At discharge Min. voltage	47V
Weight	15 kg

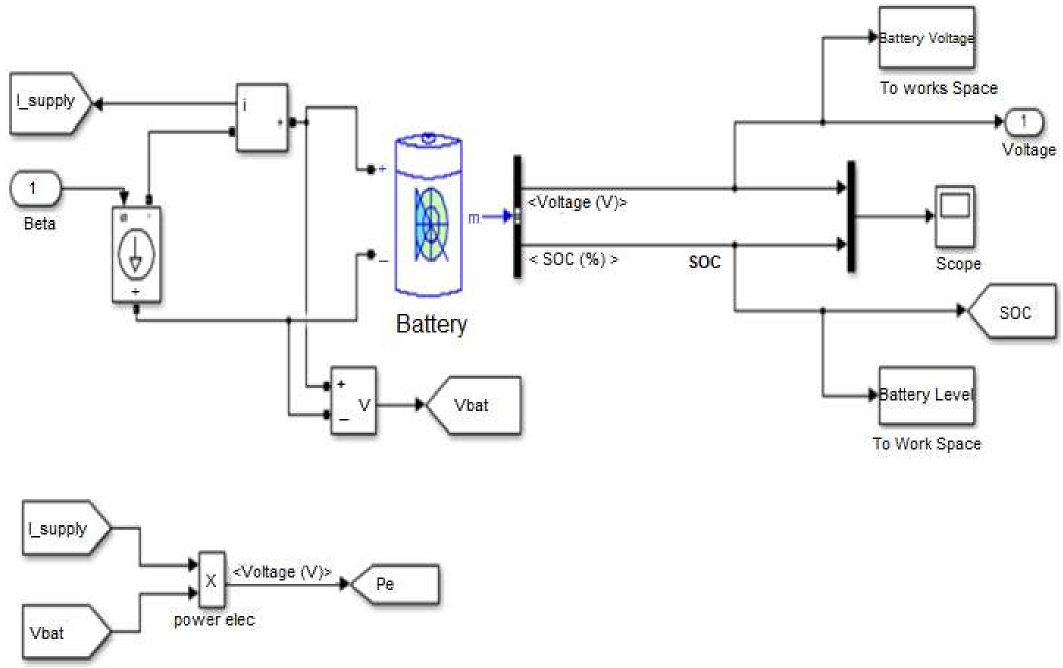

Figure 3-3-Block model of the battery

3.5 Estimation of Solar Panel

The evaluation of solar panels encompasses the examination of various elements to ascertain the dimensions and capability of the solar power system required for a specific application. An integral part of estimating solar panels involves comprehending the solar radiation data presented in Table 3-3, representing daily and monthly electricity consumption measured in kilowatt-hours (kWh). This information is crucial in determining the appropriate scale of the solar panel system. Additionally, it is essential to consider the regional solar irradiance levels, which indicate the amount of sunlight available at the specific location where the solar panels are intended to be installed. Here the block model of the battery using MATLAB is described which is a necessary component to feed energy to run a motor also in case of solar panel is used at the top of the vehicle the energy will be conserved in the battery. Table 3-2 depicts the specification and the diagram of the subsystem of a battery shown in Figure 3-3. Given that solar panels do not achieve 100% efficiency, the actual electricity output is influenced by factors such as the overall system efficiency, encompassing solar panel efficiency, inverter efficiency, and losses in electrical wiring and connections. Make sure to incorporate these considerations into your estimation. Consider the power rating of the solar panels, typically measured in watts (W) or kilowatts (kW) shown in Figure 3-6. This information helps in determining the total capacity of the solar panel system. Temperature affects the behavior of solar radiation in several ways. The most direct impact is on the atmosphere, where temperature variations can lead to changes in air density, composition, and cloud formation. These atmospheric changes, in turn, affect the transmission and scattering of solar radiation which is shown in Figure 3-5.

3.5.1 Panel Size

The panel size and specification shown in Figure 3-4 are determined by the power demand of the vehicle and the available solar energy. To estimate the panel size, consider the average daily solar energy available at your location, the efficiency of the solar panels, and the desired range or power supply from solar energy. The equation to estimate the panel size is:

$$A_{panel} = \left(\frac{P_{load}}{G * \eta_{panel}}\right) * T \tag{3-47}$$

where A_{panel} is the required solar panel area in square meters, P_{load} represents the required power in Watt by the vehicle, G is the average daily solar irradiance (light intensity) in Watt-per square meter, η_{panel} represents the solar panel's efficiency, and T is the average daily driving period in hours.

3.5.2 Mathematical equation for solar module

The equation to estimate the panel is:

$$A_{panel} = \left(\frac{P_{load}}{G * \eta_{panel}}\right) * T \tag{3-48}$$

$$P_{load} = C_{battery}/(\gamma_{battery} * \gamma_{ch} * \gamma_{cc}) = 1052/(0.9 * 0.9 * 0.9) \tag{3-49}$$

$$P_{load} = 1052/0.729 = 1443\ Wh \tag{3-50}$$

Where A_{panel} is panel power, $\gamma_{battery}$ Battery efficiency, γ_{ch} is charging efficiency, γ_{cc} During the winter season, the minimum solar irradiation corresponds to 4.5 kWh/kW$_p$ indicates the efficiency of the DC-DC converter from the solar panel. So that PV-solar panel wattage

$$Panel_{Wattage} = 1443 / 4.5 \tag{3-51}$$

$$= 320\ Watt \tag{3-52}$$

Hence 75 V, maximum 400-watt panel shown in Figure 3-7 can be sufficient to operate a solar-equip induction motor-driven Electric Vehicle. (Normally 100 W bifacial monocrystalline solar panels which have more than 20% high efficiency used in solar vehicles occupy 1m sq. space on the rooftop of the Electric Vehicle.)

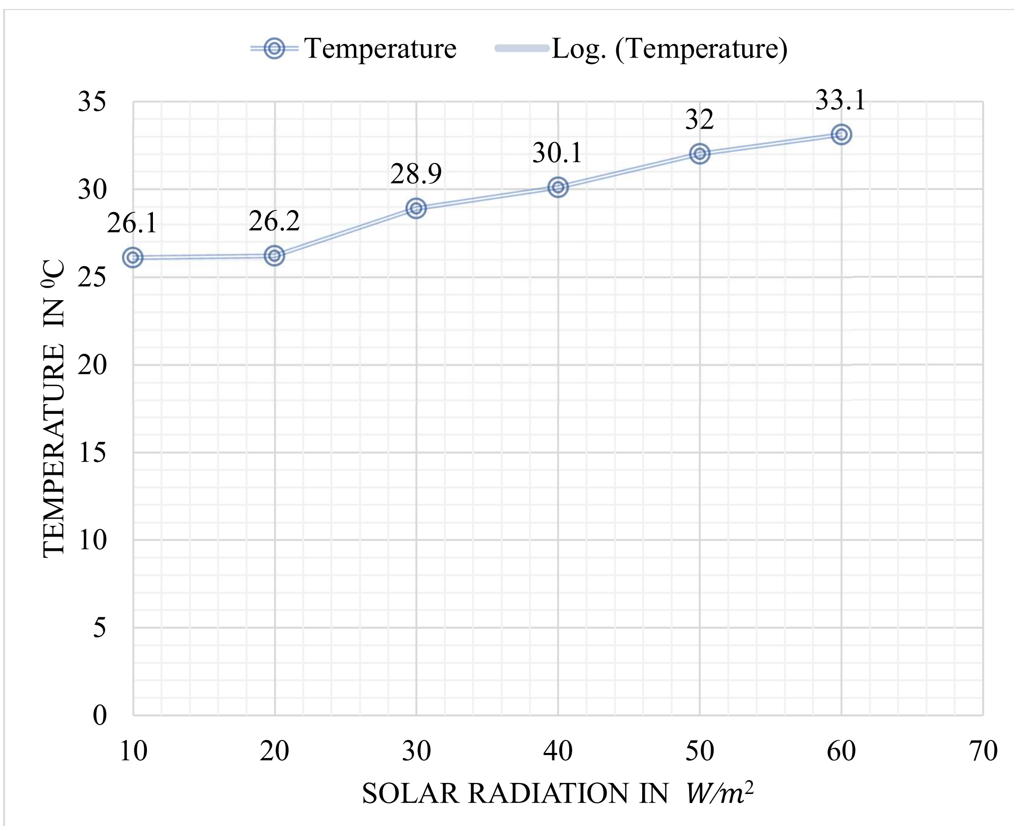

Figure 3-4-Solar Radiation in W/m^2

Table 3-3- Solar Radiation -Month Wise at ground

Period	“ Jan”	“ Feb”	“ Mar”	“ April”	“ May”	“ Jun”	“ Jul”	“ Aug”	“ Sep”	“ Oct”	“ Nov”	“ Dec”
PV-Solar Radiation, kWh/m2 /d	6.24	7	7.1	7.83	7.79	5.5	4.17	3.98	4.19	5.988	5.96	6.2
Clearness Index	0.59	0.651	0.649	0.645	0.661	0.495	0.398	0.402	0.538	0.589	0.659	0.655
Average Temp, degree C	16.9	21.9	25.9	28.9	32.9	29.9	24.9	24.9	24.99	25.98	21.98	18.95
Wind Velocity, km/h	8.9	9.8	11.9	14	18.5	18.9	18.3	14.5	11.2	7.99	7.9	9.97

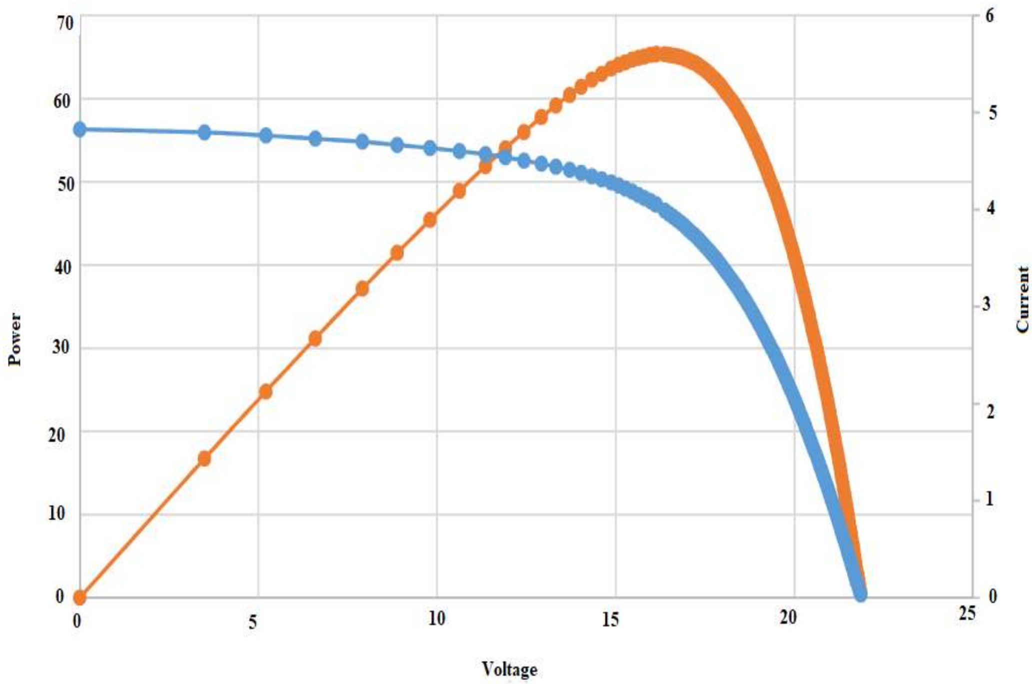

Figure 3-5-Solar Power vs. Voltage-Current Curve

Table 3-4-Specification of Solar Panel (PV)

Solar Panels type	**Mono-crystalline (Loom Solar)**
Maximum power rating (Pmax)	2 x 200 Watt ± 3% 8.13 A
Average output	0.129KW
Capacity Factor	15.5%
Gross Production	630KWh/Year
Minimum output	400W
PV Penetration	75%

Hour of operation	4345h/Year
Dimensions of Module	2108 mm × 1048 mm × 35 mm
Module Weight	24.52 kg
Power Voltage (Max.) V_{mp} (V)	25.95 V
Power Current (Max.) Imp (A)	9.85A
Voltage (Open Circuit) V_{oc}	49.7V
Current (Short Circuit) I_{sc}	11.29A
Module Efficiency (%)	20.14

3.5.3 MATLAB Simulink-based design of Solar module to be mounted on the Roof-top of the EV

3.5.3.1 *Solar Panel Configuration:*

3.5.3.1.1 Series/Parallel Configuration:

3.5.3.1.1.1 Series Connection:

Increases the overall voltage of the system. For example, if each panel provides 20 V, connecting 5 panels in series will yield 100 V.

3.5.3.1.1.2 Parallel Connection:

Increases the overall current of the system while maintaining the same voltage as a single panel.

3.5.3.2 *Cell Specifications:*

- Panel efficiency: 18–22% (typical for monocrystalline panels).
- Rated power per panel: 100–300 W, depending on size and type.
- Temperature coefficient: Define power loss with rising temperature (e.g., -0.3%/°C).

Designing a solar module for mounting on the rooftop of an electric vehicle (EV) involves considering various factors and Figure 3-7 describes the MATLAB/ Simulink design for 200Watt solar design.

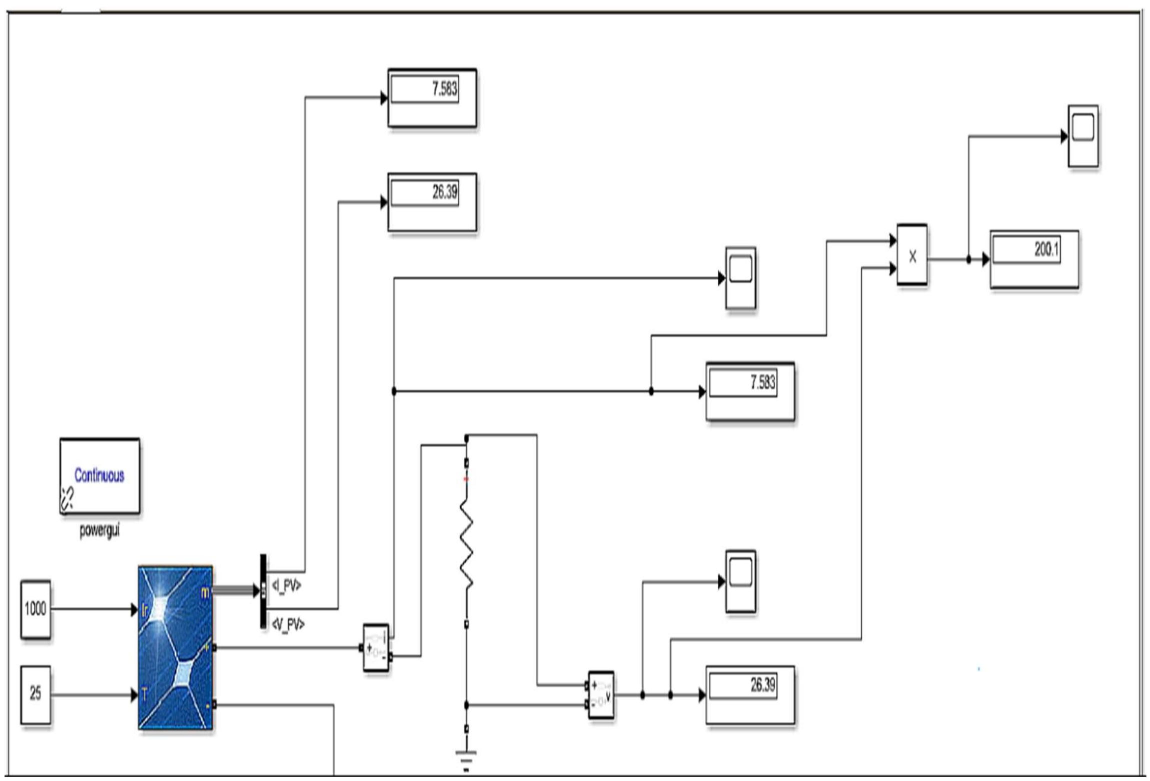

Figure 3-6-200-Watt Solar Module MATLAB Model

3.5.3.3 *Simulation Parameters:*

The block in Figure 3-7 is a photovoltaic (PV) array consisting of modules connected in series and parallel. Here is a detailed description of the figure:

3.5.3.3.1 Parameters Section:

3.5.3.3.1.1 Array data:

- The user has selected **Parallel strings** as 1, indicating only one string of PV modules connected in parallel.
- **Series-connected modules per string** are set to 1, suggesting that the configuration consists of individual modules connected in series without any series strings.

3.5.3.3.1.2 Module Data:

- **Module type** is set to **User-defined**, allowing the user to input custom characteristics for the PV module.
- **Maximum Power (W)**: The maximum power of the module is set to 200.112 W.
- **Open circuit voltage (Voc)**: The open-circuit voltage is 32.9 V.
- **The voltage at maximum power point (Vmp)**: The voltage at the maximum power point is 26.4 V.
- **Temperature coefficient of Voc**: This is set to -0.35601 (%/°C), indicating the temperature dependence of the open-circuit voltage.
- **Cells per module**: The module consists of 54 cells.
- **Short-circuit current (Isc)**: The short-circuit current is 8.21 A.
- **Current at maximum power point (Imp)**: The current at the maximum power point is 7.58 A.
- **Temperature coefficient of Isc**: This is set to 0.07 (%/°C), indicating how the short-circuit current changes with temperature.

3.5.3.3.1.3 Model Parameters:

- **Light-generated current (IL)**: The light-generated current is 8.2317 A.
- **Diode saturation current (Io)**: The diode saturation current is set to 2.4410e-10 A.
- **Diode ideality factor**: This is set to 0.97953, representing the ideality of the diode in the model.
- **Shunt resistance (Rsh)**: The shunt resistance is 124.8068 ohms, affecting the leakage current.
- **Series resistance (Rs)**: The series resistance is 0.32995 ohms, influencing the losses in the module.

3.5.3.3.1.4 Display Section:

- The figure also includes settings for displaying **I-V** (current-voltage) and **P-V** (power-voltage) characteristics for the selected irradiances: 1000, 500, and 100 W/m². It includes an option to show **one module at 25°C and specified irradiances**.

Figure 3-7 represents the detailed configuration of the PV module for simulation, including electrical characteristics and the effects of temperature on performance.

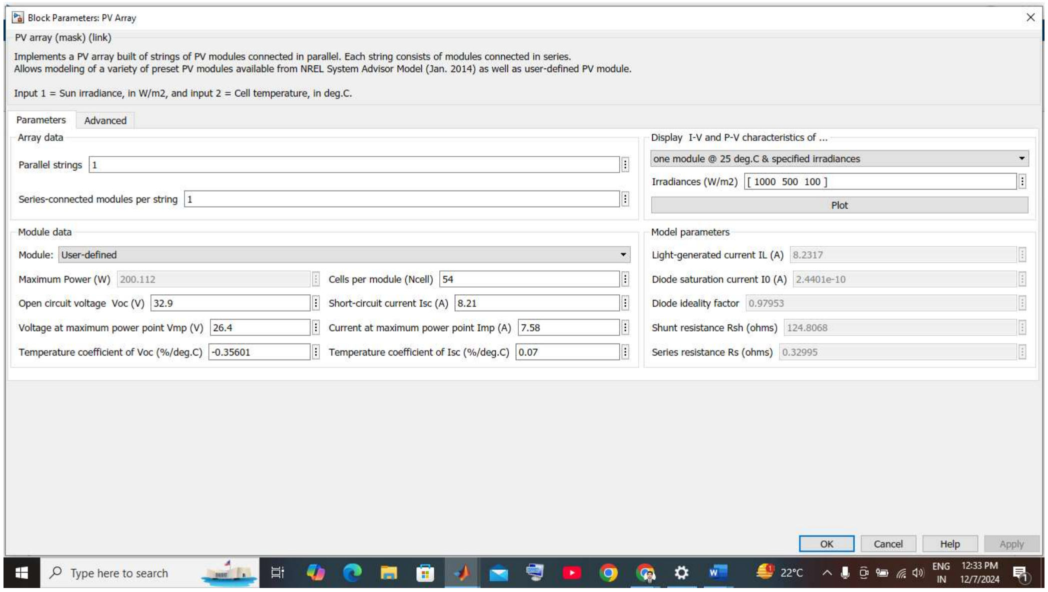

Figure 3-7-Simulation Parameters

3.5.4 Output power in Scope-MATLAB Simulink-based design of Solar module to be mounted on the Roof-top of the EV

The results from MATLAB/Simulink about a solar module are explained in Figures 3-8 and Figure 3-9.

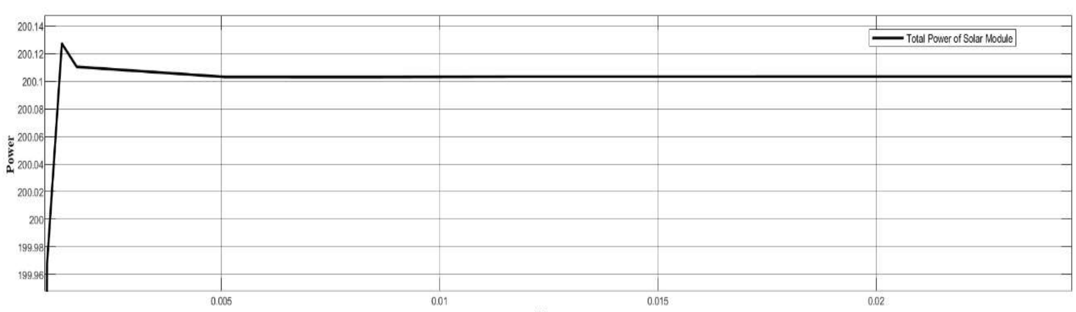

Figure 3-8- Power generated from rooftop solar module for IM-driven EV

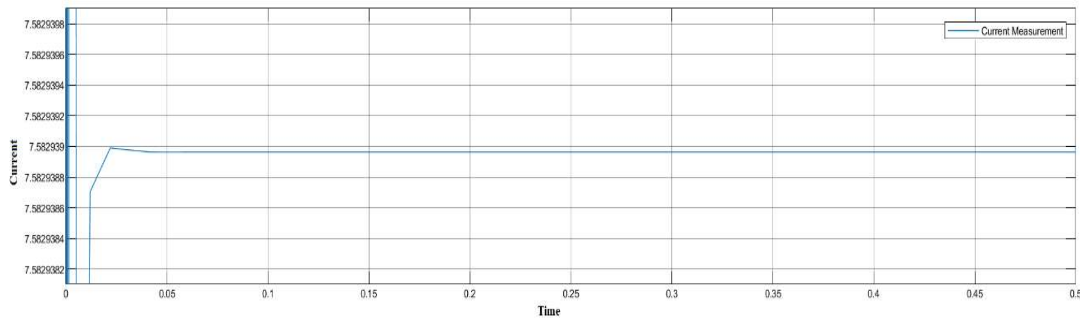

Figure 3-9- Graph showing scope current measurement, Simulink design for rooftop solar module

3.6 Role of Power Electronics Converter in Proposed Solar-Powered Induction Motor-Driven Electric Vehicles:

3.6.1 Power Converter

3.6.1.1 *Converter Type:*

DC-DC Boost Converter: Increases the voltage to the desired battery level.

DC-DC Buck Converter: Reduces voltage to match the load.

Hybrid Buck-Boost Converter: Handles variable voltage requirements.

3.6.1.2 *Efficiency:*

90–95% for high-quality converters.

3.6.1.3 *Control Strategy:*

Implement feedback loops for stable voltage and current regulation.

3.6.1.4 *Output Voltage:*

Designed to match battery charging specifications (e.g., 48 V or 96 V).

In the Proposed Solar-Powered Induction Motor-Driven electric vehicle (EV) drive systems shown in Figure 3-10, power electronics are vital for efficiently delivering and controlling electrical energy from the battery to the propulsion unit. These devices manage and convert power, ensuring it is available in the right form and quantity where and when it is needed. Typically, EV drive systems consist of a battery pack, power electronics converters (like the inverter), an Induction Motor, and control units. The inverter is a crucial power electronics component that converts high-voltage DC power from the battery pack into three-phase AC power suitable for the Induction Motor, using pulse width modulation (PWM) techniques to create an AC output waveform from the DC input. Modern inverters also feature intelligent control algorithms for variable frequency drive, enhancing the efficiency and performance of the induction motor. During regenerative braking, the Induction Motor functions as a generator, and the generated AC power must be converted back to DC power for battery charging. This conversion is handled by a power electronics device known as a rectifier. In addition to power conversion, power electronics in the EV drive system improve efficiency, power factor correction, and reduce electrical system harmonics. Advanced power electronics devices made from wide-bandgap materials like Silicon Carbide (S_i C) or Gallium Nitride (G_aN) provide higher efficiencies, compactness, and better thermal characteristics, thereby enhancing overall solar-powered Induction motor-driven Electric Vehicle performance. Power converters are widely used in various applications to enhance controllability and efficiency, particularly in automotive systems. In solar-powered induction motor-driven electric vehicles, bidirectional converters are crucial for converting DC from the battery to AC for the motor drive. There are different topologies of traction inverters, including voltage source inverters (VSI), current source inverters (CSI), impedance source converters (ZSI), and soft switching inverters. Selecting the best type of inverter for a solar-powered electric vehicle (EV) driven by an induction motor involves considering efficiency, reliability, and compatibility with the solar power source.

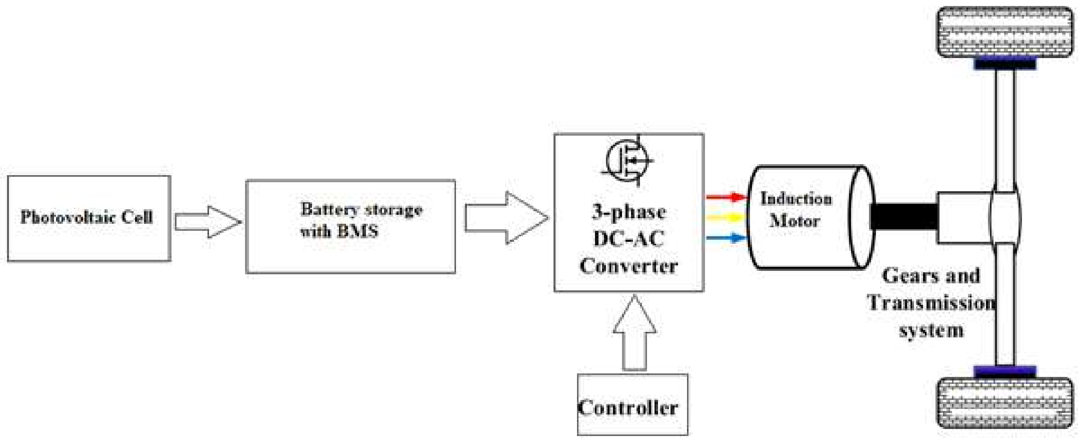

Figure 3-10-PV-Induction Motor EV Block Diagram

To ensure Maximum Power Point Tracking (MPPT) for a Photovoltaic (PV)-powered Induction Motor (IM) system, an MPPT controller is employed. The MPPT algorithm continuously adjusts the operating point of the PV system to extract the maximum available power, regardless of varying sunlight conditions[108].

3.6.1.4.1 PV Array:
The PV array generates DC power based on sunlight intensity.

3.6.1.4.2 MPPT Controller:
The MPPT controller constantly monitors the output voltage and current from the PV array, adjusting the operating point to ensure the PV system operates at its Maximum Power Point (MPP). It does this by dynamically changing the duty cycle of a DC-DC converter.

3.6.1.4.3 Converter:
A converter (usually a buck or boost converter) is used to match the PV voltage to the required voltage for the induction motor (IM). It is controlled by the MPPT controller to ensure that the system operates at the optimal voltage and current.

3.6.1.4.4 Inverter:
The DC power from the PV system is converted into AC power using an inverter to drive the induction motor. The inverter converts the regulated DC voltage to an AC supply suitable for the IM.

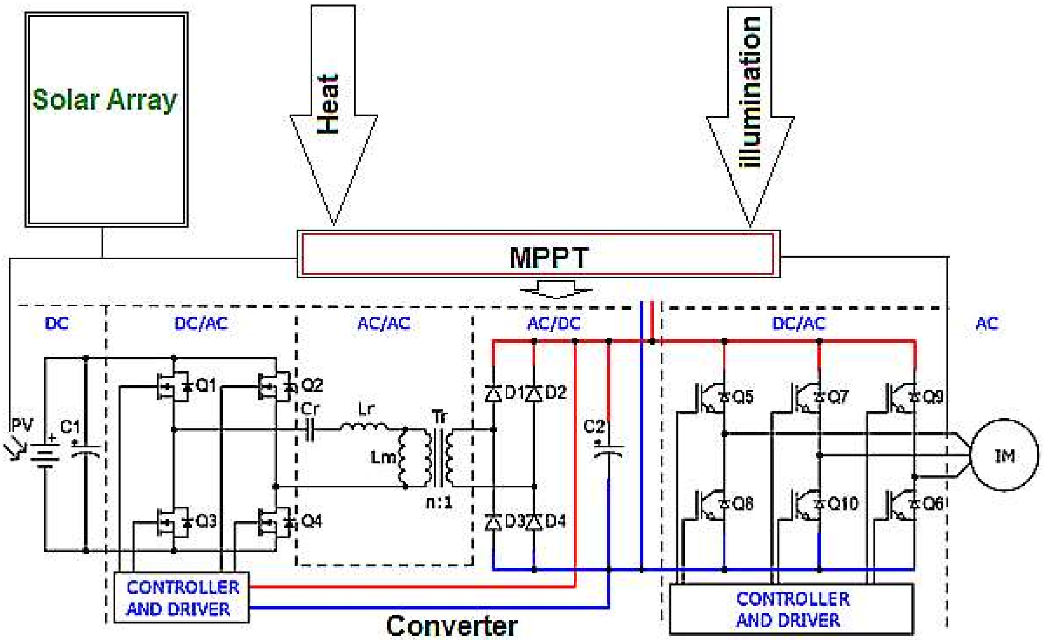

Figure 3-11- Inverter for PV-powered Induction Motor

This setup ensures that the PV system operates optimally and supplies the correct voltage and current to the induction motor, thereby improving the overall system efficiency. Illustrated in Figure 3-11 is a schematic of a solar off-grid inverter combined with a solar uninterruptible motor drive, capable of operating with or without a battery. Without sufficient sunlight, the inverter cannot provide uninterrupted operation, but it is more cost-effective than battery-powered alternatives. If a battery is included, a maximum power point tracking controller is necessary. Using a three-phase rectifier, which includes diodes and thyristors, is recommended for achieving smoother DC voltage. Since a full-bridge rectifier cannot operate in inverter mode, a semi-controlled version suffices. Inverter operation requires the ability to reverse the DC bus voltage polarity, which is not allowed. The DC bus, marked by red and blue wires, is versatile and can connect to different rectifiers, DC/DC converters, and multiple inverters. Closing the SW switch grounds the DC bus to the grid. The three-phase inverter generates variable-frequency voltage for motor speed control based on the DC bus voltage. The universal bus connects to a single-phase inverter, which uses Sinusoidal Pulse Width Modulation to generate sinusoidal voltage. The three-phase inverter, driving the induction motor, also connects to the DC bus and can be controlled simply or with advanced techniques like Space Vector Pulse Width Modulation or field-oriented control. The semiconductors are considered lossless for simplicity, and the main voltage and thyristor firing are symmetrical. These details are depicted in the schematic circuit.

3.6.2 Three-Phase Inverter Bridge

3.6.2.1 *Components:*

- IGBTs (Insulated Gate Bipolar Transistors) or MOSFETs: Switches that convert DC to AC.

- Gate Driver Circuit: Controls the switching of IGBTs/MOSFETs.

- Control Unit: Implements Pulse Width Modulation (PWM) to generate a pure sine wave output.

- Configuration: Typically, a six-switch (two for each phase) or a twelve-switch configuration for more advanced control.

3.6.2.2 *Working Principle:*

1. Solar Panels: Generate DC electricity from sunlight. The voltage and current vary with sunlight intensity.

2. DC-DC Converter: Adjusts the voltage to a level suitable for charging the battery or supplying the DC bus.

3. Battery Pack: Stores energy and supplies power to the inverter when solar power is insufficient.

4. DC Link Capacitor: Smooth out voltage fluctuations, providing a stable DC supply to the inverter.

5. Three-Phase Inverter Bridge: Converts the DC voltage to three-phase AC voltage using PWM to create a pure sine wave output.

6. Motor Controller: Regulates the frequency and amplitude of the AC voltage to control the speed and torque of the induction motor.

7. Induction Motor: Converts electrical energy to mechanical energy to drive the vehicle.

The three-phase pure sine wave inverter topology, with its associated DC-DC converter, BMS, and motor controller, is the most suitable for a solar-powered electric vehicle driven by an induction motor. This configuration ensures efficient energy conversion, stable motor operation, and optimal performance of the electric vehicle. In electric vehicles (EVs), inverters and modulation schemes are critical components of the power electronics system that controls the electric motor. Here's an overview:

3.6.3 Inverter Topology for Solar-powered Induction Motor-driven Electric Vehicles

An inverter in an EV converts the direct current (DC) from the battery into alternating current (AC) to drive the electric motor. The key types of inverters used in EVs include:

3.6.3.1 *Voltage Source Inverters (VSI):*

The most common type uses insulated-gate bipolar transistors (IGBTs) or metal-oxide-semiconductor field-effect transistors (MOSFETs) to switch the DC voltage into AC voltage. The VSI can produce variable frequency and amplitude to control the speed and torque of the motor.

3.6.3.2 *Current Source Inverters (CSI):*

Less common, CSIs convert DC into AC by controlling the current. They are often used in applications where current control is more critical than voltage control.

3.6.3.3 *Multilevel Inverters:*

These inverters can produce higher-quality AC waveforms by using multiple voltage levels, reducing harmonic distortion and improving efficiency. Common types include Neutral Point Clamped (NPC) inverters and Cascaded H-Bridge inverters.

3.6.4 Modulation Schemes

Modulation schemes are used to control the switching of the inverter to produce the desired AC output. The common modulation techniques include:

3.6.4.1 *Pulse Width Modulation (PWM):*

- Sinusoidal PWM (SPWM): Generates a sinusoidal waveform by modulating the width of the pulses according to a reference sinusoidal signal. It's widely used due to its simplicity and effectiveness.

- Space Vector PWM (SVPWM): A more advanced method that optimizes the switching pattern to improve efficiency and reduce harmonic distortion. SVPWM is popular in high-performance applications.

3.6.4.2 *Direct Torque Control (DTC):*

Controls the torque and flux directly by selecting appropriate inverter states. DTC provides fast dynamic response and is used in applications where precise torque control is essential.

3.6.4.3 *Hysteresis Band Modulation:*

Maintains the current within a hysteresis band around the reference value. It's simple to implement but can result in variable switching frequency, leading to potential noise and losses. Among these components, the inverter is particularly important as it converts direct current (DC) from the battery into alternating current (AC) needed to power the motor. This inverter also regulates the frequency, voltage, and current of the AC power supplied to the motor, allowing precise control of its performance. Additionally, the converter or charger is responsible for overseeing the charging of the EV's battery by converting AC power from an external source, such as a charging station or wall outlet, into DC power suitable for charging the battery. Some EV models also feature onboard chargers to support various charging options. Developing a mathematical model for the power electronics in EVs involves representing these components and their interactions. A simplified model for an EV's power electronics system may include the following key elements:

3.6.5 Battery Model

- The battery's characteristics can be illustrated using a simplified circuit model known as the Thevenin equivalent circuit. This model typically comprises an ideal voltage source along with an internal resistance (R_{internal}.)

$V_{battery} = E_{open\,circuit} - I_{battery} \times R_{internal}$ *(3-53)*

where $E_{open\,circuit}$ Represents the voltage of the open circuit of the battery.

3.6.6 DC-DC Converter Model

- A DC-DC converter is commonly employed to control the voltage level between the battery and the inverter. A buck or boost converter can be modeled depending on the design.

- The basic equation for a buck converter is

$V_{out} = D \times V_{in}$ *(3-54)*

where D is the duty cycle.

3.6.7 Inverter Model

- The inverter's role is to transform direct current (DC) electricity from the battery into alternating current (AC) electricity for the electric motor. A simple model for an inverter includes the modulation index m and the frequency ($f_{switching}$)

$V_{out} = m \times V_{DC}$ (3-55)

$P_{out} = V_{out} \times I_{out} = m \times V_{DC} \times I_{DC}$ *(3-56)*

3.6.8 Electric Motor Model

- The electric motor can be modeled using equations that relate the mechanical output power $P_{mech}$to the electrical power P $_{out}$ and losses.

$P_{mech} = P_{out} - P_{losses}$ *(3-57)*

3.6.9 Overall Power Flow

- The overall power flow in the system can be expressed as:

$P_{battery} = P_{DC} - DC + P_{inverter} + P_{motor} + P_{losses}$ *(3-58)*

These models are simplified and actual systems may involve more complex dynamics, non-linearities, and control strategies. Advanced simulation tools and control algorithms are often used for accurate modeling and design optimization in power electronics for electric vehicles.

3.7 MPPT/Controller

3.7.1 Maximum Power Point Tracking (MPPT)

3.7.1.1 *MPPT Usage:*

Essential for maximizing power extraction from solar panels under varying irradiance and temperature conditions.

3.7.1.2 *MPPT Algorithms:*

Perturb and Observe (P&O)

Incremental Conductance (Inc. Cond.)

Fuzzy Logic or Artificial Neural Networks (advanced).

3.7.1.3 *Efficiency:*

Typically, 95–99%, depending on the algorithm and controller hardware.

3.7.1.4 *Simulation Consideration:*

Include dynamic irradiance input to study MPPT's performance under fluctuating sunlight.

Maximum Power Point Tracking (MPPT) stands as an essential technology within solar panel systems, encompassing those integrated onto the roof of electric vehicles (EVs). Its primary function revolves around optimizing the power yield of solar panels by continuously adjusting their operational parameters to align with the maximum power point of the solar array. This technology proves indispensable in enhancing the efficiency of solar energy utilization in EVs, guaranteeing that solar panels operate at their peak capacity. The algorithm illustrating MPPT is depicted in Figure 3-12, accompanied by various conventional MPPT techniques commonly employed in solar applications, notably within solar-powered EVs.

3.7.2 Conductance Incremental

This algorithm employs the power curve's voltage $(\frac{dP}{dV})$ and current $(\frac{dP}{dI})$ rate of change. It then contrasts these incremental conductance values with the solar panel's instantaneous conductance to ascertain the direction of the maximum power point.

3.7.3 Open-circuit fractional voltage (FOCV)

The FOCV methodology works based on the concept that the voltage at the maximum power point is typically related to the open-circuit voltage. By approximating this relationship, the algorithm adjusts the operating point of solar panels to optimize power output.

3.7.4 Model Predictive Control (MPC)

- MPC employs a mathematical representation of both the solar panels and the electrical system.
- It predicts the system's future behavior and optimizes the operating point to maximize power output.
- MPC is known for its ability to handle dynamic and changing environmental conditions.

3.7.5 Hill Climbing Search

- Similar to P&O, Hill Climbing adjusts the operating point in the direction that leads to an increase in power.
- However, it may have faster convergence and reduced oscillations compared to P&O by incorporating additional control logic.

3.7.6 Neutral Networks and Machine Learning

- Advanced MPPT methods may employ neural networks or machine learning algorithms to adapt to changing environmental conditions.

- These methods can acquire knowledge and improve the Maximum Power Point Tracking (MPPT) procedure using historical data and live sensor feedback.

3.7.7 Fuzzy Logic Controls

Fuzzy logic controllers utilize language-based rules to make decisions. In terms of Maximum Power Point Tracking (MPPT), a fuzzy logic controller can adjust the operating point based on linguistic rules related to power and voltage change rates. Choosing the appropriate MPPT strategy depends on factors such as system complexity, costs, and the specific requirements of the solar-powered electric vehicle.

3.7.8 Perturb & Observe

This represents one of the most straightforward MPPT techniques available and this type of MPPT is widely used which is shown in Figure 3-13. It regularly adjusts the operating conditions of solar panels, monitoring power output variations. Upon detecting changes, it fine-tunes the operating parameters to enhance power output, progressively approaching the maximum power point.

3.7.8.1 *Purpose of the P&O MPPT Algorithm:*

The P&O MPPT algorithm aims to track the Maximum Power Point (MPP) of a PV array by incrementally perturbing the operating voltage and observing the resulting power change. It adjusts the voltage to ensure the PV system operates at the MPP, thus maximizing the energy output [109].

3.7.8.2 *Process Description:*

Step 1: Initialize Parameters

- The algorithm begins by setting the initial conditions:

-$V_{initial}$: Initial voltage.

-$I_{initial}$: Initial current.

- A small perturbation step size (Δ V) is defined to increment or decrement the operating voltage.

Step 2: Calculate Initial Power

- The initial power ($P_{initial}$) is calculated:

$$P_{initial} = V_{initial} \times I_{initial} \qquad \textit{(3-59)}$$

Step 3: Start Iterative Process

- The algorithm enters a loop that continues until the convergence condition is met (i.e., power change becomes negligible).

Step 4: Perturb the Voltage

- A small change (Δ V) is applied to the operating voltage, resulting in a new perturbed voltage:

$$V_{perturbed} = V_{initial} + \Delta V \qquad \textit{(3-60)}$$

Step 5: Measure New Power

- Using$V_{perturbed}$, the current ($I_{perturbed}$)) is measured, and the new power ($P_{perturbed}$) is calculated:

$$P_{perturbed} = V_{perturbed} \times I_{perturbed} \qquad \textit{(3-61)}$$

Step 6: Compare Power Values

- The new power ($P_{perturbed}$) is compared to the initial power ($P_{initial}$):

- If $P_{perturbed}$ >$P_{initial}$:

  - The perturbation is in the correct direction.

- Update the operating point: $V_{initial}$ =$V_{perturbed}$.

- Else:

- The perturbation is in the wrong direction.

- Reverse the perturbation direction: $V_{perturbed} = V_{initial} - \Delta V$.

Step 7: Check Convergence

- The algorithm calculates the change in power ΔV between successive iterations:

$$\Delta P = \left|P_{perturbed-}P_{initial}\right| \qquad (3\text{-}62)$$

- If ΔP is less than a predefined convergence threshold (e.g., 0.01), the algorithm concludes that the MPP has been reached.

Step 8: Output MPP

- Once the convergence condition is satisfied, the operating point corresponds to the Maximum Power Point (MPP), and the algorithm terminates.

3.7.8.3 *Limitations of P&O MPPT:*

- Oscillations Around MPP:

- The algorithm tends to oscillate near the MPP due to continuous perturbation, causing small power losses.

- Slow Convergence:

- Under rapidly changing environmental conditions, it may struggle to track the MPP accurately.

- Fixed Step Size:

- A fixed ΔV can lead to inefficiency if not chosen correctly. Smaller ΔV improves accuracy but slows tracking, while larger ΔV increases oscillations.

- DC-DC Converters: To adjust the voltage and ensure compatibility with the load (e.g., battery or motor).

This flowchart provides a clear and structured representation of how the P&O algorithm works, illustrating the feedback and iterative process necessary to achieve MPPT in a PV-powered EV system.

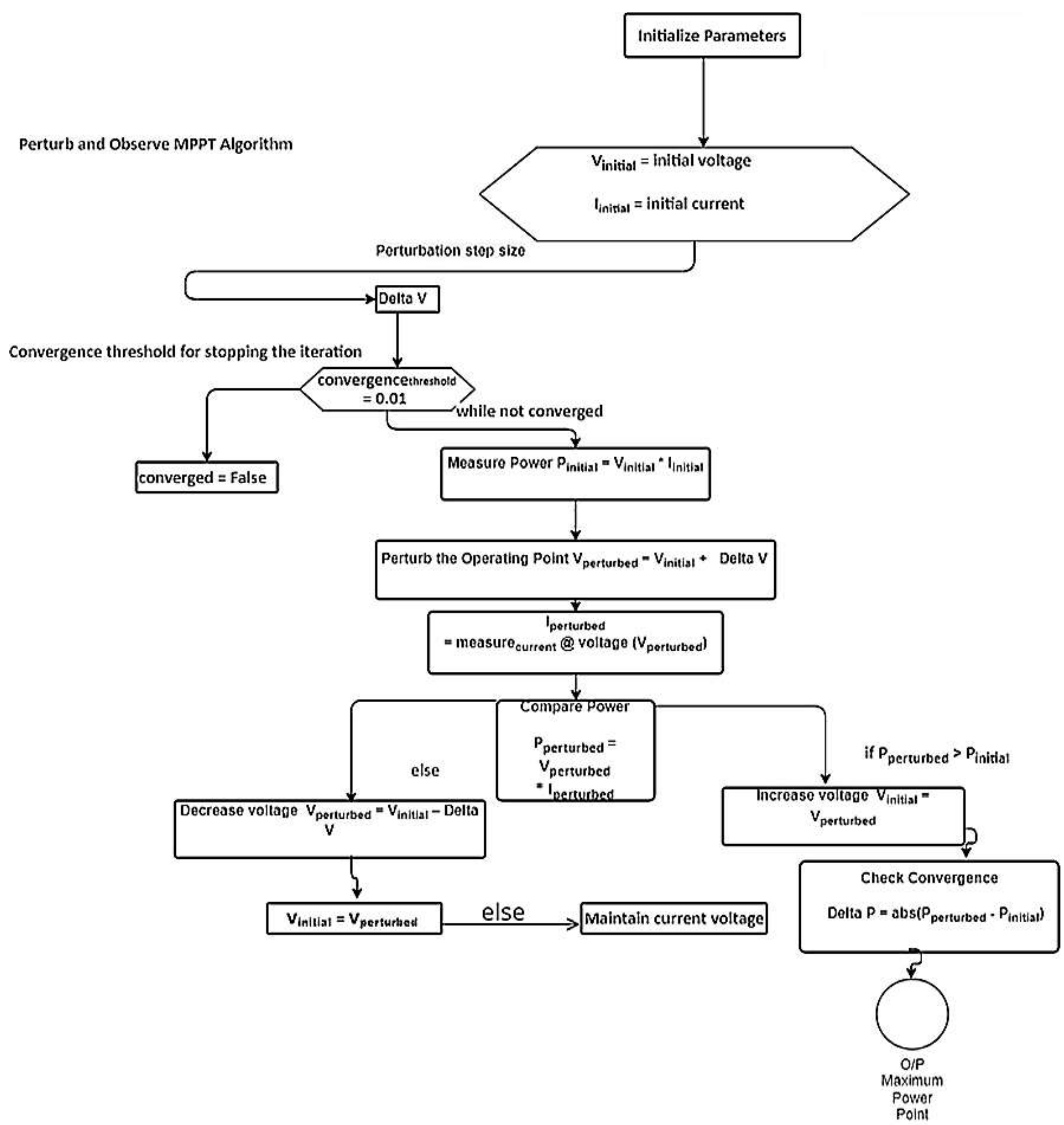

Figure 3-12- Optimizing Solar Harvesting in EVs with MPPT

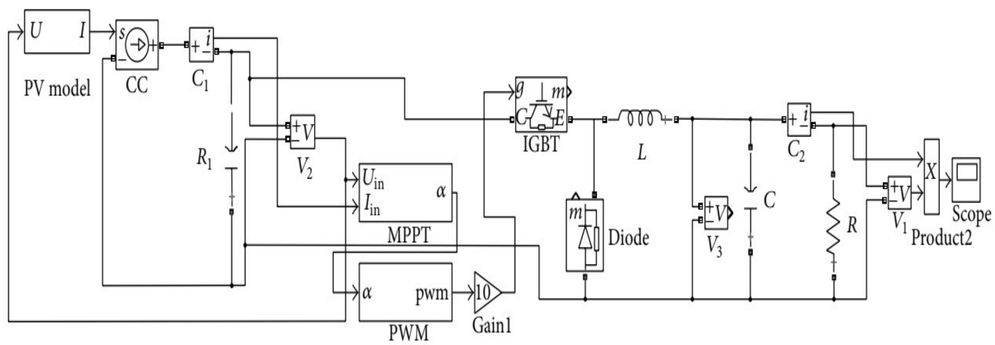

Figure 3-13-Model for Maximum Power Point Tracking System

3.7.9 Charge Controller Block

Figure 3-13 provides details about implementing MPPT for an electric vehicle and the Charge controller shown in Figure 3-14 is vital for preserving energy in electric vehicles. It is responsible for regulating the voltage supplied to the vehicle's motor, which is converted to AC when using an induction motor for propulsion. Using a controller that meets the specified ratings of 12 volts and 10 amps is crucial to achieving the best performance.

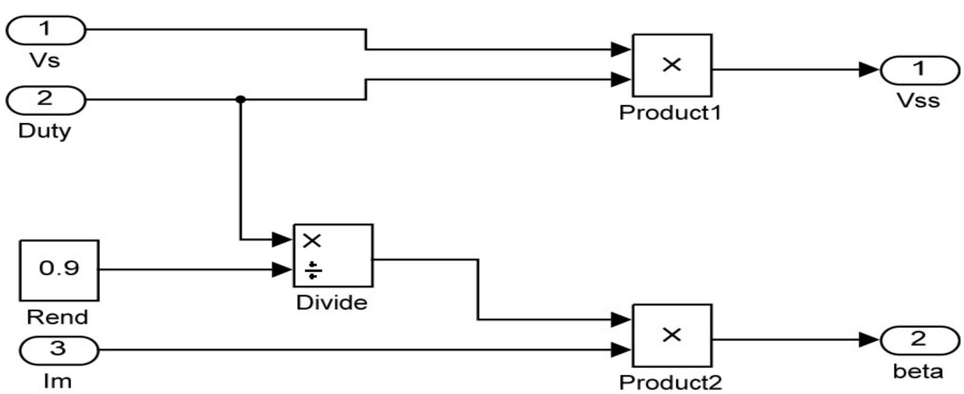

Figure 3-14- Mathematical Model of Charge Controller

3.8 Specification of Designed photovoltaic-based IM-driven electric vehicle systems (Mini EV)

3.8.1 Charge Management Device:

The solar charge Management Device also known as the "Charge controller" serves as a bridge between the solar panels and the battery bank, regulating the charging procedure to avert overcharging and guaranteeing effective energy transmission. The power electronics converter in electric vehicles depicted in Figure 3-15 and PWM controllers manage the battery voltage by swiftly alternating the solar panel's output, ensuring a secure voltage level, making them ideal for smaller solar setups. In contrast, MPPT controllers enhance power output by continually adapting the solar panels' operating point to achieve maximum power, making them more efficient and better suited for larger solar installations.

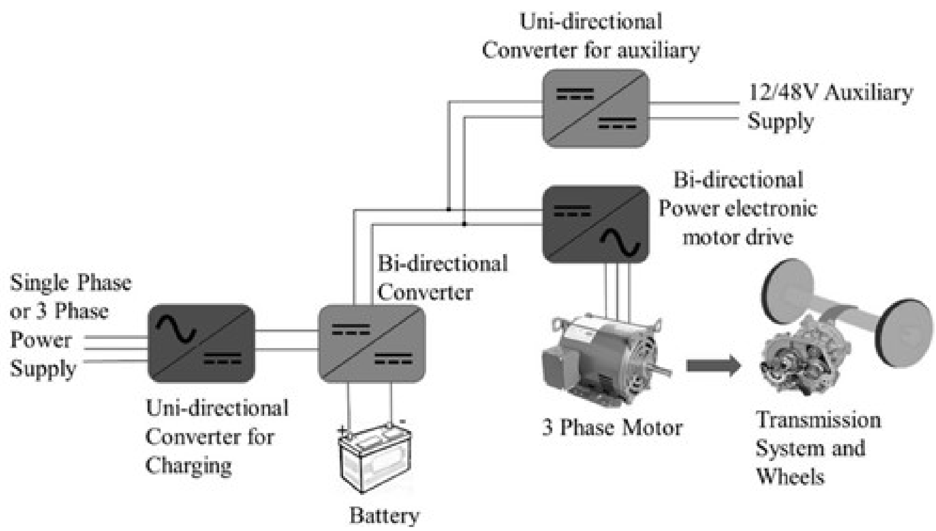

Figure 3-15-Power Electronics converter in EV

3.9 Chassis & Frame

The fundamental framework of every vehicle comprises the frame and chassis, housing all internal components designed to safeguard passengers. A truss structure is essential for ensuring heightened safety. Torsional Rigidity, a crucial aspect in vehicle design is mathematically represented by the torsional constant (J) and shear modulus (G). This parameter is pivotal for maintaining structural integrity. Now, delving into the specifics of an electric vehicle chassis, it is imperative to construct a robust truss framework. This design not only fortifies the overall structure but also upholds Torsional Rigidity, ensuring resistance to twisting forces. The chassis serves as the foundational skeleton, integrating seamlessly with the vehicle's components to create a cohesive unit. In the context of electric vehicles, the chassis plays a pivotal role in supporting the battery pack, motor, and other critical elements. Manufacturers improve the safety and performance of electric vehicles by thoroughly addressing Torsional Rigidity in chassis design, ensuring compliance with the rigorous standards of contemporary automotive engineering.

3.9.1 Chassis/ Body and Structural Dimension

The chassis body is shown in Figure 3-16, Designing the chassis of an electric vehicle involves various engineering principles, including structural mechanics and materials science. The chassis plays a vital role by offering structural stability to the vehicle and accommodating different subsystems like the battery pack, electric motor, and suspension system. Let's break down the mathematical calculations related to the chassis design, based on the given data:

Dimensions of the Chassis:

The chassis body is a Mild Steel (MS) plate with dimensions:

- Length (L): 1150 mm
- Width (W): 1250 mm
- Height (H): 1300 mm

3.9.2 Clearance from Ground and Calculating Chassis Volume:

The clearance or height from the ground is specified as 560 mm. The volume of the chassis can be calculated using the formula:

$$Volume = Length \times Width \times Height \quad (3\text{-}63)$$

Substituting the given values:

$$Volume = 1150mm \times 1250mm \times 1300mm \quad (3\text{-}64)$$

3.9.2.1 *Determining the Ground Clearance Volume:*

The volume below the chassis, representing the ground clearance space, can be calculated using the formula:

$$GroundClearanceVolume = Length \times Width \times Clearance \quad (3\text{-}65)$$

Substituting the given values:

$$GroundClearanceVolume = 1150mm \times 1250mm \times 560mm \quad (3\text{-}66)$$

3.9.2.2 *Calculating the Volume Occupied by the Chassis Above Ground:*

The volume occupied by the chassis above ground level can be found by subtracting the ground clearance volume from the total chassis volume:

$$ChassisVolumeAboveGround = ChassisVolume - GroundClearanceVolum \quad (3\text{-}67)$$

3.9.2.3 *Determining the Mass of the Chassis:*

The mass of the chassis can be estimated based on the density of Mild Steel (MS) and the volume of the chassis:

$$Mass = Volume \times Density \quad (3\text{-}68)$$

The density of Mild Steel is typically around 7.85 g/cm³ or 7850 kg/m³. Convert the volume from cubic millimeters to cubic meters for consistency.

$$Mass = ChassisVolume \times Density \quad (3\text{-}69)$$

3.9.3 Structural Analysis:

Additional computations and evaluations are necessary to verify the chassis's ability to endure the anticipated loads and pressures during its functioning. This encompasses assessing stress, strain, and safety margins. Techniques like finite element analysis (FEA) can be utilized for evaluating the chassis's robustness and structural soundness [110].

Figure 3-16-Chasis body

The torsional rigidity is calculated as follows:

3.9.4 Torsional Rigidity

$$Torsional\ Rigidity\ = (G\ *\ J)\ /\ L \tag{3-70}$$

where: Torsional Rigidity: represents the torsional stiffness or rigidity of the structure.

G is the shear modulus of the steel. (782943 megapascals (MPa).

J is the torsional constant (Rectangular solid section: $\mathrm{J} = (\mathrm{b} * \mathrm{h3}) / 3$ where b represents the dimension of width and h represents the section’s dimension of height) and L is the structure length (1.5 meters)

$$T = 2 * 1000 * \left(\frac{0.33}{2}\right) = 330Nm \tag{3-71}$$

$$\Theta = 0.224\ deg. \tag{3-72}$$

$$Kt = 330/0.224 = 1473\, Nm/degree \quad (3\text{-}73)$$

Chassis Torsional Stiffness or Rigidity lies between 330 to 3300 for small Solar Powered Electric Vehicle.

3.10 Wheel

Pneumatic Wheel type

$$Force = mass * acceleration\ where\ mass = Weight\ in\ kg/(gravity\ in\ m/s) = 250/9.81 = 25\, kg \quad (3\text{-}74)$$

So, the impact force will be near about 2500N, now we observe impact force at the rear, front, and side of the vehicle

3.11 Model of Dynamic Forces exerted by Photovoltaic-based Induction Motor-driven Electric Vehicle using MATLAB

Figure 3-17 illustrates the Model of Dynamic Forces applied by a Photovoltaic-powered induction motor-driven electric vehicle using MATLAB/Simulink. A photovoltaic-powered induction motor-driven electric vehicle experiences dynamic forces that arise from the interaction of its various components and operating conditions. These dynamic forces can significantly impact the vehicle's performance, efficiency, and overall design considerations. One of the primary dynamic forces is the varying power output from the photovoltaic (PV) panels due to changes in solar irradiance and panel orientation. This fluctuation in power affects the torque and speed of the induction motor, leading to variations in the vehicle's acceleration and speed control. The dynamic nature of solar power also requires an effective maximum power point tracking (MPPT) system to optimize power extraction from the PV panels continuously.

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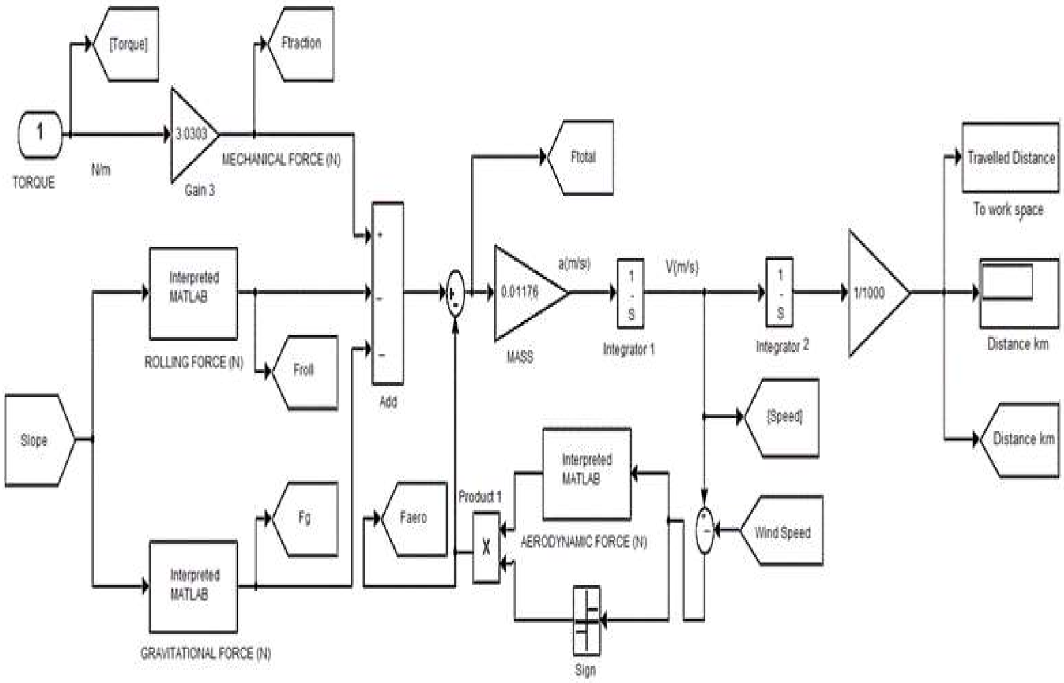


Figure 3-17-Dynamic forces model for PV-powered EV using MATLAB

Additionally, the torque ripple generated by the induction motor during operation contributes to dynamic forces that influence vehicle stability and ride comfort. Advanced motor control algorithms, such as field-oriented control (FOC) or direct torque control (DTC), are employed to minimize torque ripple and ensure smooth operation. Furthermore, regenerative braking introduces dynamic forces during deceleration, where the motor acts as a generator to recover energy and recharge the battery. Managing regenerative braking forces effectively is crucial for maximizing energy efficiency and extending the vehicle's range.

Overall, understanding and mitigating these dynamic forces are essential for designing efficient and reliable photovoltaic-powered induction motor-driven electric vehicles, ensuring optimal performance and user experience while utilizing renewable energy sources.

3.12 Chapter Summary

This thesis investigates the development of a photovoltaic (PV)-based induction motor (IM)-driven electric vehicle (EV) system, focusing on dynamic force modeling, energy management, and system design optimization. Utilizing MATLAB/Simulink, the study integrates critical elements such as force dynamics, powertrain modeling, solar energy capture, and energy storage to enhance vehicle performance. Structural analysis, chassis volume estimation, and ground clearance calculations ensure mechanical reliability, while advanced control strategies like Maximum Power Point Tracking (MPPT), neural networks, and machine learning are incorporated for optimal energy management. The system is designed for a mini-EV configuration, emphasizing efficiency and sustainability.

Key components of the system include:

3.12.1.1 *Dynamic Force Modeling:*

Estimation of rolling resistance, aerodynamic resistance, and gradient forces under varying operating conditions.

3.12.1.2 *Photovoltaic Energy System:*

Roof-mounted solar panels are modeled with precise mathematical equations to optimize energy capture.

3.12.1.3 *Powertrain System:*

Comprehensive design of the electric motor, inverter, DC-DC converter, and battery models for efficient power delivery.

3.12.1.4 *Energy Management:*

Use of algorithms like Hill Climbing Search, Conductance Incremental, and Open-Circuit Fractional Voltage (FOCV) for MPPT to ensure maximum utilization of solar energy.

3.12.1.5 *Structural Design:*

Analysis and optimization of the chassis and frame for weight and volume efficiency, enhancing vehicle performance and stability.

3.12.1.6 *Simulation Framework:*

MATLAB/Simulink-based design and simulation to validate the system's behavior under various driving conditions and solar irradiance levels.

3.13 Key Observations

3.13.1.1 *Dynamic Forces in EV Motion:*

The forces exerted by the mini-EV, including rolling resistance, aerodynamic drag, gradient resistance, and acceleration forces, play a significant role in energy consumption. Precise modeling ensures better energy efficiency.

3.13.1.2 *Integration of Solar Panels:*

The rooftop solar panel design, based on mathematical modeling and size estimation, contributes significantly to extending the vehicle's range by supplementing the battery's charge.

3.13.1.3 *Energy Efficiency:*

The use of MPPT techniques (e.g., Hill Climbing Search and FOCV) and advanced controllers increases energy capture efficiency and ensures maximum power delivery to the motor.

3.13.1.4 *Battery and Motor Sizing:*

Proper estimation of battery capacity and induction motor sizing is critical for achieving a balance between power output, range, and cost efficiency.

3.13.1.5 *Structural Analysis:*

Optimized chassis design and proper ground clearance improve vehicle performance, durability, and safety.

3.13.1.6 *Neural Networks and Machine Learning:*

These tools show potential in predicting energy requirements, optimizing charge management, and improving overall system efficiency.

3.14 Chapter Conclusion

This research presents a comprehensive framework for designing and optimizing photovoltaic-based induction motor-driven electric vehicles. Key outcomes include:

3.14.1.1 *Enhanced Range and Efficiency:*

Through optimized solar panel integration and MPPT techniques, the system achieves superior energy efficiency and extended operational range.

3.14.1.2 *Sustainable Energy Utilization:*

The design leverages renewable energy effectively, reducing reliance on conventional charging methods.

3.14.1.3 *Robust Design:*

Structural and mechanical optimization ensures safety, reliability, and performance in diverse operating conditions.

3.14.1.4 *Advanced Control Systems:*

The integration of intelligent algorithms and machine learning enhances energy management and system adaptability to dynamic conditions.

The developed MATLAB/Simulink simulation framework validates the system's feasibility, providing a practical foundation for future PV-based mini-EVs. This research contributes to the growing field of sustainable transportation by offering an efficient and cost-effective design approach for electric vehicles powered by renewable energy sources.

4 Performance assessment of a Brushless Direct Current motor-powered EV

4.1 Brushless Direct Current Motor for EV propulsion application

In contrast to alternative motors, BLDC motors offer the benefit of generating higher torque at equivalent levels of current and voltage. Their high power and enhanced efficiency make brushless DC motors a desirable option for use in EV pulse applications. However, one drawback of BLDC motors is the cost associated with the magnets used in their rotors. The mechanical strength of these magnets poses challenges in achieving high torque output. Furthermore, the persistent magnetic field restricts the ability to weaken the field, necessitating an increase in the switching angle to extend the functionality of the constant power region.

4.2 The dynamic equation describing an electric vehicle (EV) equipped with a brushless DC (BLDC) motor

When considering a brushless motor as the prime mover in an electric vehicle (EV), the dynamic equation can be derived based on the principles of electromechanical dynamics. Here is an overview of the dynamic equation for an EV with a brushless motor:

4.2.1 Mechanical Equation:

The movement of the vehicle follows a mechanical equation that is derived from Newton's second law of motion:

$$M * \frac{d^2x(t)}{dt^2} = Fa(t) - Fr(t) - Fl(t) \tag{4-1}$$

In this context, 'M' represents the combined weight of the vehicle, including both the driver and any payload it carries. x(t) shows the position at time t of the vehicle. Fa(t) is the applied force of driving on the vehicle.

Fr(t) represents the force of resistance acting against the motion of the vehicle (including rolling resistance, aerodynamic drag, etc.). $F_l(t)$ is the force generated by the brushless motor.

When considering a brushless motor as the prime mover in an electric vehicle (EV), the dynamic equation can be derived based on the principles of electromechanical dynamics. Here is an overview of the dynamic equation for an EV with a brushless motor:

4.2.2 Electrical Equation

The electrical equation establishes a connection between voltage, current, and back electromotive force (EMF) within the brushless motor, and it is explained as follows:

$$V_{s_a}(t) = R_s * I_s(t) + L_s * dI_s(t)/dt + V_m(t) \tag{4-2}$$

Where:

$V_s(t)$ shows stator voltage.

R_s shows resistance.

$I_s(t)$ shows stator current.

Ls shows stator inductance.

$V_m(t)$ is the back EMF generated by the motor.

4.2.3 Torque Equation

The torque equation establishes a connection to stator current and electromagnetic torque generated by a brushless motor:

$$T_e(t) = k_i * I_s(t) \tag{4-3}$$

Where $T_e(t)$ shows in the equation electromagnetic torque. k_i shows in the equation the torque constant of the motor. The above equations describe the dynamics of an electric vehicle with a brushless motor as the prime mover. The driving force ($F_a(t)$) and resistive force ($F_r(t)$) depend on factors such as the accelerator pedal position, road gradient, and vehicle speed. The force generated by the brushless motor ($F_l(t)$) depends on the electromagnetic torque $T_e(t)$, which, in turn, is related to the stator current ($I_s(t)$) through the torque constant (k_i). The stator voltage ($V_s(t)$) is determined by the stator resistance (R_s), stator current ($I_s(t)$), stator inductance (L_s), and back EMF ($V_m(t)$) generated by the motor.

4.3 MATHEMATICAL MODELING FOR BLDC MOTOR

The equivalent circuit of the BLDC Motor is shown in Figure 4-1, The voltage equation of the mathematical model.

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} e_A \\ e_B \\ e_C \end{bmatrix} \qquad (4\text{-}4)$$

R Resistance of stator and L is inductance

$$Electromagnetic\ Torque\ (\tau) = I \frac{d}{dt}\ \omega\ Load\ Torque\ (\tau) + B\ \omega \qquad (4\text{-}5)$$

I -Moment of Inertial ω angular motion

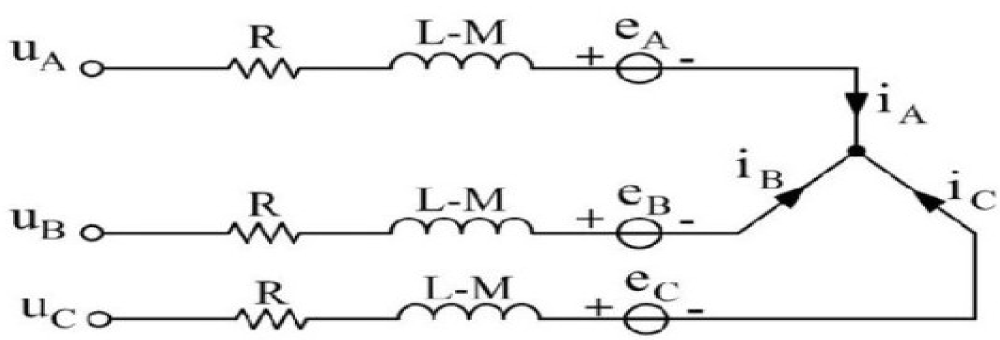


Figure 4-1-Equivalent circuit of a BLDC motor

4.3.1 Performance Assessment of a Brushless Direct Current (BLDC) Motor-Powered Electric Vehicle

BLDC motors are increasingly popular for EV propulsion systems due to their high efficiency, compact size, and reliability. This section discusses the performance metrics for BLDC-powered EVs, including acceleration, energy consumption, range, and system efficiency.

4.3.1.1 *The Dynamic Equation Describing an EV Equipped with a BLDC Motor:*

The dynamic model of an EV powered by a BLDC motor integrates various forces acting on the vehicle, such as inertia, aerodynamic drag, rolling resistance, and gradient resistance.

4.3.1.1.1 Governing Equation:

Total tractive force F_t required is

$$F_t = F_a + F_r + F_g + F_i \tag{4-6}$$

here

$F_a = \frac{1}{2}\,\rho\, C_d\, A\, v^2$ (Aerodynamic drag Force)

$F_r = mgC_r$ (Rolling Resistance)

$F_g = mg \sin\theta$ (Gradient Resistance)

$F_i = m\frac{dv}{dt}$ (Inertial Force)

4.3.2 Comparison of BLDC Motor Performance for Traction Systems Using Multiple Criteria

The performance of the motor is described in Table 4-1, whereas key criteria for evaluating BLDC motor performance in EV applications include:

Efficiency Map: Motor efficiency at various operating points.

Torque Ripple: Smoothness of motor output.

Thermal Performance: Heat generation and dissipation under load.

Reliability: Mean Time Between Failures (MTBF).

4.3.2.1.1 Performance Comparison

Table 4-1- Motors performance comparison

Criteria	BLDC Motor	Induction Motor	PMSM
Peak Efficiency	92-96%	87-92%	93-97%
Torque Ripple	Low	Moderate	Very Low
Cost per kW	High	Moderate	High
Control Complexity	Moderate	Low	High

4.3.3 Mathematical Modeling for BLDC Motor

A BLDC motor's mathematical model is described in terms of its electrical, mechanical, and electromagnetic subsystems.

4.3.3.1 *Electrical Model*

For a 3-phase BLDC motor:

$$v_a = Ri_a + L\frac{di_a}{dt} + e_a \tag{4-7}$$

$$v_b = Ri_b + L\frac{di_b}{dt} + e_b \tag{4-8}$$

$$v_c = Ri_c + L\frac{di_c}{dt} + e_c \tag{4-9}$$

Where:

- R: Resistance per phase
- L: Inductance per phase
- e: Back EMF (depends on rotor position)

4.3.3.2 *Mechanical Model*

The rotor dynamics are governed by:

$$T_e = J\frac{dw}{dt} + B\omega + T_l \qquad (4\text{-}10)$$

Where:

- T_e: Electromagnetic torque

-ω: Rotor speed

- J: Moment of inertia

- B: Friction coefficient

- T_l: Load torque

Efficiency Evaluation of a BLDC Motor

Efficiency is a crucial parameter for BLDC motors used in EVs. It can be evaluated as:

$$\eta = \frac{P_{out}}{P_{in}} \qquad (4\text{-}11)$$

Where:

- $P_{in} = V * I$ (Input power)

- $P_{out} = T * \omega$ (Output power)

4.3.3.3 *Efficiency Map*

Efficiency maps for BLDC motors are often plotted against speed and torque. Peak efficiency is typically achieved at medium speeds and loads.

4.3.3.3.1 Efficiency Map of a Brushless DC (BLDC) Motor

An efficiency map is a graphical representation that shows the efficiency of a motor across a range of operating speeds and torques. These maps are crucial for understanding the optimal operating conditions of BLDC motors and are widely used in electric vehicle (EV) propulsion system design.

4.3.3.3.2 Characteristics of BLDC Motor Efficiency Map

4.3.3.3.3 Axes:

- X-Axis: Speed (rpm)

- Y-Axis: Torque (Nm)

4.3.3.3.4 Contours:

- Represent different efficiency levels (e.g., 70%, 80%, 90%, etc.).

- Peak efficiency is typically achieved at medium speed and medium torque.

4.3.3.3.5 Key Operating Regions:

- Low Speed, Low Torque: Reduced efficiency due to increased losses from resistance and low power output.

- Medium Speed, Medium Torque: Optimal efficiency where the motor operates near its peak performance point.

- High Speed, High Torque: Efficiency drops due to increased core losses, switching losses, and heating effects.

- Peak Efficiency: Around 92% at 4000 rpm and 15 Nm.

- Efficiency Drops: Below 75% at very low torque (e.g., <5 Nm) or very high speed (>6000 rpm).

4.3.3.4 ***Factors Affecting Efficiency Map:***

Iron Losses: Increase at higher speeds due to eddy currents and hysteresis.

Copper Losses: Increase with higher torque demands due to higher current flow.

Switching Losses: Increase at higher frequencies in the inverter.

Thermal Effects: Elevated motor temperatures reduce efficiency.

Control Algorithm: Field-oriented control (FOC) can enhance efficiency, especially under dynamic conditions.

4.3.3.5 *Evaluation Parameters*

The performance of an EV equipped with a BLDC motor is assessed using the following key parameters:

4.3.3.5.1 Energy Efficiency:

- Measured in terms of the energy consumed per kilometer (Wh/km).

- Dependent on driving conditions, vehicle weight, and motor efficiency.

4.3.3.5.2 Vehicle Range:

- The maximum distance the EV can travel on a full battery charge.

- Affected by driving cycles, motor efficiency, and battery capacity.

4.3.3.5.3 Acceleration:

- Evaluate the time taken to achieve speeds such as 0–50 km/h or 0–100 km/h.

- Highlights the motor's torque delivery capability.

4.3.3.6 *Thermal Performance:*

- Motor heating during operation under continuous or peak loads.

- Evaluate the efficiency of the cooling system.

4.3.4 Technical Data for Evaluation

In this section, we present the technical data necessary for evaluating the performance of a Brushless DC (BLDC) motor-based system for electric vehicles (EVs). The specifications provide key parameters that influence the system's overall efficiency, performance, and practicality under real-world conditions, as shown in Table 4-2. These parameters are essential for assessing the vehicle's energy consumption, driving characteristics, and ability to perform in various scenarios such as acceleration and braking.

4.3.4.1 *Motor Type (Brushless DC Motor):*

A Brushless DC (BLDC) motor is widely used in electric vehicles (EVs) due to its high efficiency, low maintenance requirements, and reliable performance. Unlike traditional brushed motors, BLDC motors do not use brushes for commutation, reducing mechanical wear and increasing durability. They are powered by electronic controllers that ensure precise torque and speed control.

4.3.4.2 *Rated Power (10–50 kW):*

The rated power indicates the maximum continuous power output of the BLDC motor. This range (10–50 kW) is suitable for small to medium-sized electric vehicles (EVs), providing an optimal balance between performance and energy efficiency. The motor's power capability directly affects the vehicle's speed, range, and ability to handle different driving conditions.

4.3.4.3 *Maximum Speed (3000–10,000 rpm):*

The maximum speed is the top rotational speed the motor can achieve. For BLDC motors used in EVs, speeds between 3000 rpm and 10,000 rpm are typical. The high-speed capability of the motor allows for efficient operation across a range of driving conditions, especially for applications requiring high-speed performance on highways or longer roads.

4.3.4.4 *Battery (Lithium-ion, 48V, 100Ah):*

The battery is a crucial component in EV systems. Lithium-ion batteries are chosen for their high energy density, long lifespan, and lightweight compared to other battery types. A 48V system with a 100Ah capacity provides sufficient energy storage for small EVs, ensuring a balance between weight, cost, and performance.

4.3.4.5 *Vehicle Weight (1000–1500 kg):*

The vehicle weight directly affects the performance, energy consumption, and range of the EV. This range of 1000–1500 kg is typical for compact to mid-sized electric vehicles, providing a practical combination of weight, stability, and space for the battery, motor, and other vehicle components.

4.3.4.6 *Energy Consumption (150–200 Wh/km):*

Energy consumption measures the amount of energy the vehicle uses to travel a kilometer. This value varies depending on factors such as vehicle weight, driving style, and terrain. A range of 150–200 Wh/km is typical for small EVs, indicating moderate efficiency and the ability to provide a reasonable driving range on a single charge.

4.3.4.7 *Acceleration (0–50 km/h in 4–6 seconds):*

The acceleration time from 0 to 50 km/h reflects the vehicle's performance in urban settings, where quick acceleration is essential for city driving. A time of 4–6 seconds indicates a responsive motor that can handle stop-and-go traffic, offering a smooth and efficient driving experience.

4.3.4.8 *Regenerative Braking Efficiency (10–20% energy recovery):*

Regenerative braking allows the vehicle to recover a portion of the energy that would otherwise be lost during braking and convert it back into electrical energy to recharge the battery. An efficiency range of 10–20% indicates the ability to recover energy during deceleration, thereby improving overall energy efficiency and extending the vehicle's range.

This technical data provides the foundation for evaluating the performance of a BLDC motor-powered electric vehicle. By assessing each parameter, the feasibility of using such a system in various applications can be determined, ensuring that the system can deliver high efficiency, satisfactory performance, and practicality for small EVs.

Table 4-2-BLDC specification for evaluation

Parameter	Value/Range
Motor Type	Brushless DC Motor (BLDC)
Rated Power	10–50 kW
Maximum Speed	3000–10,000 rpm
Battery	Lithium-ion (48V, 100Ah for small EVs)
Vehicle Weight	1000–1500 kg
Energy Consumption	150–200 Wh/km
Acceleration (0–50 km/h)	4–6 seconds
Regenerative Braking Efficiency	10–20% energy recovery

4.3.4.9 *Results and Discussion:*

The following results are based on typical evaluations of BLDC motor-powered EVs:

4.3.4.9.1 Energy Consumption:

- Urban Cycle: 170 Wh/km (due to frequent acceleration and braking).
- Highway Cycle: 140 Wh/km (at constant speeds).

4.3.4.9.1.1 Range:

- With a 48V, 100Ah battery:
  - Urban Cycle: ~140 km.
  - Highway Cycle: ~170 km.

4.3.4.9.1.2 Acceleration:

- 0–50 km/h: ~5.2 seconds.
- 0–100 km/h: ~11 seconds.

4.3.4.9.1.3 Efficiency:

- Motor efficiency peaks at ~94% under moderate loads.
- Regenerative braking improves overall vehicle efficiency by recovering ~12% of kinetic energy.

4.3.4.9.1.4 Thermal Stability:

- Continuous operation at rated power for 2 hours causes a temperature rise of ~60°C, which remains within safe limits due to effective cooling systems.

4.3.4.9.1.5 Comparison with Other Motor Types:

- BLDC motors offer higher efficiency and torque density than induction motors, making them ideal for small EVs.
- However, control complexity and cost are higher compared to induction motors.

4.3.5 Case Study

A compact electric sedan powered by a 15 kW BLDC motor and a 60 kWh battery was tested:

- Driving Conditions: Mixed urban and highway cycles.
- Results:
  - Total energy consumption: 16 kWh/100 km.
  - Range: 375 km on a full charge.
  - Motor temperature after 3 hours of operation: 85°C (with air-cooling).
  - Peak regenerative braking recovery: 18% of battery energy.

The performance evaluation highlights the suitability of BLDC motors for EV propulsion, with superior efficiency, energy recovery capabilities, and dynamic performance. These advantages, combined with their lightweight and compact design, make BLDC motors an excellent choice for modern electric vehicles. However, advanced thermal management systems and optimized control algorithms are necessary for further performance improvements[111].

4.4 Chapter Summary

This Chapter focuses on the performance assessment of a Brushless Direct Current (BLDC) motor for electric vehicle (EV) propulsion applications. The study explores multiple performance criteria for traction systems, emphasizing the BLDC motor's efficiency, torque production, and dynamic response under various conditions. A comprehensive mathematical model of the BLDC motor is developed, which includes:

- Electrical Equations: Governing the motor's phase currents and back-emf.

- Mechanical Equations: Linking the torque generated by the motor to the rotational dynamics.

- Dynamic Equations: Describing the EV's movement under the influence of motor torque, road resistance, and external forces.

The chapter evaluates the motor’s behavior using theoretical and simulation methods, comparing it to alternative motor technologies. Various parameters such as speed, load, torque, and efficiency are analyzed to determine the BLDC motor's suitability for EV applications.

4.5 Key Observations

4.5.1.1 *High Efficiency:*

The BLDC motor demonstrates superior efficiency compared to other motor types under steady-state and dynamic conditions, making it ideal for EV propulsion.

4.5.1.2 *Torque Performance:*

The torque equation reveals that BLDC motors provide consistent torque with minimal ripples, which is crucial for smooth vehicle operation.

4.5.1.3 *Dynamic Behavior:*

The dynamic model indicates that BLDC motors respond well to rapid changes in load and speed, enabling effective traction control.

4.5.1.4 *Energy Optimization:*

Efficiency evaluation highlights the motor's ability to operate near its maximum efficiency range when paired with appropriate control strategies, such as Maximum Torque Per Ampere (MTPA) control.

4.5.1.5 *Scalability for EV Applications:*

The motor is adaptable to various EV configurations due to its high power density and compact size.

Also

- BLDC motors deliver superior energy efficiency, especially in stop-and-go urban traffic.

- The dynamic torque response ensures excellent drivability and smooth acceleration.

- Integration with regenerative braking systems significantly enhances the overall efficiency of EVs.

4.6 Conclusion

The BLDC motor is a highly effective propulsion system for electric vehicles, offering an excellent balance of performance, efficiency, and reliability. Through mathematical modeling and performance assessment, the chapter demonstrates the motor’s ability to meet the demanding requirements of EV traction systems. Key findings include:

4.6.1.1 *Enhanced Efficiency:*

motors maintain high efficiency across a wide range of operating conditions, which is critical for improving EV range and reducing energy consumption.

4.6.1.2 *Precise Control:*

The dynamic equations and torque characteristics show that BLDC motors are well-suited for applications requiring precise and rapid control.

4.6.1.3 *Viability for EVs:*

Given its robust performance metrics, the BLDC motor is a cost-effective and scalable solution for EV propulsion, making it an attractive choice for both small and large electric vehicles.

This chapter concludes that with proper controller design and optimization, BLDC motors can significantly enhance the performance and energy efficiency of modern electric vehicles.

5 Performance evaluation of an electric vehicle powered by an IM

5.1 Comparison performance of Induction Motors for Traction Systems Using Multiple Criteria for the Electric Vehicle Application

Induction motors play a significant role in consuming electrical energy, often operating inefficiently under light loads, leading to energy wastage. Accurately estimating their performance is crucial, typically done through indirect methods like the modified Air Gap Torque method. This method, which doesn't require invasive torque or speed measurements, utilizes voltage, current data, stator resistance, and mechanical losses to estimate efficiency. The focus of this thesis is on enhancing the computation of modified stator resistance for the Air Gap Torque method, considering mechanical loss effects. The proposed approach aims to improve resistance calculation using a direct method and explores the possibility of deriving it directly from the motor's nameplate data, relying on line voltages, currents, and nameplate data only. Simulation analysis and experimental validation with three-phase induction motors are conducted, comparing efficiency estimation methods for in-service induction motors. Induction motors are widely used in industries, consuming a significant portion of electrical energy and impacting financial and power system planning due to energy losses. Evaluating their efficiency has become crucial, especially with the rise of condition monitoring systems. Efficiency, computed as the ratio of shaft power to electrical power, can be estimated indirectly from voltage and current data, considering the limitations of installing torque meters.

Various efficiency estimation methods exist for in-service induction motors, such as the slip method, current, equivalent circuit, and air-gap torque methods. The slip method, particularly effective with rotor speed measurements, linearizes torque/speed curves for accurate estimation, with proposed enhancements for better torque estimation accuracy [112]. This is the range of operations each motor can carry out in the course of a task. The motor's fidelity, or its resistance to sudden breakdowns and capacity to maintain prolonged running without routine maintenance, is the basis for the dependability factor.

5.1.1 Efficiency Evaluation of an Induction Motor

The subsequent sections of this paper describe the primary stages of the proposed methodology, focusing on efficiency estimation as a critical aspect, within the context of exploring a conventional condition monitoring system tailored for Induction Motors (IMs).

5.1.1.1 *Estimation of Rotor Speed:*

The rotor speed of an induction motor is determined by analyzing current data samples using motor current signature analysis. This method involves detecting low-frequency eccentricity components that impact the motor's fundamental frequency. Estimating rotor speed instead of directly measuring it is preferred due to its non-invasive nature, making it ideal for evaluating the efficiency of an operational induction motor.

5.1.1.2 *Correction of Rated Speed:*

For precise estimation of the adjusted stator resistance, the motor needs to function near the specified operating point provided by the induction motor (IM). However, it is essential to recognize that the rated speed mentioned on the nameplate might have a considerable margin of error. As a result, the speed labeled as rated may correspond to a different torque value instead of the stated rated torque in practical terms. To tackle this issue, an offline adjustment of the rated speed is conducted before the stator resistance estimation, as recommended.

5.1.1.3 *Determining the Adjusted Stator Resistance:*

The process involves using a specific algorithm that considers the rated operation point of an induction motor (IM) and adjusts for the corrected rated speed. This algorithm is activated only when the IM operates near this designated point. Since the mechanical torque is the unknown variable to be estimated, the algorithm relies on monitoring the IM rotor rotation speed to determine how close it is to the rated operation point. The algorithm periodically checks the IM rotor rotation speed and starts the computation only when it closely matches the corrected rated speed. If this condition isn't met and the algorithm hasn't previously estimated a stator resistance, it uses a reference value for stator resistance to calculate the Air Gap Torque. This reference value can come from either a physical resistance measurement or an estimated value suitable for a motor of the corresponding power rating. After determining the adjusted stator resistance, it is used to calculate the torque under various load conditions of the induction motor. This torque, known as the Air Gap Torque, is a reliable estimate of shaft torque. It is computed in real-time for each data sample, and the evaluation of induction motor efficiency considers the estimated shaft torque.

5.1.1.4 *Evaluated Induction Motor:*

Simulation experiments were carried out using a 0.5-horsepower 2-pole Induction Motor (IM). Details regarding the IM's specified values and characteristics are available in the accompanying Table 5-1 (a) (b). The dynamic modeling of the IM included the utilization of state-space equations and the integration of mechanical losses to ensure a thorough simulation process.

Table 5-1-For IM (a) Specification and (b)Characteristics

(a)

V_{rated} (in Volt)	I_{rated} (in Amp)	F_{rated} (in HZ)	n_{rated} (in RPM)	PF_{rated}
220	1.18	60	3500	0.954

(b)

Rs	Rr	L_m	Ls	Lr
2.2 Ω	0.903 Ω	1.00129 H	1.02868 H	0.979 H

The experiments were carried out using a 0.5-HP 2-pole induction motor (IM). Table 5-2 details the rated values and parameters for the induction motor, where Rs denotes the measured stator resistance. The configuration of the experimental setup is shown in Figure 5-1 for testing an induction motor's performance. The components and their roles are:

5.1.1.4.1 **Power Supply:**

- Provides the electrical power to drive the induction motor. This could be an AC power source.

5.1.1.4.2 **Induction Motor:**

- The main test object in the setup. It is a type of electric motor powered by alternating current, widely used in various applications due to its robustness and efficiency.

5.1.1.4.3 **Three-Phase AC System (A, B, C):**

- The induction motor is typically a three-phase machine, requiring three-phase input power (labeled as A, B, and C in the diagram).

5.1.1.4.4 **AC/DC Converter:**

- Converts alternating current (AC) into direct current (DC) for measurement and processing purposes. This ensures that signals can be analyzed by the processor.
- .

5.1.1.4.5 **Processor:**

- A central unit (likely a microcontroller or computer) processes the signals from the Hall Effect transducers to analyze the motor's performance. It may calculate efficiency, power factor, or other performance metrics.

5.1.1.4.6 **Electromagnetic Brake System with Load Cell:**

- Simulates load conditions for the motor by applying a controllable resistive torque. The load cell measures the torque produced by the motor under different operating conditions.

5.1.1.4.7 **Torque Meter:**

- Directly measures the torque output of the motor and provides data to validate performance parameters like torque-speed characteristics.

Table 5-2- Evaluated data from experimental trials.

V_{rated} (in Volt)	I_{rated} (in Amp)	F_{rated} (in HZ)	n_{rated} (in RPM)	PF_{rated}	Rs
220	1.98	60	3700	0.754	2.99Ω

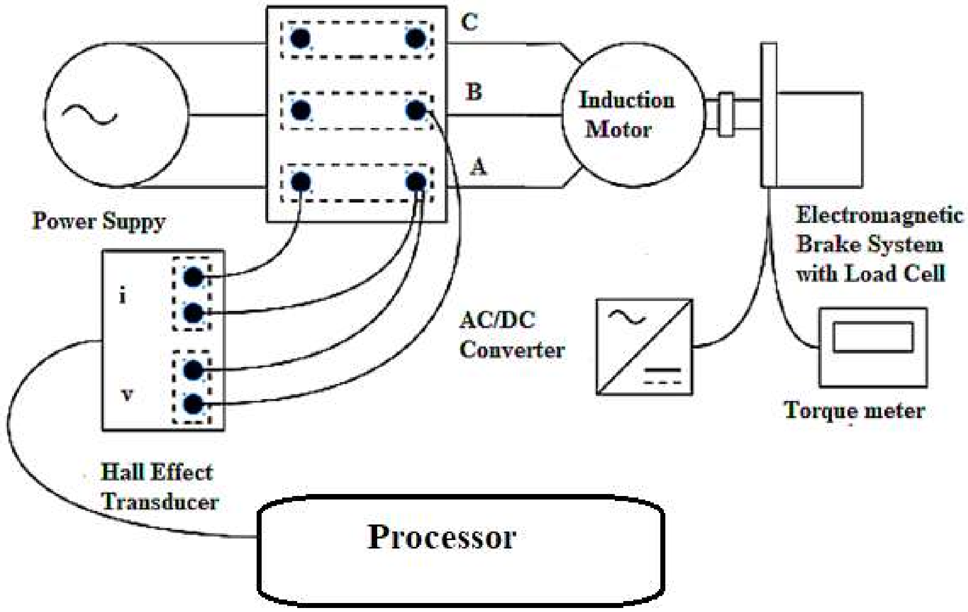


Figure 5-1-Experimental apparatus configuration for testing[112]

Figure 5-2 presents an image demonstrating the setup used for experimental testing. This setup comprises several components: voltage and current Hall effect transducer boxes, an electrical connections box, an induction motor, an electromagnetic brake system with a load cell, a torque display, an AC/DC converter for the brake system's power supply, and a data acquisition system. The electromagnetic brake system, tailored for a 0.5-HP two-pole induction motor, simulated load and torque variations. It operated with DC voltage controlled by the AC/DC converter, while a load cell measured shaft torque, and an ID02-B indicator digitally displayed torque readings.

For measuring the induction motor's phase-to-phase voltages, three voltage transducers and three current transducers were used. The current transducers had specific parameters such as primary nominal current, primary current measurement range, secondary nominal current, conversion ratio, supply voltage, and accuracy. Similarly, the voltage transducers had their specifications, including primary nominal current, primary current measurement range, secondary nominal current, conversion ratio, supply voltage, and accuracy. These transducers' secondary sides were linked to the data acquisition hardware in a Single-ended configuration.

The data acquisition system employed was the NI USB-6215 module, with features like a 16-bit, 240 kS/s single-channel sampling rate, 15 analog inputs, two analog outputs, four digital input lines, four digital output lines, four programmable input ranges, digital triggering, and two counter/timers. The analog inputs had specific specifications regarding maximum voltage, maximum voltage range, accuracy at maximum voltage range, minimum voltage range, accuracy at minimum voltage range, sampling frequency, sampling time, and acquisition length. Each data acquisition session captured machine parameters under a specific load condition for 25 seconds, but only the initial 100 seconds were utilized for analysis, with signals transmitted to a personal computer [112].

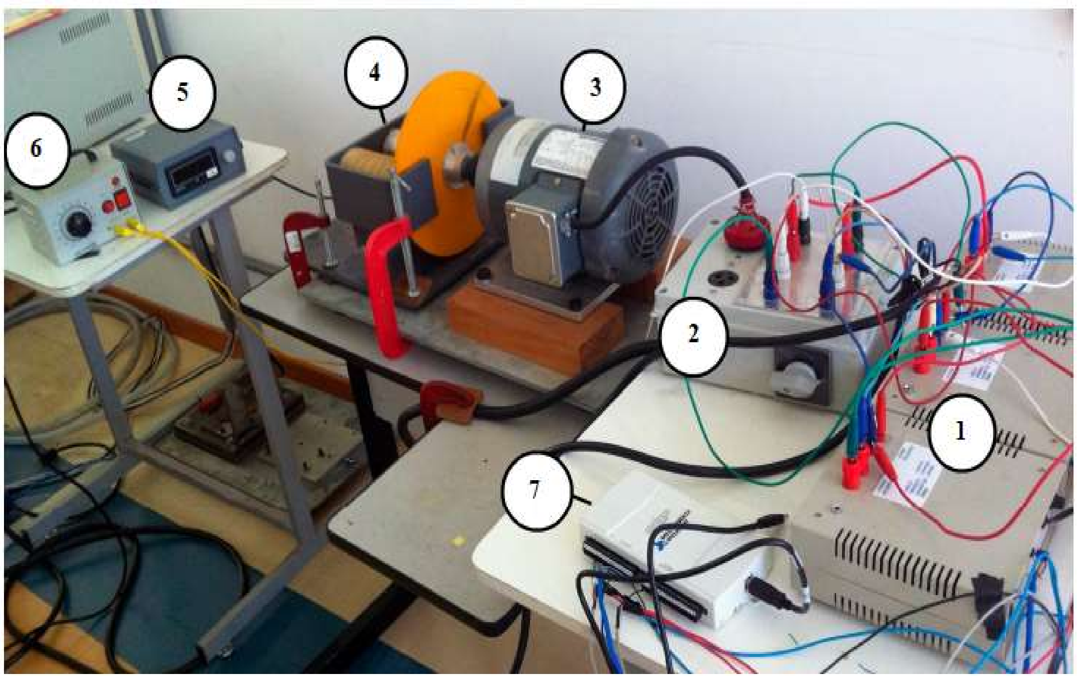


Figure 5-2-Image demonstrating the setup used for testing [112]

5.1.2 Observations

This section describes the evaluation of induction motor efficiency using simulation and experimental tests, incorporating the suggested methodology and other chosen methods. After determining stator resistance, the methodology is applied under various load conditions for the induction motor (IM). Efficiency factors are calculated according to specified conditions, and a graph depicting efficiency versus load conditions concerning the rated condition is provided.

The efficiency values are calculated based on actual measurements. During simulation tests, the IM model utilizes the reference mechanical torque shown in Figure 5-3 and rotational speed ω_r. Conversely, experimental tests utilize measured torque T_{shaft} and rotor speed ω_r depicted in Figure 5-4 and Figure 5-5.

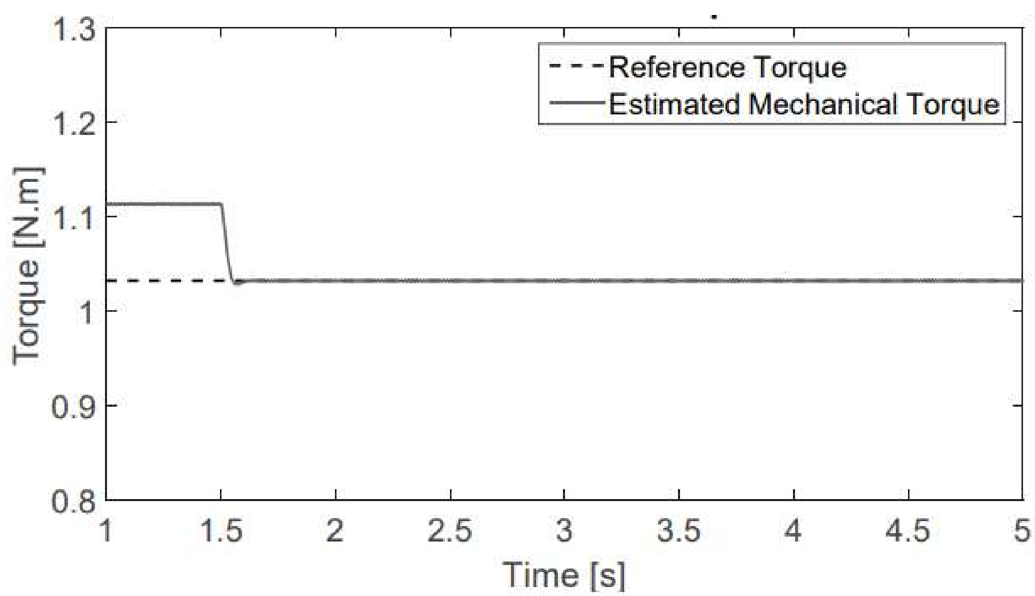
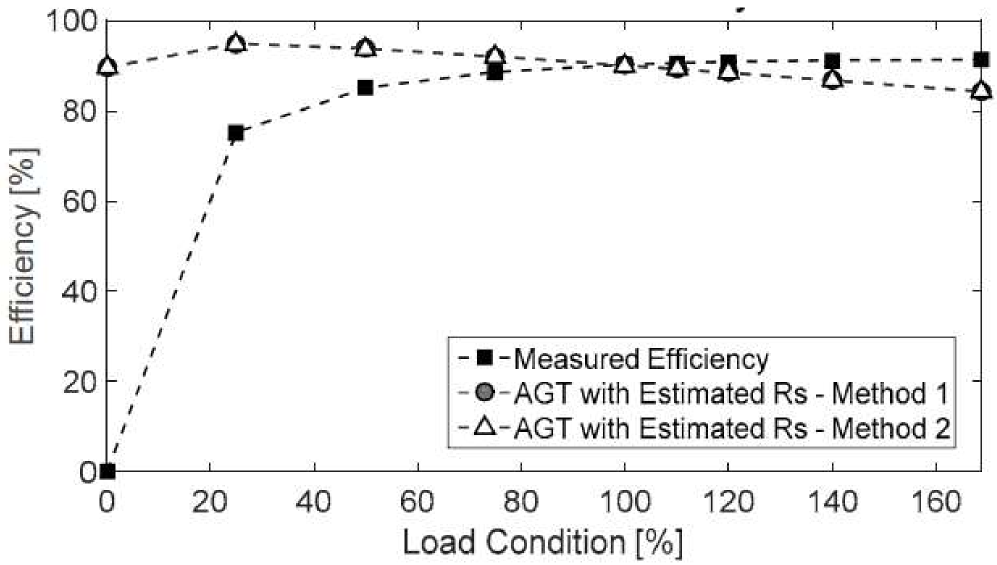
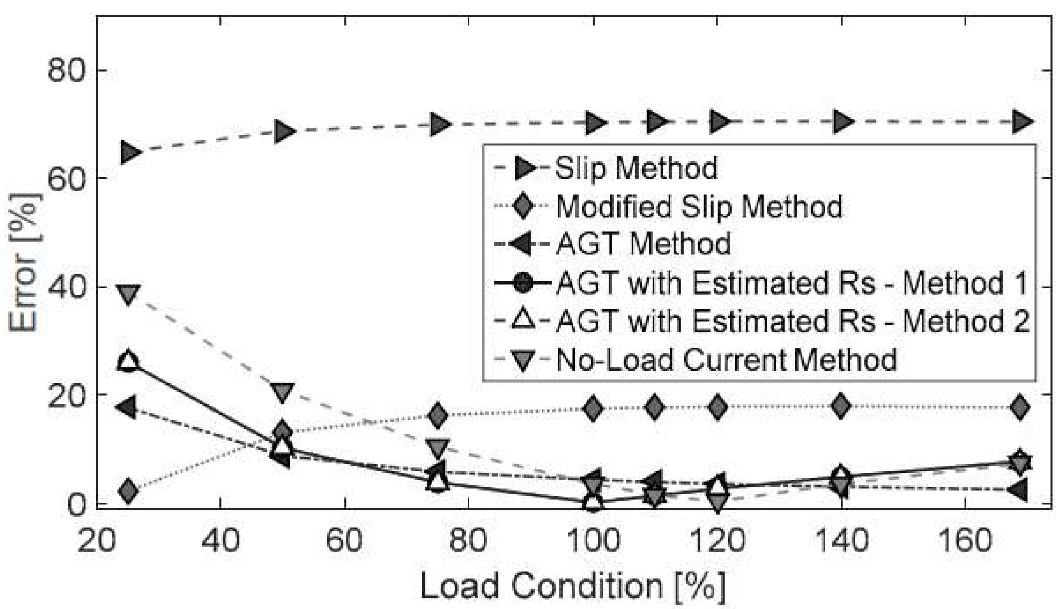


Figure 5-3- Estimation of Torque for IM

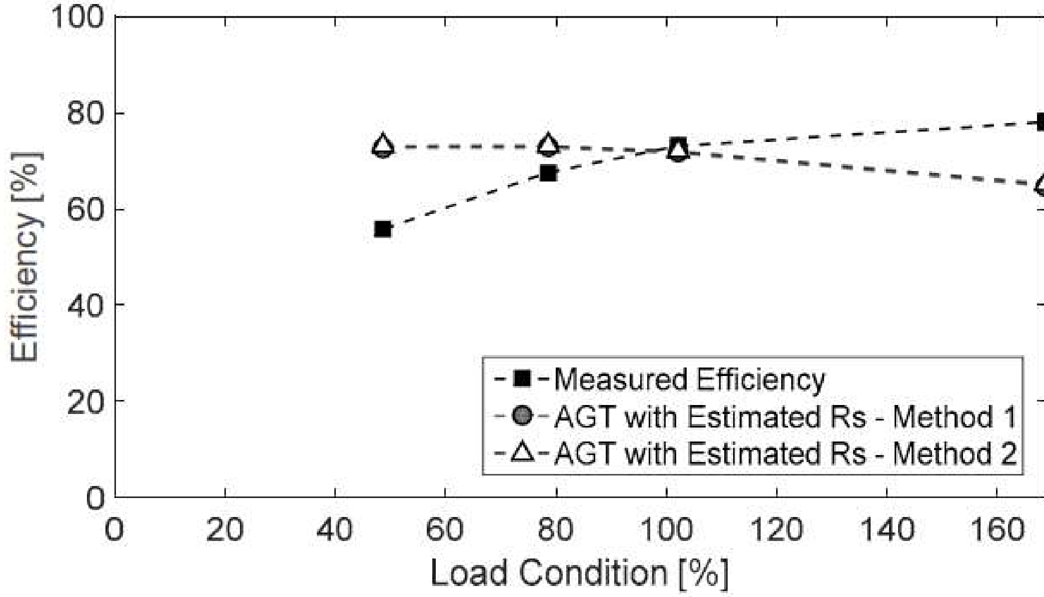


(a)

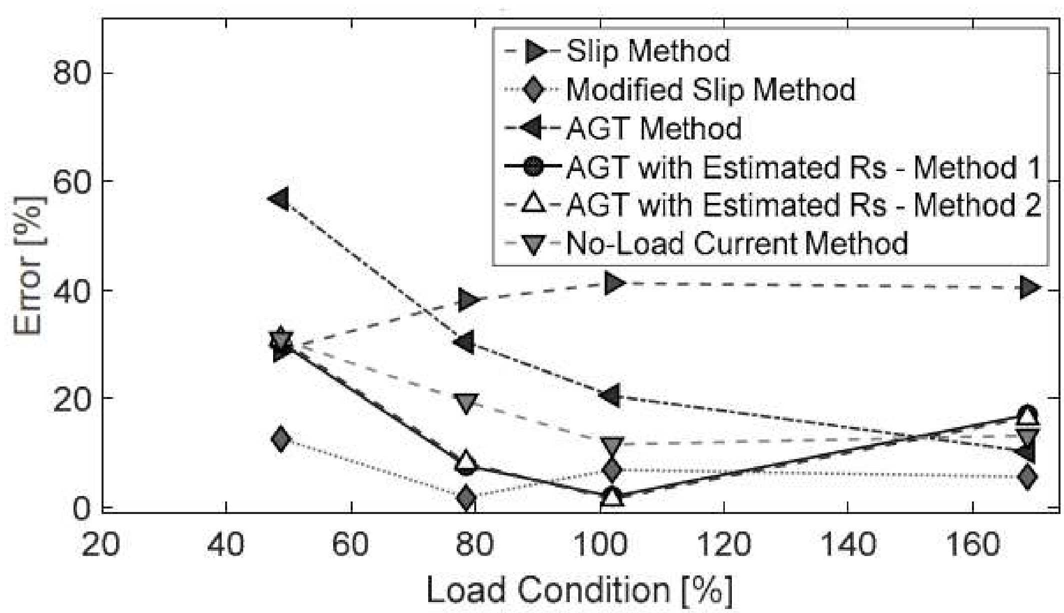


(b)

Figure 5-4- Simulation: (a) Motor Efficiency (b) Estimation Error



(a)



(b)

Figure 5-5- (a) Experimental result of Efficiency (b) Estimation Error for Induction Motor

The torque estimated through the AGT with adjusted stator resistance denoted as T_{shaft} was considered. The efficiency results obtained from AGT and the estimated stator resistance showed virtually no difference. In simulations, the error in efficiency estimation compared to theoretical values was minimal starting from a load condition of 50 percent, and decreased as the load condition approached the rated condition. Between load conditions of 70 percent and 145 percent, the error remained below 5 percent. Experimental tests revealed negligible efficiency estimation errors around 80 percent and 100 percent load conditions, with errors of approximately 5 percent and 3 percent, respectively. However, at the highest load condition around 165 percent, the error increased to about 16 percent.

A comparison was conducted among various methods for assessing IM efficiency. The efficiency calculated using the proposed methodology was compared with coefficients obtained from other established methods such as the standard slip method, modified slip method with rated speed correction, standard air-gap torque method, and no-load current method - all recommended for in-service IMs. The efficiency estimation errors for all methods, relative to theoretical efficiency[112].

5.2 Induction Motor for Electric Vehicle Propulsion Application

Induction motors (IM), including electric traction, stand as the most prevalent equipment in various industries, owing to their affordability and robustness. With notable efficiency, precise speed regulation, and absence of transmission, IM finds common application in electric vehicles (EVs). The optimal utilization of an IM Drive, depicted in Figure 5-6 showcasing IM characteristics and the variation of parameters concerning EV speed, lies within EVs. Despite being relatively less sophisticated than other options, they boast widespread recognition. This accounts for their reliable performance and minimal maintenance requirements. Vector control drives, offering extensive speed modulation, are frequently employed for IM operation. The performance of IM is influenced by machine design, power electronics, and control mechanisms, delineating three distinctive operational zones: constant torque, constant power, and reduced power at high speeds. Key advantages of induction motors encompass reliability, robustness, low upkeep, affordability, and suitability for rugged environments.

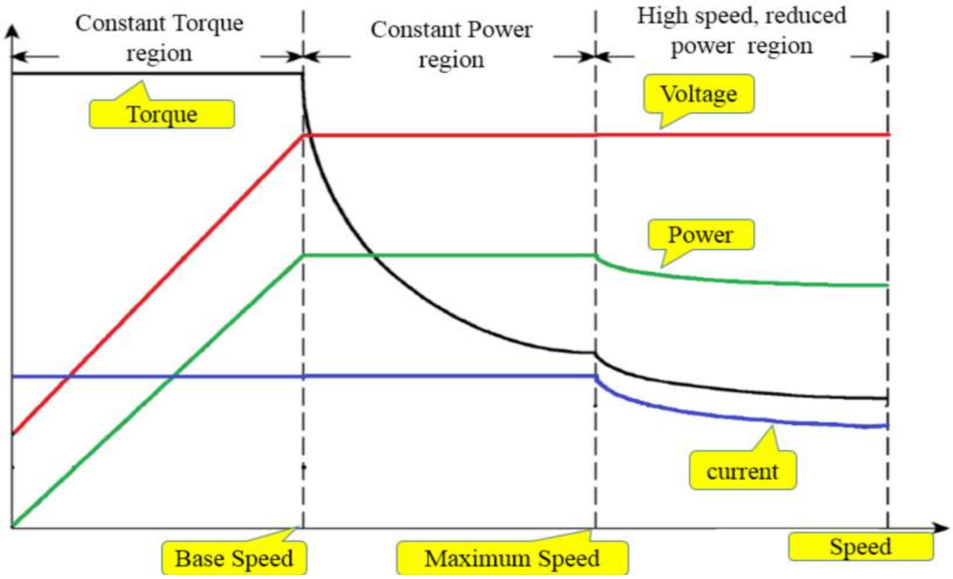


Figure 5-6-IM characteristics and EV speed variation

5.3 The dynamic equation governing the motion of an EV equipped with an induction motor

Modeling an EV with an IM involves several dynamic equations that describe the interactions between the vehicle's components. One common approach is to use a simplified model that captures the essential dynamics. Provided a basic dynamic equation for an EV with an IM. Let's consider a simplified electric vehicle model with the following components:

5.3.1 DC Bus Dynamics:

V_{dc}: DC bus voltage

I_{dc}: DC bus current

R_{dc}: DC bus resistance

L_{dc}: DC bus inductance

The dynamic equation for the DC bus can be described by:

$$V_{dc} = R_{dc} \cdot I_{dc} + L_{dc} \cdot \frac{dI_{dc}}{dt} \quad (5\text{-}1)$$

5.3.2 Induction Motor Dynamics:

P_{mech}: Mechanical power

P_{elec}: Electrical power

T_{elec}: Electrical torque

J: Moment of inertia

ω_m: Angular velocity of the motor

T_{load}: Load torque

R_s: Resistance of Motor's Stator

L_s: Inductance of Stator

R_r: Resistance of rotor

L_r: Rotor inductance

5.3.3 The induction motor's dynamic equation can be characterized by

$$P_{mech} = T_{elec} - T_{load} \quad (5\text{-}2)$$

$$P_{elec} = V_{dc} \cdot I_s \quad (5\text{-}3)$$

$$T_{elec} = \frac{2}{3} \cdot P_{elec} \quad (5\text{-}4)$$

$$J \cdot \frac{d_{\omega m}}{dt} = T_{elec} - T_{load} \quad (5\text{-}5)$$

$$V_s = R_s \cdot I_s + L_s \cdot \frac{dI_s}{dt} + \omega_m \cdot L_s \cdot I_s \quad (5\text{-}6)$$

$$V_r = R_r \cdot I_r + L_r \cdot \frac{d_{dt}}{dt} + \omega_m \cdot L_r \cdot I_r \quad (5\text{-}7)$$

$$I_s = I_{dc} - I_r \quad (5\text{-}8)$$

The equations that describe the motion of an electric vehicle (EV) equipped with an induction motor can be expressed as follows:

5.4 INDUCTION MOTOR's MATHEMATICAL MODEL

The computational representation of an IM can be elucidated by the subsequent equation $|A^{-1}|$ The computational model when θ = 0 can be 2- an axis

$$|A^{-1}| = \begin{bmatrix} \sqrt{2/3} & -1/\sqrt{6} & -1/\sqrt{6} \\ 0 & 1/\sqrt{2} & -1/\sqrt{2} \\ 1/\sqrt{3} & 1/\sqrt{3} & 1/\sqrt{3} \end{bmatrix} \tag{5-9}$$

And $|A|$ can be explained as

$$|A| = \begin{bmatrix} \sqrt{2/3} & 0 & 1/\sqrt{3} \\ -\sqrt{1/6} & 1/\sqrt{2} & 1/\sqrt{3} \\ -1/\sqrt{6} & -1/\sqrt{2} & 1/\sqrt{3} \end{bmatrix} \tag{5-10}$$

The mathematical model described in Figures 5-7 and 5-8 can be represented as a Simulink-based block diagram when θ =0, demonstrating a two-axis configuration.

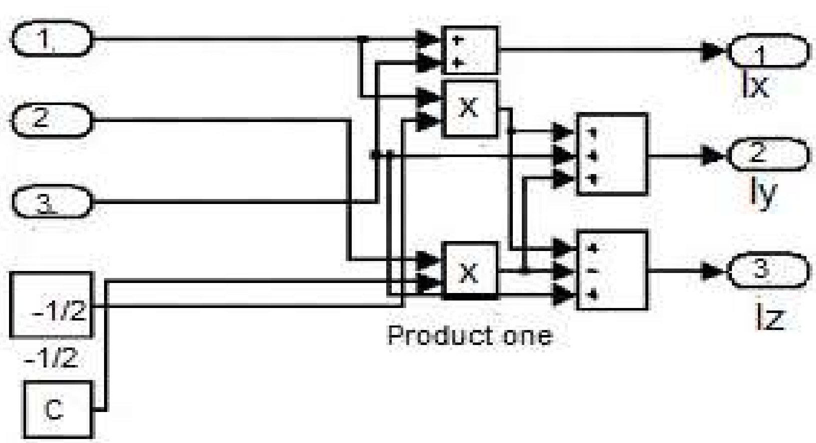


Figure 5-7- MATLAB Simulation model for 2-axis

5.4.1 Simulink-based BLOCK DIAGRAM

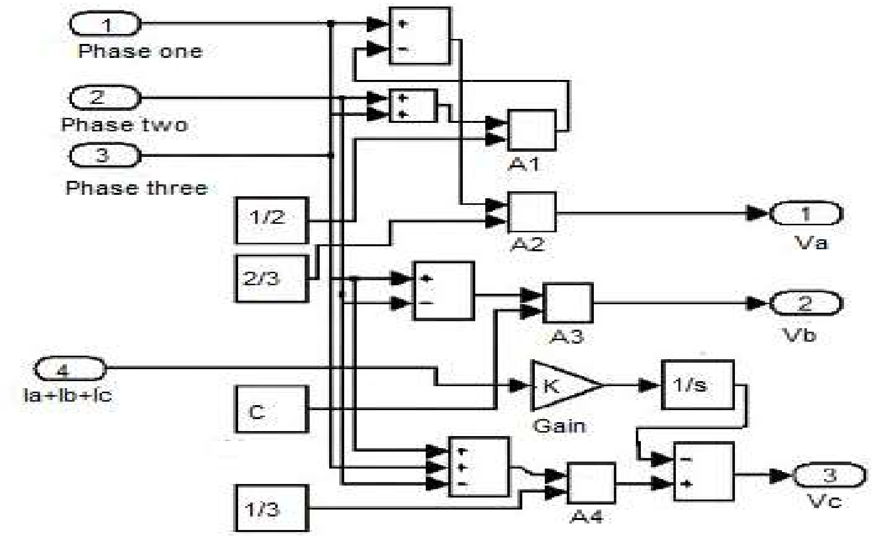


Figure 5-8- 3-axis MATLAB Mathematical model for 3-axis

The application of the depicted running dynamic model for an Induction motor equivalent circuit, as illustrated in Figure 5-9, can be established, and its schematic representation is elucidated.

Flux Linkage Equations:

$$\sigma_s^{qs} = \omega_b \int (v_s^{qs} + \frac{r}{x}\,(\sigma_s^{mq} - \sigma_s^{qs}))dt \qquad (5\text{-}11)$$

$$\sigma_s^{ds} = \omega_b \int (v_s^{ds} + \frac{r}{x}(\sigma_s^{md} - \sigma_s^{ds}))dt \qquad (5\text{-}12)$$

Current Relationships:

$$i_s^{qs} = \frac{\sigma_s^{qs} - \sigma_s^{mq}}{x} \qquad (5\text{-}13)$$

$$i_s^{ds} = \frac{\sigma_s^{ds} - \sigma_s^{md}}{x} \qquad (5\text{-}14)$$

Electromagnetic Torque:

$$T_m = \frac{3}{2} \times \frac{P}{2} (\sigma_s^{ds} i_s^{qs} - \sigma_s^{qs} i_s^{ds}) \quad \textit{(5-15)}$$

Rotational Dynamics:

$$J \frac{d\omega}{dt} = T_e - T_m - T_d \quad \textit{(5-16)}$$

Here

r, x: Resistance and reactance, respectively.

ω_b, ω_r Base and rotor angular frequencies.

T_m: Electromagnetic torque.

T_e, T_d : External torque and damping torque.

J: Moment of inertia.

P: Number of poles.

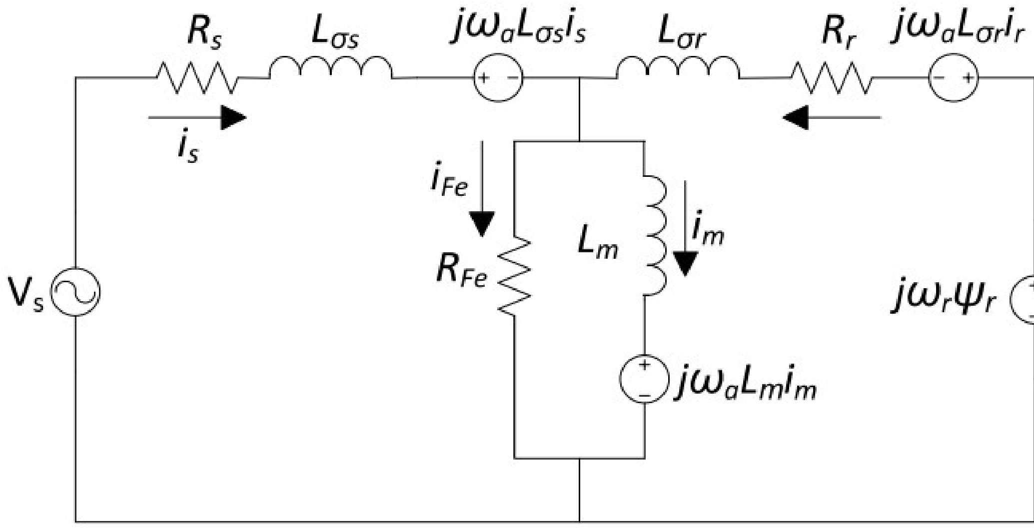


Figure 5-9- Equivalent circuit of an Induction motor [113]

5.5 Performance evaluation of EVs with IMs

The power-to-weight ratio of an electric vehicle equipped with an induction motor as its primary propulsion system can be determined by dividing the motor's power output by the vehicle's total weight.

5.5.1 Power Output

The equation provided enables the determination of the power output generated by the induction motor:

$$Pmotor = Te * \omega m \quad (5\text{-}17)$$

Where:

- P_{motor} is the power output of the motor.
- T_e is the generated electromagnetic torque by the motor.
- ω_m shows the angular velocity of the motor

5.5.2 Total Weight

The combined weight of the vehicle encompasses the vehicle's mass, the weight of the driver, the payload, and additional elements illustrated in Figure 5-10 shows the efficiency of an induction motor plotted against its rotational speed (in rpm).

5.5.2.1 *-Efficiency vs. Speed:*

The efficiency curve indicates the motor's ability to convert electrical energy into mechanical energy. Operating at higher efficiencies contributes to better motor power output - (P_{motor}).

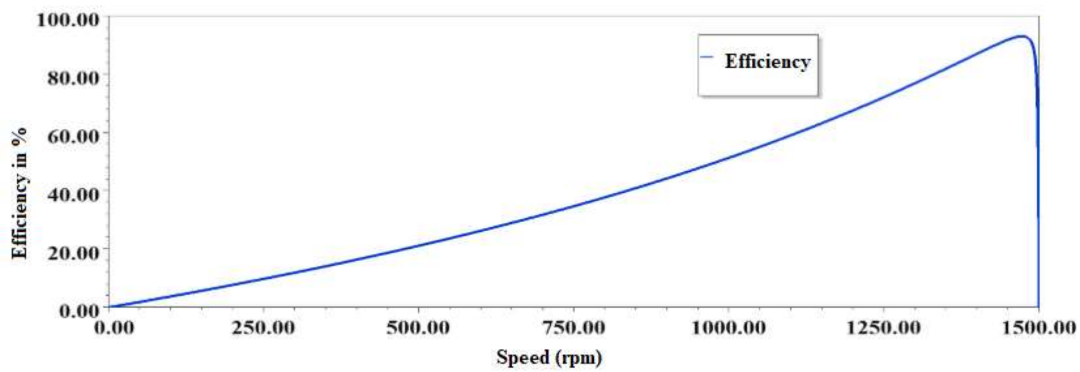


Figure 5-10-Efficiency of Induction Motors [77]

5.5.2.2 *Optimized Design:*

For a given motor and weight, achieving higher PWR involves operating at speeds where motor efficiency is high. This maximizes the usable power without significant energy losses.

5.5.2.3 *Efficiency Trend:*

- At low speeds (0–500 rpm), the efficiency is very low, indicating significant losses, as induction motors are less effective at starting conditions.

- Efficiency increases steadily with speed, peaking at around 1500 rpm, where the motor operates close to its rated condition.

- Beyond this point, efficiency might decline due to increased losses (such as core, friction, or windage losses).

5.5.2.4 *Peak Efficiency:*

- The motor achieves its highest efficiency at a speed close to 1500 rpm, likely near the synchronous speed of a typical 4-pole induction motor operating at 50 Hz.

- This peak efficiency is close to 95–98%, indicating the motor's optimal performance at this operating point.

5.5.2.5 *Practical Implications:*

- Operating the motor at or near its rated speed ensures minimal energy losses, crucial for applications like electric vehicles (EVs) where efficiency impacts range and performance.

5.5.3 Relation to Power-to-Weight Ratio (PWR)

The Power-to-Weight Ratio (PWR) is a separate metric that measures the motor's ability to produce power relative to the total weight of the vehicle. Here's how it connects to the motor efficiency and speed:

5.5.3.1 *Motor Power (P_{motor})*

- (P_{motor}) is directly related to the motor's efficiency. At speeds near the peak efficiency, the motor can deliver the maximum usable power with minimal energy losses.

- Using this figure, you can identify the optimal operating range of the motor to maximize the output power Power (P_{motor}) while maintaining efficiency.

5.5.3.2 *Vehicle Weight (W_{total})*

- (W_{total}) includes the motor, battery, and chassis weight. A lightweight design helps increase the PWR, improving vehicle performance (e.g., acceleration and range).

5.5.3.3 *PWR Implications:*

- Maximizing PWR requires a balance between reducing the weight of the vehicle (W_{total}) and using an efficient motor (P_{motor}) that operates near its peak efficiency range.

- The figure helps in selecting motor specifications and determining the best operating range for optimal PWR.

5.5.4 Ratio between Power-to-Weight

The ratio power-to-weight is given by

$$PWR = P_{motor} / W_{total} \quad (5\text{-}18)$$

Where:

- PWR is the ratio between power-to-weight.
- Pmotor shows the output power of the motor.
- Wtotal is the total weight of the vehicle.

The effectiveness of the electric vehicle's motor is depicted in Figure 5-11. This aggregate weight is designated as W_{total}. which shows a comparison of efficiency (%) for two different electric vehicle (EV) systems powered by photovoltaic (PV) energy. Specifically, it compares:

-PV-based BLDC motor system (represented by gray bars).

- PV-based induction motor system (represented by blue bars).

The efficiency is plotted on the vertical axis (in %) against the output power on the horizontal axis (in watts, ranging from 200 W to 2000 W).

Key Observations:

5.5.4.1.1 Efficiency Trend:

- Both systems (BLDC and induction motor) show increasing efficiency as the output power increases from 200 W to 2000 W.

- The efficiency improvement stabilizes at higher power levels, where both systems approach their peak performance.

5.5.4.1.2 Efficiency Comparison:

- PV-based induction motor system consistently shows higher efficiency compared to the PV-based BLDC motor system across all output power levels.

- The difference in efficiency becomes more noticeable at lower power levels (e.g., 200–800 W), where the induction motor exhibits a clear advantage.

- At higher power levels (e.g., 1600–2000 W), the efficiencies of both systems converge, but the induction motor still maintains a slight lead.

5.5.4.1.3 Peak Efficiency:

- The PV-based induction motor system achieves a peak efficiency of close to 96% at 2000 W.

- The PV-based BLDC motor system achieves a slightly lower peak efficiency, approximately 94%, at the same power level.

5.5.4.1.4 Implications for EV Systems:

5.5.4.1.4.1 System Choice:

- For applications requiring high output power and efficiency, the PV-based induction motor system is more suitable due to its superior performance.

- The BLDC motor system may still be viable for lower-power applications or where other factors (e.g., cost or control simplicity) are critical.

5.5.4.1.4.2 Energy Utilization:

- The higher efficiency of induction motors implies better energy utilization, translating to longer driving ranges or reduced PV panel requirements for a given energy output.

5.5.4.1.4.3 Suitability for PV Systems:

- Induction motors exhibit better performance under varying load conditions, making them more compatible with PV-based systems that may experience fluctuating power outputs

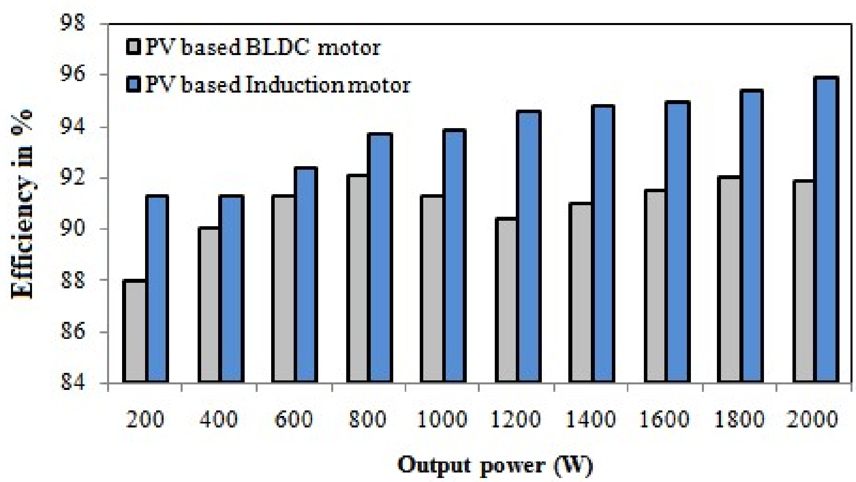


Figure 5-11- Efficiency (%) comparison for different EV systems [86]

5.6 Characteristics of Induction Motor

A traction motor for an EV must adhere to different operating standards than are currently in use. While traveling, the electric vehicle might have to adjust its velocity, increase torque when navigating uphill, and brake abruptly. Figure 5-12 illustrates the Torque-Speed Characteristics. In industrial settings, most loads remain constant and are classified accordingly.

"It is observed that the motor's behavior on the road deviates significantly or infrequently from the torque-speed curve during operations such as sudden stops or starts."

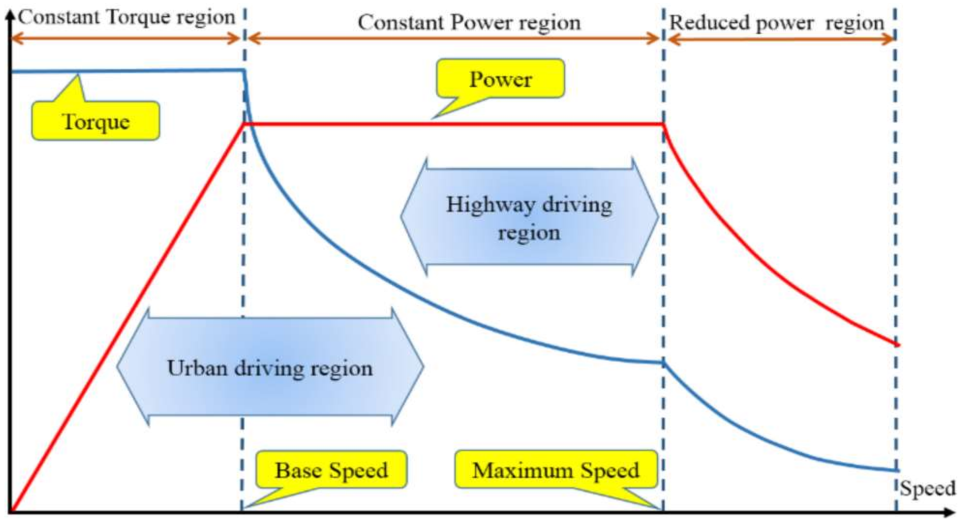


Figure 5-12- Speed-torque characteristics of EV motors

5.7 Efficiency Electric Vehicle when IM is a prime mover

When an Induction Motor (IM) is used as the prime mover in an electric vehicle (EV), the efficiency of the entire propulsion system is influenced by various factors related to the motor, power electronics, and overall vehicle design.

5.7.1 The efficiency (η) of an induction motor can be determined by comparing the mechanical power output to the electrical power input.

$$\eta = P_{output} / P_{input} \qquad (5\text{-}19)$$

Where: η represents efficiency.

P_{output} represents the mechanical power output of the motor.

P_{input} represents electrical power input to the motor.

5.7.2 Comparison of Electric Motors for Traction Systems Using Multiple Criteria for the Electric Vehicle Application

We assess and rank BLDC and induction motors for their suitability in electric vehicle applications, employing various paradigms. The scope of operations each motor can perform during a task is considered. The reliability factor is grounded in the motor's fidelity, gauging its resistance to abrupt failures and its capability to sustain extended operation without regular maintenance. Efficiency, linking the electrical and mechanical outputs, is a key aspect, encompassing the model's effectiveness in utilizing fewer resources for power sources and electronic systems. Electric motors are typically designed to operate with maximum efficiency at the observed output. To comprehend the overall performance of BLDC and induction motors, refer to Table 5-3, while the reliability of IM and BLDC drawn pictorial are in Figure 5-13.

Table 5-3-Performance evaluation of BLDC, Induction motors in EV[24] [65]

S.N.	Parameters	BLDC Motor	Induction Motor
01	Rotor Magnet	A set of permanent magnets is used in BLDC motors in place of the rotor's windings.	The rotor of an induction motor is devoid of magnets.
02	Starting current	It is rated for the beginning current. It is not necessary to have a unique starter circuit.	Since the beginning current can be up to seven times the rate, the stator circuit should be carefully chosen. Typically, a star-delta starter is used.
03	Output Power/frame	Higher	The size of the output power frame is average. Output power to power frame size is smaller than with BLDC because both

			the stator and the rotor must be wound.
04	Speed/ torque Characteristics	Flat is the speed/torque characteristic. It permits operations with rated loads at all speeds.	The speed/torque characteristic is nonlinear.
05	Controller	The motor must always be driven by a controller. It will also be utilized to control the motor's variable speed.	Operation at a fixed speed does not require a controller. Only the desired variable speed needs a controller.
06	Efficiency	greater effectiveness	more than BLDC, but less
07	Cost of motor	due to the permanent magnet, higher	Lower Compared to BLDC
08	Size	The BLDC motor is more compact.	Greater in size than BLDC
09	Application	Electric automobiles, hybrid transports, DVD/CD	Lifts, cranes, hoists, large exhaust fans, driving lathe machines, crushers, etc
10	Dynamic Response	Brushless machines do not have maintenance cost-related problems.	For the induction machine, the cost of production and maintenance is the lowest.

11	Noise Level	Low	High as compared to BLDC
12	Robustness	Less robust compared to IM	Robust
13	Maintenance	High comparatively	Low maintenance required
14	Rotor Inertia	There is less rotor inertia. It makes certain dynamics possible.	There is more rotor inertia. This makes it possible for weak dynamical traits.
15	Reliability	Less Reliable	Highly reliable

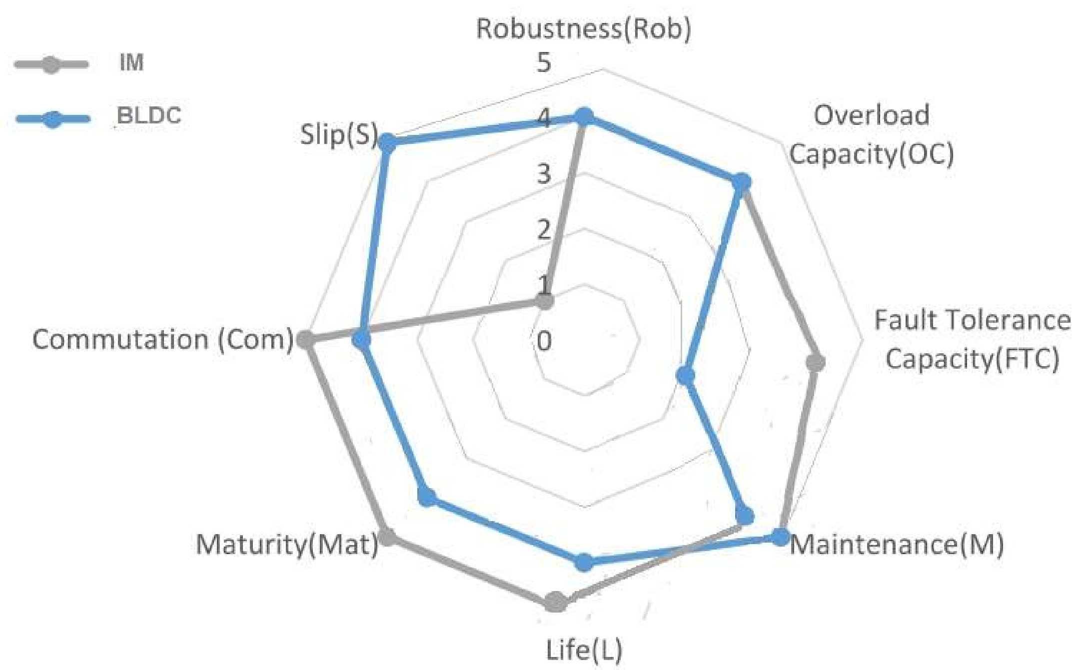


Figure 5-13-Reliability of IM and BLDC [2]

To produce low-cost EVs, manufacturers always looking for low-cost motors for electric vehicle propulsion applications. A cost observation is shown in Table 5-4.

Table 5-4-Cost of Induction Motor EVs

S.N.		BLDC Motor	Induction Motor
1	Cost of Controller basis	High	Low
2	Cost of Motor	High	Low

5.8 Highlights

Table 5-5 presents a comparative analysis of the efficiency percentages in electric vehicle (EV) systems incorporating photovoltaic (PV) technology, utilizing both Brushless DC (BLDC) motors and induction motors. The investigation spans various output power levels, ranging from 200W to 2000W. At the lower 200W output power, the PV-based BLDC motor EV system indicates an efficiency of 87.966%, while the PV-based induction motor EV system achieves a slightly superior efficiency of 91.236%. This signifies an approximate 3.27% efficiency improvement for the proposed induction motor system compared to the existing BLDC motor system at this power level. As the output power increases to 400W, 600W, and 800W, the efficiency of the PV-based BLDC motor system consistently improves. Nevertheless, the PV-based induction motor system consistently outperforms the BLDC motor system, demonstrating efficiency values of 91.22 percent, 92.365 percent, and 93.665 percent, respectively. The efficiency increase ranges from 0.27% to 2.39% at these power levels, highlighting the advantages of the proposed induction motor system over the existing BLDC motor system. With the output power further increasing from 1000W to 2000W, both systems maintain high efficiency. However, the PV-based induction motor system consistently exhibits higher efficiency values than the BLDC motor system, with percentage differences ranging from 2.53% to 4.03%. Overall, observations illustrate the superior efficiency of the proposed PV-based induction motor EV system across diverse output power levels. With variances ranging from 0.27% to 4.03%, the proposed induction motor system consistently attains higher efficiency, demonstrating its potential as an energy-efficient solution for electric vehicle applications. This heightened efficiency contributes to enhanced electrical energy utilization and superior performance, positioning the PV-based induction motor EV system as a promising solution for the transportation sector. In a broader context, Induction Motors (IM) exhibit commendable fidelity, low power density, and average acceleration, achieving productivity levels exceeding 90%, making them a favored choice among EV manufacturers. On the other hand, BLDC motors showcase advanced power density, high productivity, and compact size but entail higher maintenance and controller expenses. The high-efficiency zone for Induction Motors is situated within the areas of high efficiency.

Table 5-5-Efficiency Comparison of Different EVs[86]

Output power (W)	**EV system**	
	PV-based BLDC motor	**PV based Induction motor**
200	87.966	91.236
400	89.998	91.235
600	91.235	92.365
800	92.066	93.665
1000	91.235	93.789
1200	90.366	94.562
1400	90.988	94.756
1600	91.452	94.895
1800	91.965	95.326
2000	91.856	95.897

5.8.1.1 ***Brushless DC (BLDC) motors are often considered more efficient than induction motors in many applications:***

Brushless DC (BLDC) motors are often considered more efficient than induction motors in many applications due to several inherent design and operational advantages. Below is an explanation of why this is the case:

5.8.1.1.1 Absence of Rotor Losses

- BLDC Motors:

  - The rotor in a BLDC motor is a permanent magnet, meaning there are no windings or current flow in the rotor. This eliminates rotor I^2R losses (resistive losses in the rotor windings).

- Induction Motors:

  - Induction motors rely on electromagnetic induction to generate rotor current, which inherently causes rotor losses. These losses reduce overall efficiency.

5.8.1.1.2 Precise Control of Magnetic Field

- BLDC Motors:

  - BLDC motors use electronic commutation (via an inverter and sensors) to precisely control the magnetic field in the stator. This results in near-optimal torque production and minimal losses throughout the operating range.

- Induction Motors:

  - In induction motors, the magnetic field is generated through induction, which can lead to inefficiencies, especially at partial loads or low speeds, due to slip and less precise control.

5.8.1.1.3 No Slip Losses

- BLDC Motors:

  - The rotor in a BLDC motor is synchronized with the stator's rotating magnetic field, resulting in zero slip and no associated losses.

- Induction Motors:

- Induction motors require a slip (difference between synchronous and rotor speed) to generate torque, which contributes to energy losses.

5.8.1.1.4 Higher Power Density

- BLDC Motors:

  - BLDC motors have a higher power-to-weight ratio because of their compact design and the use of permanent magnets, which provide strong magnetic fields without consuming electrical energy.

- Induction Motors:

  - Induction motors require larger and heavier components (rotors, windings) to produce the same amount of power, which can lower overall efficiency.

5.8.1.1.5 Lower No-Load and Core Losses

- BLDC Motors:

  - BLDC motors typically have lower core losses (due to reduced magnetizing current requirements) and minimal no-load losses, especially at low speeds.

- Induction Motors:

  - Induction motors experience higher magnetizing losses and core losses due to the continuous flow of current required to generate the magnetic field.

5.8.1.1.6 Efficiency at Variable Speeds

- BLDC Motors:

  - BLDC motors maintain high efficiency across a wide range of speeds and loads because the electronic controller adjusts the input voltage and current to match the operating conditions.

- Induction Motors:

  - Induction motors tend to operate less efficiently at variable speeds or partial loads unless paired with a variable frequency drive (VFD), which adds cost and complexity.

5.8.1.1.7 Cooling Requirements

- BLDC Motors:

- The absence of rotor losses and slip means BLDC motors generate less heat, reducing cooling requirements and improving energy efficiency.

- Induction Motors:

    - Induction motors often require additional cooling systems due to higher losses, especially at high loads.

5.8.1.1.8 Why Induction Motors are Still Popular:

Despite these advantages, induction motors are widely used in industrial and heavy-duty applications because:

Cost-Effective: Induction motors are generally cheaper to manufacture due to the absence of expensive permanent magnets.

Robustness: They are durable, reliable, and can handle harsh environments.

Maintenance-Free: They do not have brushes, making them nearly maintenance-free, similar to BLDC motors.

While BLDC motors are more efficient due to the absence of rotor losses, precise control, and no-slip operation, the choice between a BLDC and an induction motor depends on the specific application, cost considerations, and performance requirements. For electric vehicles and applications prioritizing high efficiency and power density, BLDC motors are often the better choice[24].

5.9 Chapter Summary

This thesis presents a comprehensive analysis and performance comparison of electric motors for traction systems, with a focus on their application in electric vehicles (EVs). It emphasizes the use of induction motors (IMs) as prime movers due to their favorable characteristics such as robustness, cost-effectiveness, and reliability. The efficiency of the induction motor is evaluated by comparing the mechanical power output to the electrical power input, and a Simulink-based block diagram is employed for dynamic simulation. The mathematical model of the induction motor, along with its dynamic equations, is developed to accurately represent its behavior in real-time EV applications.

The study also explores multiple criteria for evaluating motor performance, including the power-to-weight ratio, efficiency, and dynamic response. The performance evaluation incorporates various driving conditions and provides insights into how induction motors influence the energy consumption, acceleration, and overall propulsion of electric vehicles. Special attention is given to the development of the EV's dynamic equation, which integrates the mechanical and electrical characteristics of the induction motor.

5.10 Key Observations

5.10.1.1 *Efficiency Evaluation:*

- The efficiency of an induction motor is influenced by its load conditions, operating speed, and design parameters.

- Proper optimization of the induction motor design significantly enhances EV performance while maintaining energy efficiency.

5.10.1.2 *Power-to-Weight Ratio:*

- Induction motors exhibit a favorable power-to-weight ratio, making them suitable for lightweight EV designs. This ratio is crucial for determining vehicle performance, especially in terms of acceleration and energy consumption.

5.10.1.3 *Dynamic Modeling:*

- The Simulink-based block diagram and mathematical modeling of the induction motor provide a robust framework for analyzing dynamic responses under varying driving conditions.

- The inclusion of dynamic equations governing the EV's motion ensures a realistic representation of the motor's interaction with the vehicle load.

5.10.1.4 *Performance Comparison:*

- While induction motors are slightly less efficient than brushless DC motors (BLDC) at low loads, they outperform in terms of durability, cost, and heat management under high-stress conditions.

- Induction motors offer a competitive alternative for EV propulsion systems due to their scalability and simplified control requirements.

5.10.1.5 *Characteristics of Induction Motor for EVs:*

- Induction motors demonstrate robust characteristics such as high torque generation, adaptability to various load conditions, and seamless integration with regenerative braking systems.

5.11 Chapter Conclusion

The research establishes induction motors as a viable and efficient option for electric vehicle propulsion systems. By comparing key performance metrics such as efficiency, power-to-weight ratio, and dynamic behavior, the study highlights the advantages of using induction motors in EV applications. Through detailed simulations using Simulink and the mathematical modeling of induction motor dynamics, the research provides a solid foundation for understanding and optimizing their performance in real-world conditions.

Induction motors strike a balance between cost, reliability, and efficiency, making them particularly well-suited for medium and low-cost electric vehicles. While further optimization in design and control strategies could enhance their efficiency, their robustness and adaptability ensure their competitiveness in the evolving EV market. This thesis contributes to the growing body of knowledge aimed at advancing sustainable electric transportation by promoting efficient motor technologies for propulsion systems.

6 Performance Evaluation of an EV using MATLAB

6.1 Simulation

The assessment of an Electric Vehicle propelled by an Induction motor, utilizing a MATLAB Simulink model crafted for a PV-based induction motor drive EV system, is depicted in Figure 6-1, with its results illustrated in Figure 6-2. As per the objective, performance evaluation of an Induction Motor using MATLAB simulation designed for EV propulsion application and the result of this simulation described well in Figure 6-3 explains the three-phase input given to the Induction Motor as the three-phase AC supply given into the induction motor for EV propulsion application and the result of it the output we get as per desired expectation. Figure 6-4 explains the desired output of the IM for an Electric Vehicle application. To design and simulate a realistic model for solar-powered electric vehicles (EVs), various real-world scenarios must be considered:

6.1.1 Solar Irradiation Variations

The simulation results comprehensively evaluate solar power system performance under dynamic conditions, including variations in solar irradiation. The intensity of solar radiation is influenced by five critical factors: location (Figure 6-1), time (Figure 6-2), and panel inclination (Figure 6-3)[114]. For practical applications, these parameters are input into a custom-developed computational tool, which serves as a mathematical model. This tool computes key solar parameters such as extraterrestrial intensity, angle of declination, hour angle, hour angle at sunset, sunshine hours, angle of incidence, zenith angle, altitude angle, and air mass ratio. This type of analysis is particularly significant when selecting suitable locations for large-scale solar power generation projects, such as those proposed by government initiatives in India. The tool facilitates the study of the sun's path across different dates and months, ensuring informed decision-making for optimal plant placement and efficient energy harvesting. By simulating real-world conditions, the study provides a detailed understanding of the system's performance and highlights its adaptability to varying solar irradiance levels, thus validating its practical applicability. The following factors should be considered. A case study was conducted for a solar power system located at coordinates 27.4739°N latitude and 77.6720°E longitude, with an altitude of 186 meters, in the Mathura district of Western Uttar Pradesh. This analysis incorporated satellite-based projection positioning and circuit mapping.

6.1.1.1 *Solar Path Diagram Analysis Statement:*

The solar path diagram illustrated in the figure represents the sun's behavior, plotted using a computational tool for the location at 27.4739°N latitude and 77.6720°E longitude, with an altitude of 186 meters, situated in the Mathura district of Western Uttar Pradesh. This analysis is a crucial component in the design and optimization of solar power generation systems.

6.1.1.2 *Seasonal Variations:*

Incorporate seasonal changes in solar intensity based on tilt angle and geographic location (e.g., winter vs. summer irradiation profiles). By employing such computational tools like PV Syst software, one can estimate solar intensity, evaluate variations in critical parameters, and establish interrelations between these factors through graphical representations as shown in Figure 6-1

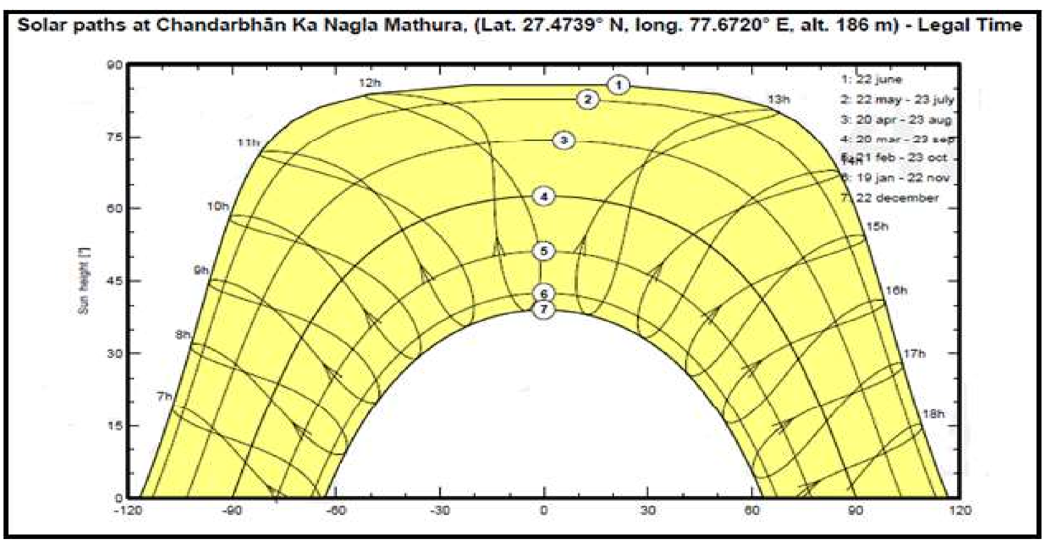


Figure 6-1-Sun Path Diagram at 27.4739°N latitude and 77.6720°E longitude

6.1.1.3 *Time of Day:*

Simulate solar irradiation from sunrise to sunset, with peaks at noon (e.g., using a Gaussian or sinusoidal curve).

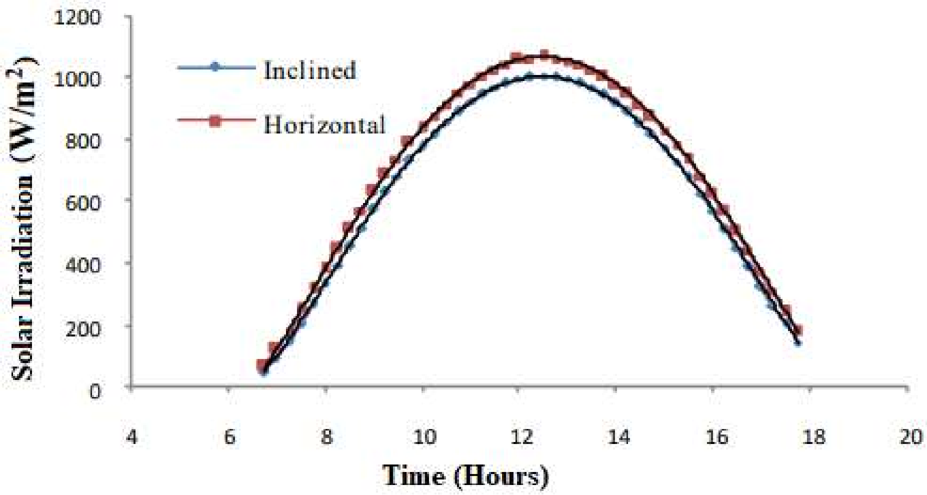


Figure 6-2-Solar Radiation Vs Time at an angle

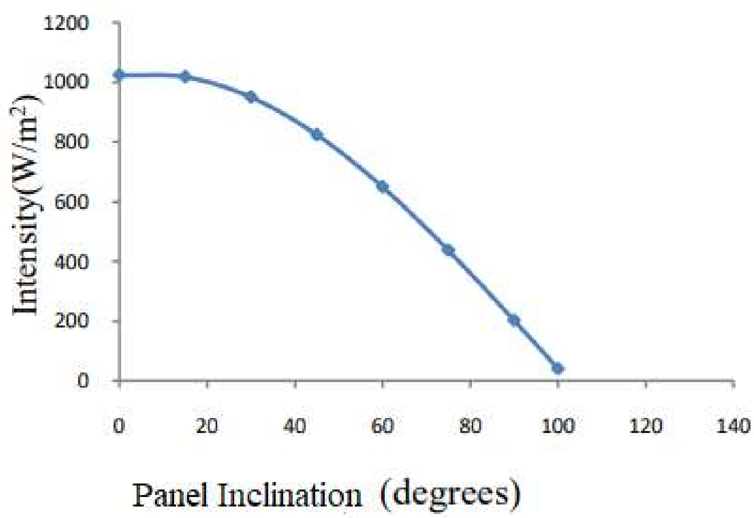


Figure 6-3-Panel Inclination Vs Solar Intensity

6.1.2 Partial Shading:

Partial shading occurs when parts of the solar array are obstructed by shadows or debris, reducing output efficiency. Variations to simulate:

6.1.2.1 *Shadow Patterns:*

Introduce dynamic shading patterns caused by trees, buildings, or passing objects (e.g., poles) and a simulation model for PV configuration shown in Figure 6-4.

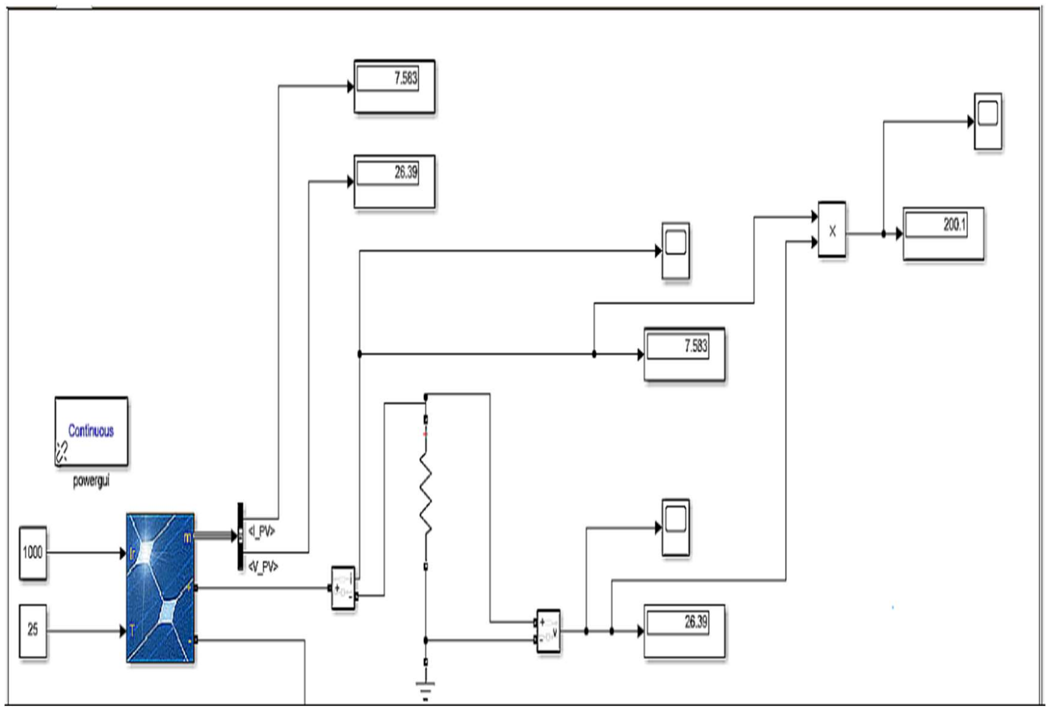


Figure 6-4- MATLAB Simulation PV Configuration

6.1.2.2 *Non-Uniform Irradiation:*

Assign different irradiation levels to each panel or cell to simulate partial shading. Figures 6-5 (a) and (b) show the Simulation result when there is no shading and so that high wattage of power is optimized whereas Figures 6-6 (a) and (b) depict the panel under shading conditions[115].

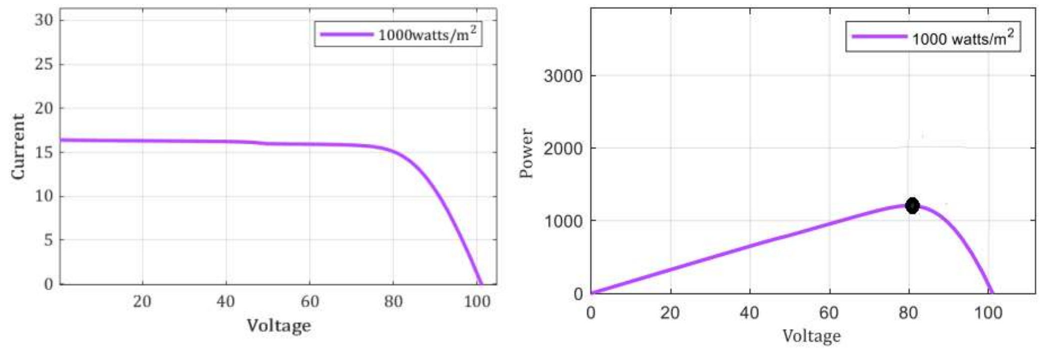


Figure 6-5-(a)I-V (b) P-V Simulation Results at no Shading Condition

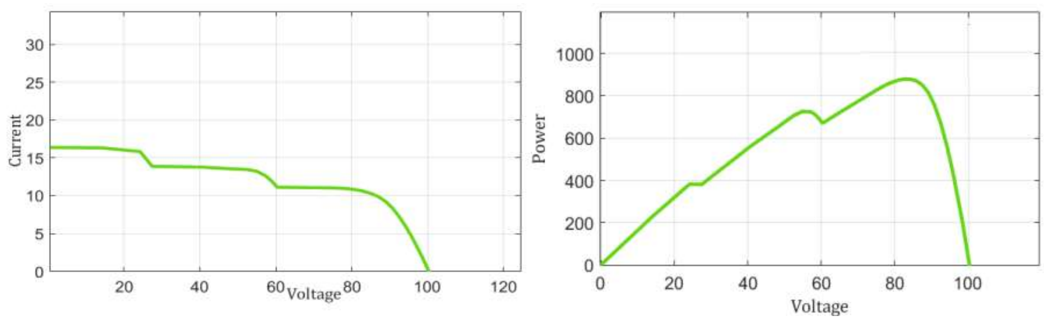


Figure 6-6-(a)I-V (b) P-V Simulation result at shading condition

6.1.3 Vehicle Speed Variations:

Driving cycles represent velocity-time profiles designed to evaluate vehicle performance under specific traffic and road conditions. These profiles help determine energy consumption, driving range, and emissions of electric vehicles (EVs). Standardized driving cycles, such as the Urban Driving Cycle (UDC), Highway Speed (HS), and FTP, simulate diverse traffic environments including urban, suburban, and highway conditions. For example, the segmenting of urban and non-urban paths for better accuracy.

Endogenous factors involve vehicle design elements like battery efficiency, motor performance, and aerodynamics. Exogenous factors include environmental conditions like temperature, wind orientation, and road topography. Driving behavior and climatic conditions also significantly affect energy efficiency. For instance, aggressive acceleration patterns and cold weather can increase energy consumption due to heating demands and reduced battery efficiency. Road gradients further influence energy usage, with uphill driving consuming more power and downhill routes enabling regenerative braking.

These insights, coupled with simulation models and experimental data, enable the analysis of EV performance under dynamic conditions, including speed variations and real-world driving scenarios, providing critical data for improving EV design and range optimization[116]. Variations include:

6.1.3.1 *Urban Driving Cycles:*

Simulate stop-and-go driving patterns typical of city traffic, with frequent acceleration and deceleration, and their time and velocity characteristics are shown in Figure 6-7.

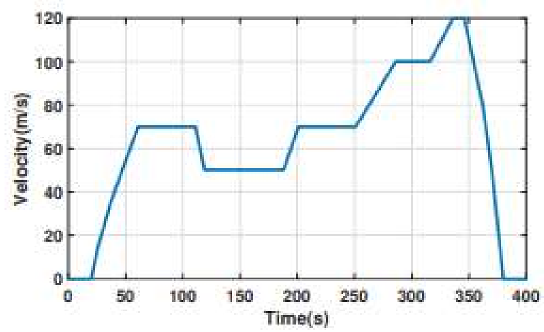


Figure 6-7-Standard Driving Cycle for Urban[116]

6.1.3.2 *Highway Speeds:*

Simulate constant high-speed driving, increasing aerodynamic drag and motor load depicted in Figure 6-8.

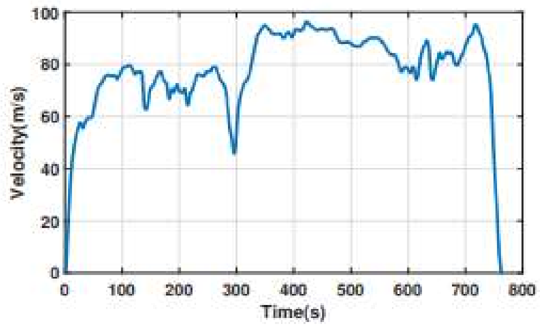


Figure 6-8-Highway Speed driving situation[116]

6.1.3.3 *Speed Profiles:*

Use standard driving cycles like the WLTP (Worldwide Harmonized Light Vehicle Test Procedure) or UDDS (Urban Dynamometer Driving Schedule) to model speed variations over time.

6.1.4 Load Changing:

The load on the motor changes due to passenger count, cargo weight, or gradient changes (e.g., driving uphill/downhill). Table 6-1 represents the data on energy consumption and battery discharge rates for an urban driving cycle, starting with a 60% state of charge and at an ambient temperature of 20°C. It highlights how the energy consumption values align with the discharge characteristics of the battery under these specific conditions, emphasizing the relationship between operational parameters and battery performance[117].

Table 6-1-Dynamic condition at Load changing

Load, kg	**50**	**100**	**150**	**200**	**250**
total energy consumption, kWh	2.23	2.26	2.29	2.36	2.39
average energy consumption, kWh/km	0.20	0.21	0.21	0.22	0.22
differences in average energy consumption, %	-	1.33	2.62	5.51	6.69
DOD %	4.95	5.02	5.09	5.17	5.24

6.1.5 Regenerative Braking:

Regenerative braking allows the motor to act as a generator during deceleration, converting kinetic energy back into electrical energy. Variations include:

6.1.5.1 *Braking Intensity:*

Simulate light braking (10–20% energy recovery) versus heavy braking (40–60% recovery).

6.1.5.2 *Vehicle Speed:*

At higher speeds, regenerative braking is more efficient due to higher kinetic energy, while efficiency drops at low speeds.

6.1.5.3 *State of Charge (SOC) Dependency:*

When the battery is nearly full, regenerative braking may need to be limited to avoid overcharging.

6.1.5.4 *Drive Cycles:*

Use drive cycles like the **HWFET (Highway Fuel Economy Test)** or **NEDC (New European Driving Cycle)** to test braking effectiveness.

During braking in electric vehicles, the electric motor functions as a generator to recover energy. Figure 6-9 illustrates the trends in total energy consumption and total energy recovery under six different driving conditions. The curves for Total Energy and Total Energy Recovery demonstrate an overall upward trend, with Total Energy being considerably higher than Total Energy Recovery. The driving cycles analyzed include the Urban Driving Cycle and Highway Driving etc.[117].

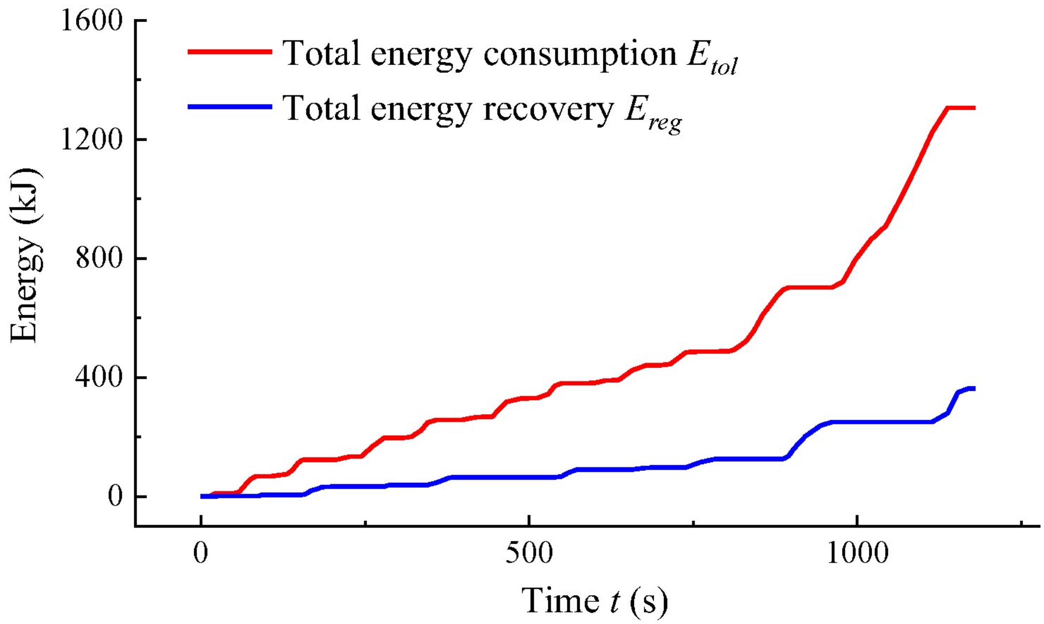


Figure 6-9-Curve between Total Energy Consumption vs. total Energy Recovery[117]

6.1.6 Simulation Parameters

For a **solar-powered electric vehicle (EV)** simulation, the parameters focus on integrating the photovoltaic (PV) system with the EV components[118]. Here's the set of parameters and the simulation model of PV PV-powered induction motor-driven electric vehicle shown in Figure 6-10.:

6.1.6.1 *Vehicle Dynamics Parameters:*

- **Vehicle Mass (m):** 1200–1500 kg (depending on passenger/cargo capacity).
- **Frontal Area (A):** 2–2.5 m².
- **Aerodynamic Drag Coefficient (Cd):** 0.3–0.35.
- **Rolling Resistance Coefficient (Cr):** 0.01–0.015.
- **Wheel Radius (r):** 0.3–0.35 m.
- **Gear Ratio (GR):** 8–12.
- **Maximum Vehicle Speed:** 100–120 km/h.
- **Gradeability:** 10–15%.

6.1.6.2 *Electric Motor Parameters:*

- **Motor Type:** Induction Motor (IM) or BLDC.
- **Rated Power:** 30–50 kW (small EV).

- **Rated Speed:** 3000–4000 rpm.
- **Peak Torque:** 150–300 Nm.
- **Efficiency Map:** Include dynamic performance analysis.
- **Control Type:** Field-Oriented Control (FOC) or Direct Torque Control (DTC).

6.1.6.3 *Photovoltaic System Parameters:*

- **PV Panel Type:** Monocrystalline or Polycrystalline.
- **Number of Panels:** Based on available rooftop area (~2–5 panels for a small EV).
- **Panel Area:** 1–1.5 m^2 per panel.
- **Panel Efficiency:** 18–22%.
- **Total Rated Power (Peak):** 200–400 W per panel.
- **Solar Irradiance:** 400–1000 W/m^2 (location-specific, such as Mathura district).
- **Temperature Coefficient:** -0.3 to -0.5% per °C.
- **Panel Configuration:** Series or parallel depending on the required voltage/current.

6.1.6.4 *Battery System Parameters:*

- **Battery Type:** Li-ion (preferred for energy density).
- **Battery Capacity:** 15–25 kWh.
- **Nominal Voltage:** 300–400 V.
- **SOC Range:** 20–90%.
- **Battery Pack Configuration:** Based on PV and motor requirements.
- **Charge/Discharge Efficiency:** ~95%.
- **Thermal Management System:** Passive or active.

6.1.6.5 *Power Electronics Parameters:*

- **DC-DC Converter:** Boost or Buck-Boost.
    - **Converter Efficiency:** 90–95%.
    - **MPPT Controller Algorithm:**
        - Perturb and Observe (P&O).
        - Incremental Conductance.
        - Fuzzy Logic-based MPPT.

- **Inverter Efficiency:** ~97%.
- **Switching Frequency:** 10–20 kHz.

6.1.6.6 *Charging System Parameters:*

- **Charger Type:** Integrated solar and grid charger.
- **Charging Power:**
    - From PV: ~200–400 W.
    - From Grid: 3.3 kW (slow), 22 kW (fast).
- **Bidirectional Converter:** For grid-connected solar EVs with V2G capability.

6.1.6.7 *Drive Cycle Parameters:*

- **Drive Cycle:** Based on the application (urban or highway):
    - Urban Dynamometer Driving Schedule (UDDS).
    - Worldwide Harmonized Light Vehicle Test Procedure (WLTP).
    - Customized cycles for regional data (e.g., typical routes in Mathura).
- **Distance Per Day:** 30–50 km (short-range).

6.1.6.8 *Environmental and Solar Inputs:*

- **Ambient Temperature:** 20–45°C (for Mathura region).
- **Road Conditions:** Urban roads (medium rolling resistance).
- **Wind Speed:** 1–3 m/s.
- **Sunlight Hours Per Day:** 6–8 hours (Mathura average).
- **Solar Panel Tilt Angle:** ~20°–25° (fixed or dynamic tracking).

6.1.6.9 *Control and Optimization Parameters:*

- **Energy Management Strategy:** To prioritize PV energy utilization while maintaining SOC.
- **Regenerative Braking Efficiency:** 30–40% recovery rate.
- **Motor Control Strategy:** FOC/DTC with torque-speed optimization.
- **PV to Battery Control Logic:** Based on SOC thresholds.

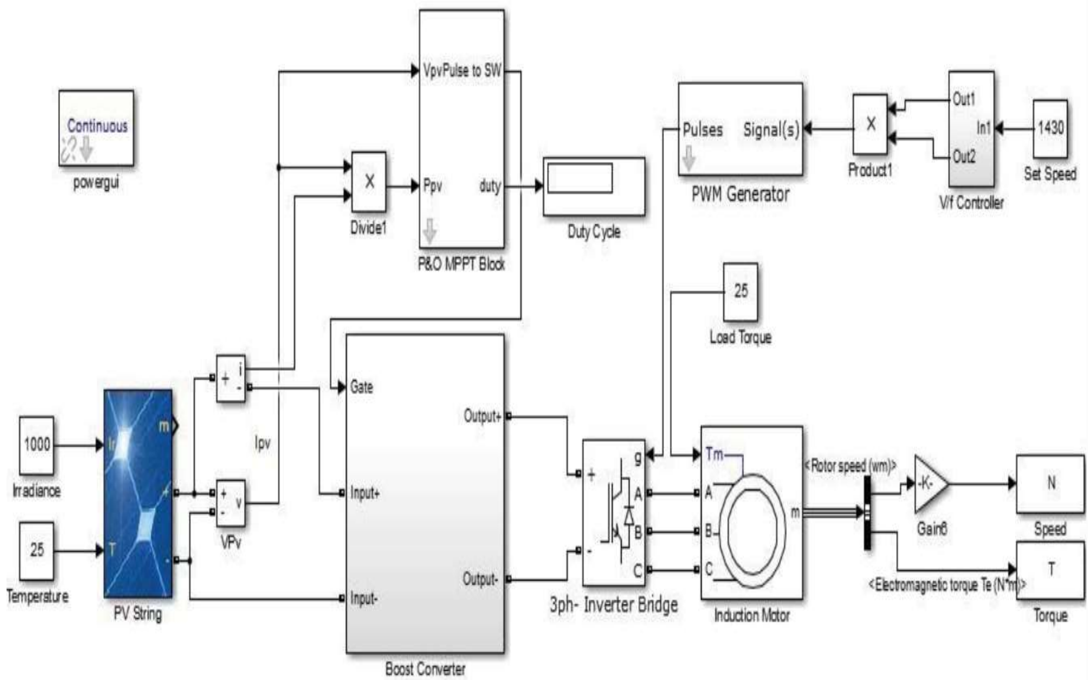


Figure 6-10- Simulink model for PV-powered induction motor vehicle

Figure 6-11 displays a time-domain plot of the stator current waveform for an induction motor.

6.1.6.10 ***Horizontal Axis (Time):***

- The x-axis represents time in seconds, indicating the evolution of the stator current over a period (approximately 1.3 seconds).

6.1.6.11 ***Vertical Axis (Stator Current):***

- The y-axis represents the stator current in amperes (A), with positive and negative values, indicating the alternating nature of the current.

6.1.6.12 ***Waveform Characteristics:***

- The waveform is periodic, showing an alternating current (AC) behavior typical of stator currents in an induction motor.
- The current has a regular frequency and exhibits peaks and troughs, corresponding to the AC sinusoidal nature with harmonic distortion.

6.1.6.13 ***Key Observations:***

- The waveform deviates from a perfect sinusoid, suggesting the presence of harmonics, which could be due to supply voltage distortion, motor loading, or non-linear effects.

- The current oscillates between approximately +6 A and -6 A, indicating the magnitude of the current drawn by the motor during operation.
- The periodicity of the waveform is consistent, reflecting the motor's steady-state operation under the given conditions.

Figure 6-12 represents a time-domain plot of the **electromagnetic** generated by an induction motor during operation. Here's a detailed explanation of its components and characteristics:

6.1.6.14 ***Axes Description:***

6.1.6.14.1 Horizontal Axis (Time):

- The x-axis represents time (possibly in seconds), showing the evolution of the electromagnetic torque over a specific time interval.

6.1.6.14.2 Vertical Axis (Electromagnetic Torque):

- The y-axis represents the torque in Newton-meters (N·m). This is the rotational force generated by the motor during operation.

6.1.6.15 ***Waveform Characteristics:***

6.1.6.15.1 Periodic Oscillations:

- The waveform exhibits periodic peaks and troughs, suggesting cyclic variations in the electromagnetic torque.

6.1.6.15.2 Torque Range:

- The torque oscillates between approximately **4.2 N·m and 5.6 N·m**, indicating that the motor operates within this range under the given conditions.

6.1.6.15.3 Non-Sinusoidal Nature:

- The waveform is not perfectly smooth, showing distinct sharp transitions between peaks and troughs. This may suggest:
  - The presence of harmonics or irregularities in the electromagnetic interaction.
  - Load or supply variations during the motor's operation.

6.1.6.15.4 Stable Frequency:

- The periodicity of the torque waveform appears consistent, indicating stable operating conditions of the motor despite fluctuations in torque magnitude.

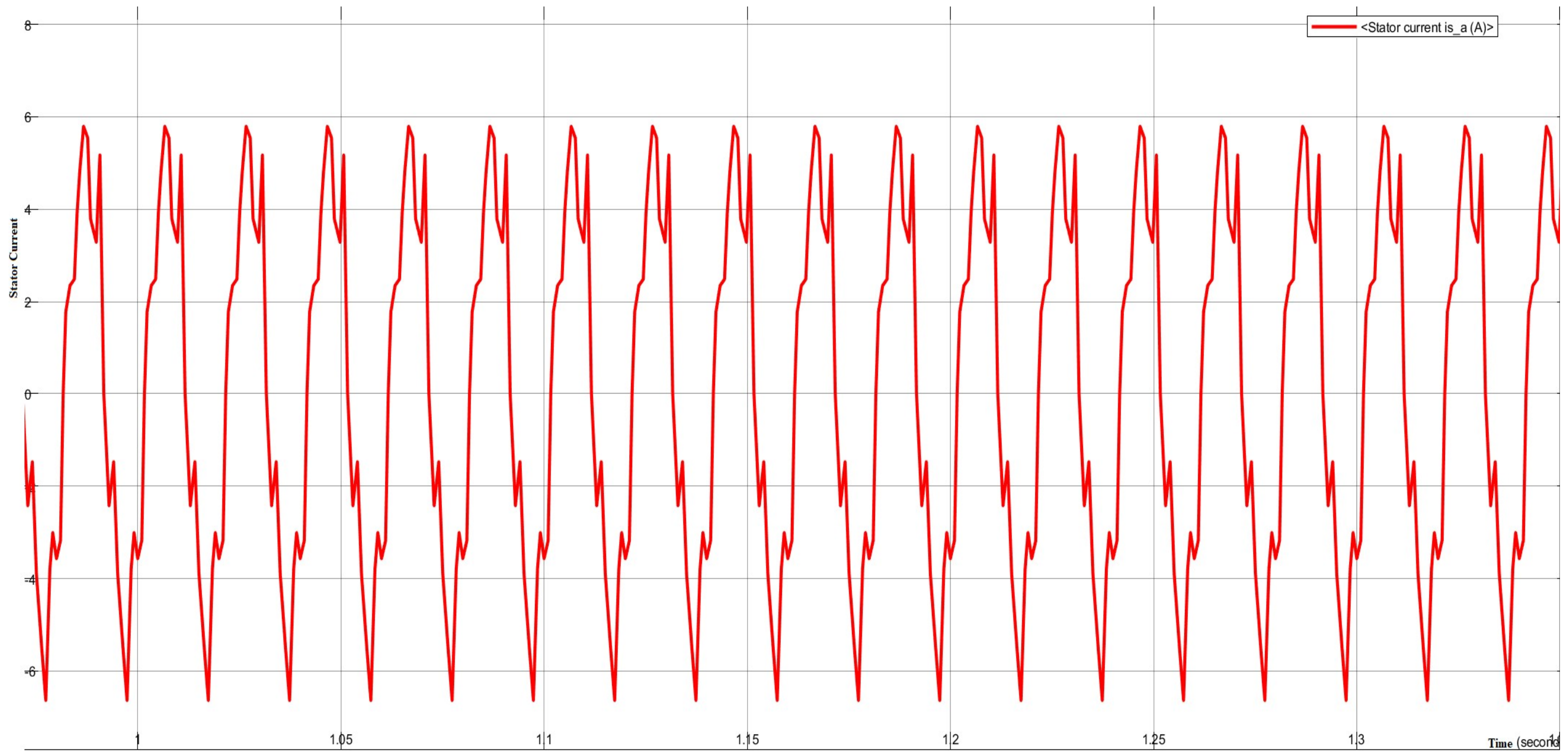


Figure 6-11-Graph between Stator current to Time

Figure 6-12-Graph for Electromagnetic Torque-Rotor Current-Rotor Speed

Due to the switching strategy employed in the power electronics driving the induction motor the trapezoidal and non-sinusoidal nature of the 3-phase current waveforms is shown in Figure 6-13.

6.1.7 PWM Control and Inverter Switching Techniques

The induction motor is typically powered by an inverter, which generates AC from a DC source. The current shape depends on the modulation technique used:

6.1.7.1 *Pulse Width Modulation (PWM):*

Most commonly, PWM is used to approximate sinusoidal waveforms. However, depending on the modulation depth, switching frequency, and load, the output currents can deviate from an ideal sine wave.

6.1.7.2 *Trapezoidal Current Shape:*

The trapezoidal current in the figure indicates that the inverter may be using a **trapezoidal approximation** or operating at a lower PWM switching frequency, causing the waveforms to appear non-sinusoidal.

6.1.7.3 *Non-Sinusoidal Characteristics:*

The non-sinusoidal shape can be explained by the following factors:

6.1.7.3.1 Harmonics:

Inverters introduce harmonics into the output waveform due to the discrete switching of power electronic devices (e.g., IGBTs or MOSFETs). Harmonic components distort the current waveform.

6.1.7.3.2 Switching Frequency:

If the PWM switching frequency is low relative to the motor's operating frequency, the waveform resolution decreases, leading to trapezoidal waveforms.

While sinusoidal waveforms are traditionally preferred for driving three-phase induction motors due to their smooth torque production and efficiency, trapezoidal waveforms can offer distinct advantages in certain applications. Below is an explanation showing why trapezoidal waveforms may sometimes be better for three-phase induction motors:

6.1.7.4 *Improved Torque Control:*

Trapezoidal waveforms often provide **higher torque per ampere** compared to sinusoidal waveforms in certain motor designs:

6.1.7.4.1 Flat Torque Profile:

Trapezoidal currents deliver a more consistent torque profile because the current is nearly constant during certain phases of the cycle.

6.1.7.4.2 Reduced Torque Ripple in Specific Cases:

When optimized, trapezoidal waveforms can minimize torque ripple in induction motors, especially under low-speed or medium-speed conditions.

6.1.7.4.3 Simplified Drive Implementation:

6.1.7.4.3.1 Reduced Complexity:

Generating trapezoidal waveforms requires simpler control algorithms and switching strategies compared to sinusoidal modulation techniques like Space Vector PWM (SVPWM) or Field-Oriented Control (FOC).

6.1.7.4.3.2 Lower Computational Burden:

Trapezoidal drive systems often use simpler modulation techniques, reducing the need for complex real-time calculations.

6.1.7.4.3.3 Cost Reduction:

Fewer hardware requirements (e.g., simpler microcontroller or DSP) can lower the overall cost of the drive system.

6.1.7.4.4 Higher Switching Efficiency:

Trapezoidal drives generally result in **reduced switching losses** in the inverter:

6.1.7.4.4.1 Reduced Switching Transitions:

Trapezoidal modulation reduces the number of transitions per cycle compared to sinusoidal PWM or SVPWM, leading to lower switching losses in power electronic devices.

6.1.7.4.4.2 Improved Power Device Utilization:

Lower losses increase the efficiency and thermal performance of the inverter.

6.1.7.4.4.3 Applicability in Low-Speed Applications:

For applications where motors operate at low or constant speeds (e.g., conveyors, low-speed industrial drives)

6.1.7.4.5 No Need for Smooth Sinusoidal Waveforms:

At lower speeds, the mechanical system's inertia smoothens out torque variations, making trapezoidal currents acceptable or even advantageous.

6.1.7.4.6 High Torque Requirements:

Trapezoidal waveforms can deliver higher torque for the same current, making them more suitable for low-speed and high-load applications.

6.1.7.5 *Compatibility with Simple Motors:*

6.1.7.5.1 Non-Critical Applications:

In applications where precise torque control is not critical, trapezoidal waveforms are sufficient and can offer adequate performance.

6.1.7.5.2 Older Induction Motor Designs:

Some legacy motors may operate effectively with trapezoidal waveforms due to their winding configuration or construction.

6.1.7.6 *Reduced Harmonic Loss in Certain Scenarios:*

Although trapezoidal waveforms inherently introduce harmonics, they can sometimes reduce specific types of losses:

6.1.7.6.1 Rotor Copper Losses:

Trapezoidal waveforms may focus power delivery in a way that reduces rotor heating in certain conditions.

6.1.7.6.2 Customized Waveforms for Applications:

Tailoring the trapezoidal waveform parameters (e.g., flatness, switching angles) can minimize unwanted harmonics.

6.1.7.7 *Solar-powered or Energy-Limited Applications:*

For solar-powered EVs or energy-constrained systems, trapezoidal waveforms can be advantageous:

6.1.7.7.1 Efficient Energy Use:

Simpler waveform generation conserves computational and electrical resources.

6.1.7.7.2 Integration with DC Sources:

Trapezoidal waveforms can be more easily generated from DC sources, especially in systems without complex inverter topologies.

6.1.7.8 *Fault Tolerance:*

Trapezoidal waveforms provide better fault tolerance in specific scenarios:

6.1.7.8.1 Resilience to Sensor Failures:

Trapezoidal drives often use less precise position or speed sensors compared to sinusoidal control systems, making them less sensitive to sensor malfunctions.

6.1.7.8.2 Simplified Feedback Loops:

Reduced dependence on precise feedback makes trapezoidal drives more robust.

6.1.7.9 *Trade-Offs and Considerations:*

While trapezoidal waveforms offer these benefits, they come with trade-offs:

6.1.7.9.1 Harmonic Content:

Trapezoidal waveforms introduce higher-order harmonics, which can lead to additional losses and noise in the motor.

6.1.7.9.2 Reduced Smoothness:

Sinusoidal waveforms produce smoother torque and are more suitable for applications requiring precise motion control.

Trapezoidal waveforms are better than sinusoidal waveforms for induction motors in scenarios that prioritize simplicity, cost-effectiveness, and robustness over precision and smoothness. They excel in applications where low-speed operation, high torque, or energy efficiency in switching are key requirements.

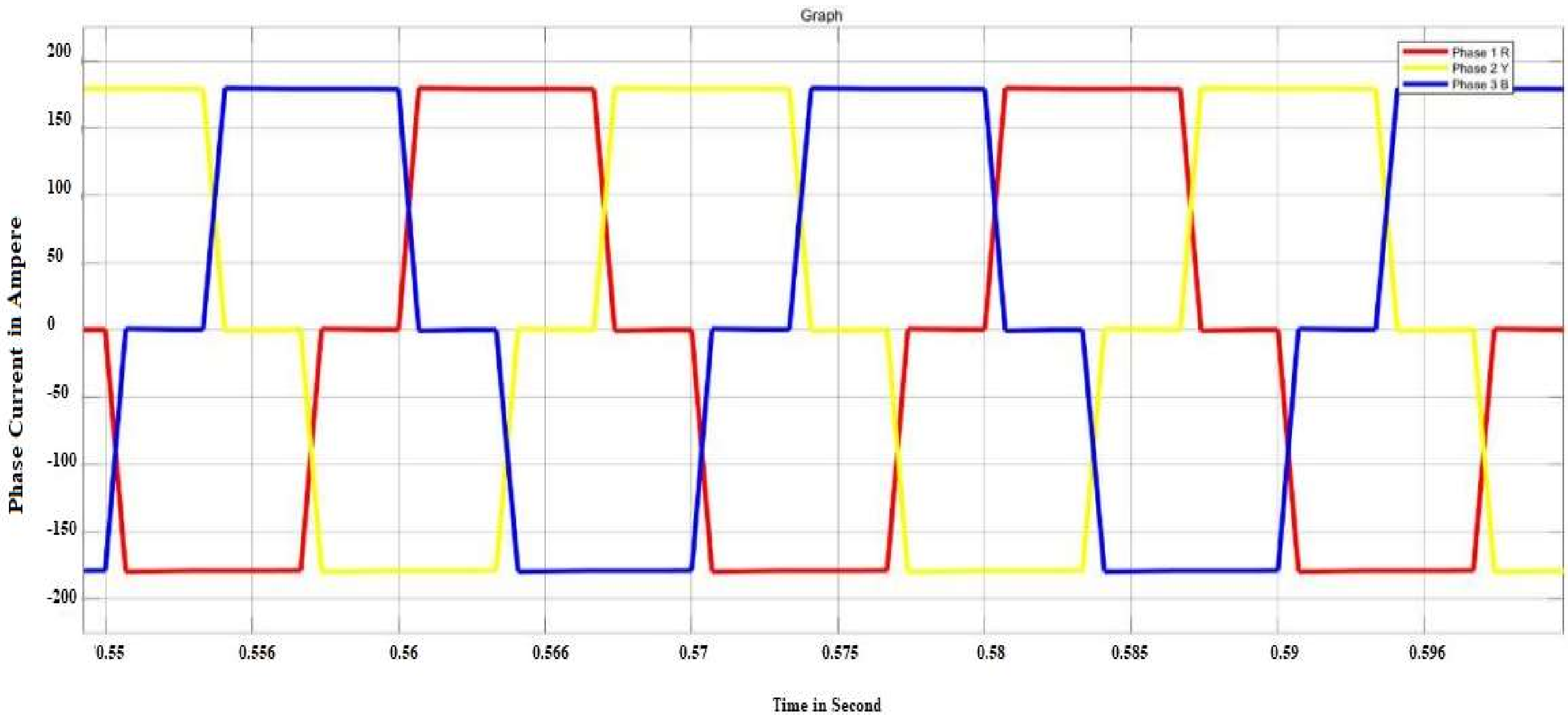


Figure 6-13-Graph shows three-phase input to IM.

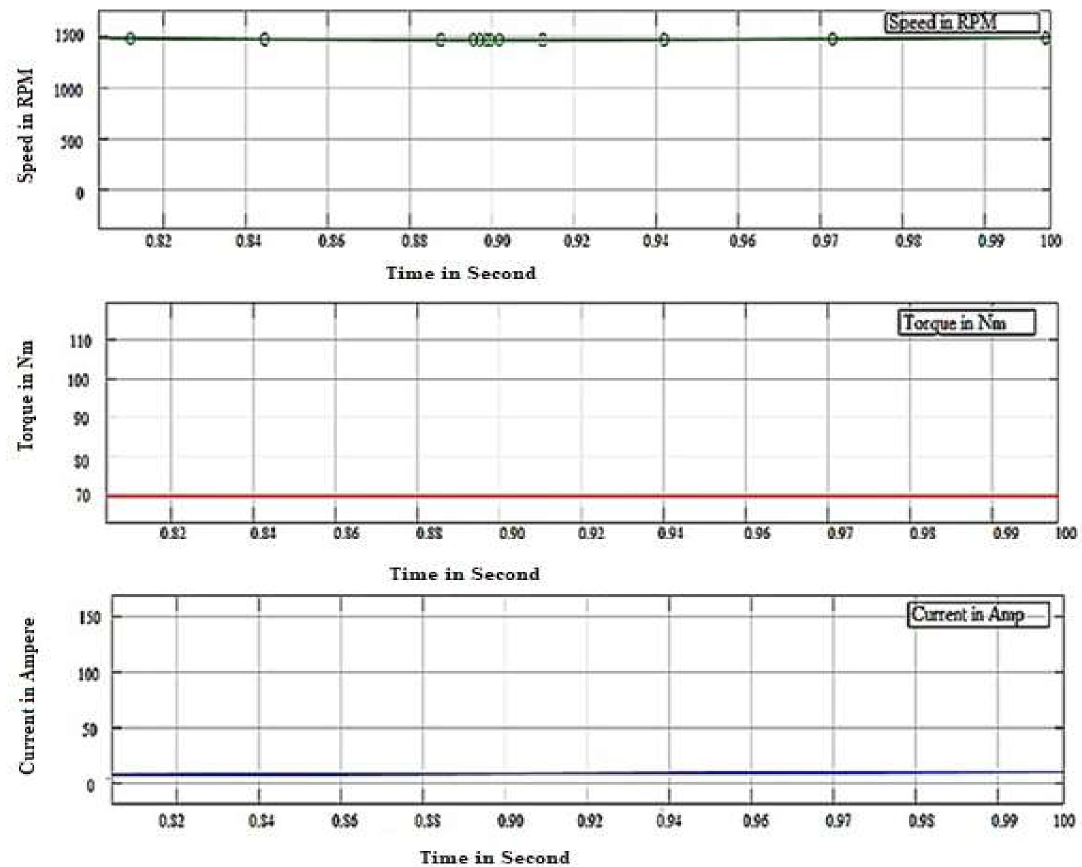


Figure 6-14-Graph shows IM 1500 rpm, 70Nm torque for EV

Figure 6-14 depicts the graph for Torque, Current, and concerning Time for the induction motor. The current study focuses on creating a simulation layout for Electric Vehicles (EVs) powered by Induction Motors (IMs), wherein the IM is integrated with the vehicle's gearbox. Figure 6-15 illustrates the outcomes of this setup, while Figure 6-16 depicts the Simscape model representing the EV body.

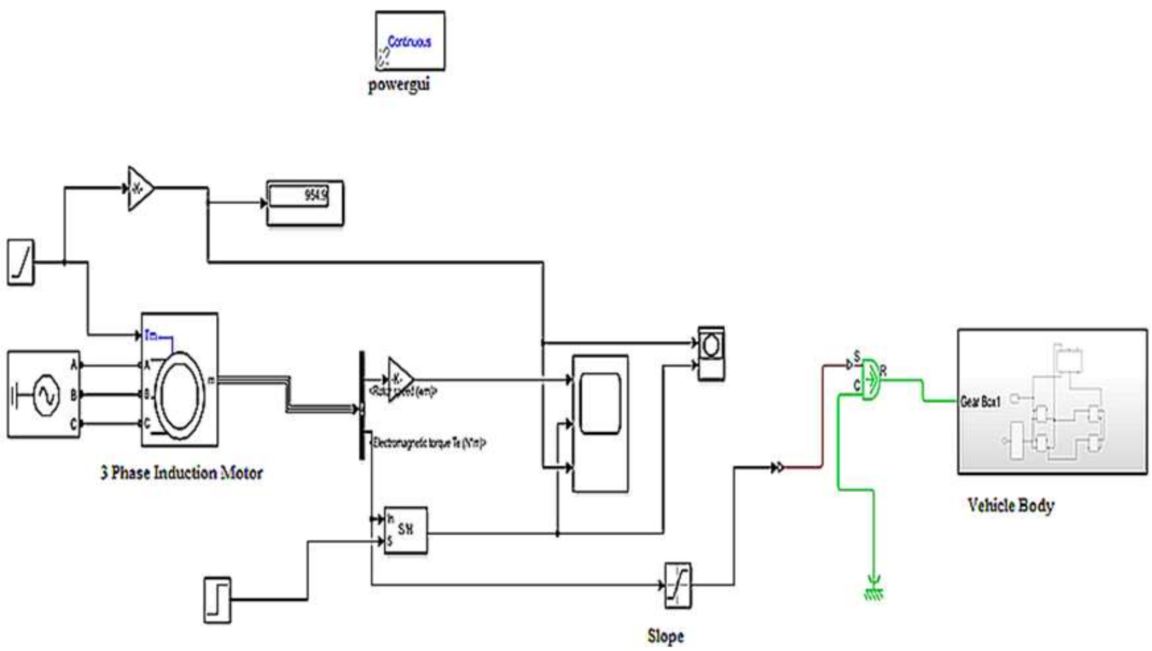


Figure 6-15-EV Body Simscape Model Subsystem

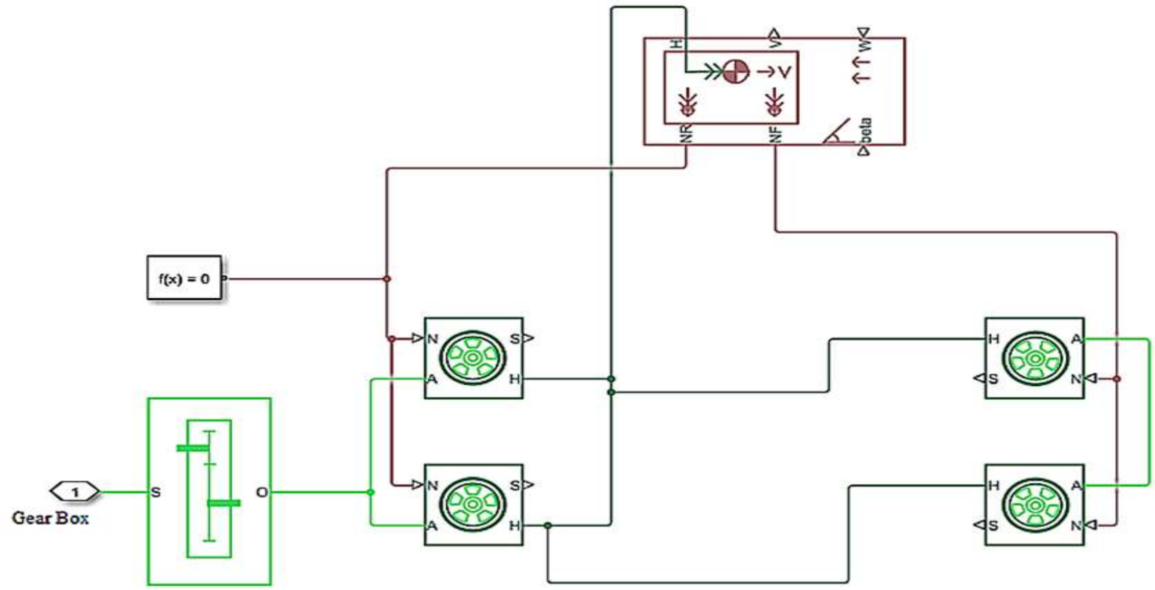


Figure 6-16-Simscape Model for EV Body

In the simulation shown in Figures 6-17, the induction motor connected to the vehicle body operates at a rated speed of 1500 rpm, with a torque output of 70 Nm and a current draw of 30 Amperes over time. The control setup includes a speed controller, braking system, and a feed-forward network designed to facilitate regenerative braking, as illustrated in Figure 6-18. Also, the induction motor-driven EV model is shown in Figure 6-19.

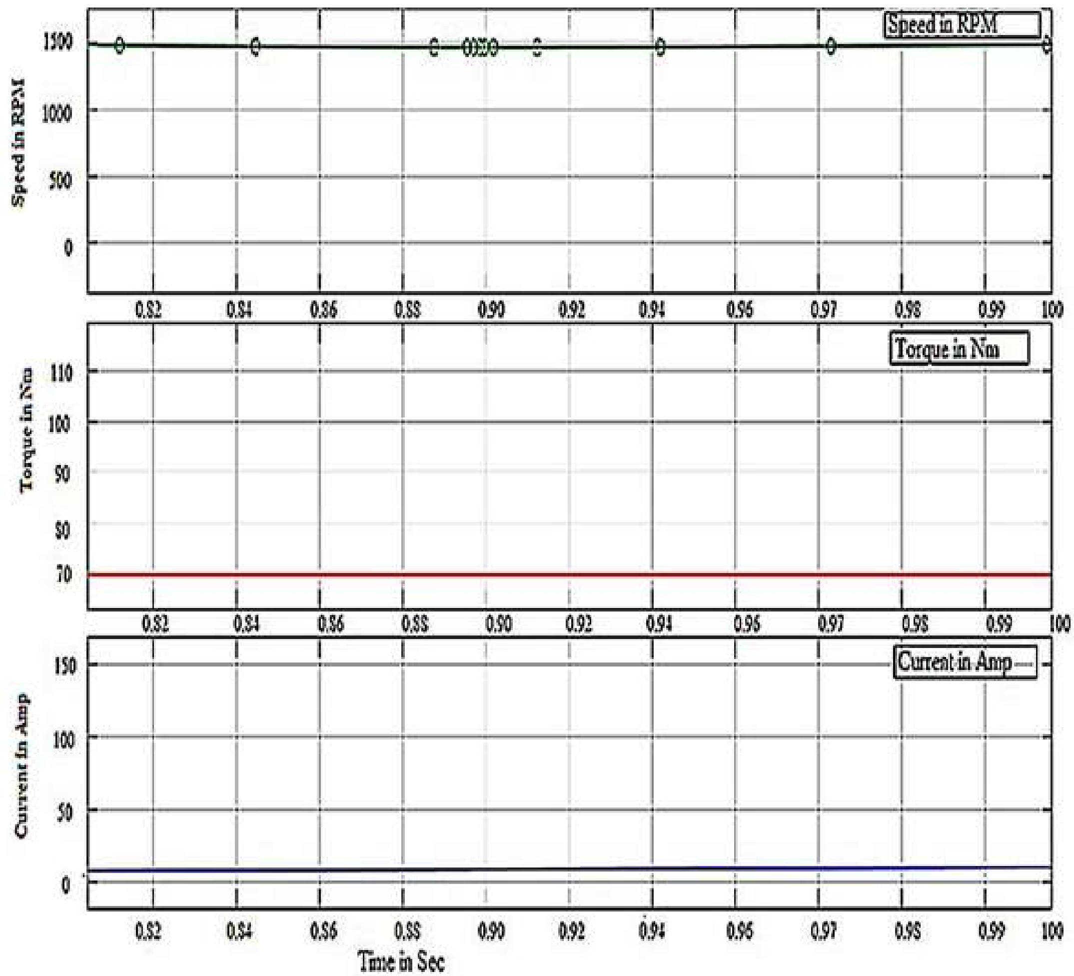


Figure 6-17-Induction Motor EV Simulation Results

6.1.8 Controllers

Controllers are critical components in electric vehicle (EV) systems, as they regulate and manage the operation of various subsystems such as motors, batteries, and power electronics.

6.1.8.1 *Role of Controllers in EVs:*

Controllers are responsible for:

6.1.8.1.1 Efficient Energy Management:

Optimize power flow between the battery, motor, and drivetrain.

6.1.8.1.2 Performance Optimization:

Ensure smooth acceleration, deceleration, and speed control.

6.1.8.1.3 Safety and Protection:

Prevent overcurrent, overvoltage, and thermal overload.

6.1.8.1.4 Dynamic Response:

Provide precise and rapid responses to driver inputs and road conditions.

6.1.8.1.5 Communication:

Interface with sensors, actuators, and external control systems.

6.1.8.2 ***Types of Controllers in EVs***

6.1.8.2.1 Motor Controllers

Motor controllers regulate the speed, torque, and direction of the motor. Common types of motor controllers include:

6.1.8.2.1.1 Induction Motor (IM) Controllers:

- Use techniques like Field-Oriented Control (FOC) or Direct Torque Control (DTC).
- Provide high efficiency and robust performance for varying loads.

6.1.8.2.2 Battery Management System (BMS) Controllers:

BMS controllers monitor and manage battery parameters, ensuring safe and efficient operation:

6.1.8.2.2.1 Functions:

- Monitor State of Charge (SOC), State of Health (SOH), and temperature.
- Balance cell voltages in series-connected battery packs.
- Protect against overcharge, over-discharge, and thermal runaway.

6.1.8.2.2.2 Control Algorithms:

- Proportional-integral-derivative (PID) for balancing.
- Kalman Filter for SOC estimation.
- Fuzzy Logic for adaptive control under dynamic conditions.

6.1.8.2.3 Power Electronics Controllers

These controllers manage the operation of DC-DC converters and inverters:

6.1.8.2.3.1 DC-DC Converter Controllers:

- Regulate voltage levels between the battery and load (e.g., motor, auxiliary systems).
- Techniques: Current-mode control, voltage-mode control, and MPPT for solar applications.

6.1.8.2.3.2 Inverter Controllers:

- Convert DC to AC for driving AC motors.

- Use PWM techniques (e.g., SPWM, SVPWM) for efficient motor operation.

6.1.8.2.4 Regenerative Braking Controllers
Manage energy recovery during braking:

6.1.8.2.4.1 Functions:
- Convert kinetic energy into electrical energy and store it in the battery.
- Optimize braking torque distribution between regenerative and mechanical brakes.

6.1.8.2.4.2 Control Strategies:
- Torque-based control.
- Blended braking (combining mechanical and regenerative braking).

6.1.8.2.5 Vehicle Control Units (VCU)
The VCU acts as the central controller, coordinating all subsystems in the EV:

6.1.8.2.5.1 Functions:
- Interpret driver inputs (e.g., accelerator, brake, and steering commands).
- Manage interactions between motor, battery, and regenerative braking systems.
- Implement energy management strategies.

6.1.8.2.5.2 Advanced Features:
- Predictive control based on traffic and terrain data.
- Real-time diagnostics and communication with external systems.

6.1.8.3 *Field-Oriented Control (FOC)*

6.1.8.3.1 Principle:
Decouples torque and flux control in AC motors using a rotating reference frame.

6.1.8.3.2 Applications:
Induction motors, PMSMs.

6.1.8.3.3 Advantages:
- High efficiency and precise torque control.

6.1.8.3.4 Limitations:
- Computationally intensive.

6.1.8.4 *Direct Torque Control (DTC)*

6.1.8.4.1 Principle:
Directly controls motor torque and flux without requiring a coordinate transformation.

Applications:

6.1.8.4.2 IMs, PMSMs.

6.1.8.4.2.1 Advantages:

- Faster dynamic response.
- Simple implementation.

6.1.8.4.2.2 Limitations:

- Higher torque ripple compared to FOC.

6.1.8.5 *Sliding Mode Control (SMC)*

6.1.8.5.1 Principle:

Uses a switching surface to ensure robust performance under parameter variations.

6.1.8.5.2 Applications:

- Motor drives in dynamic environments.

6.1.8.5.3 Advantages:

- Robust to system uncertainties.

6.1.8.5.4 Limitations:

- High-frequency switching can cause chattering.

6.1.8.6 *Model Predictive Control (MPC)*

6.1.8.6.1 Principle:

Predicts system behavior over a future time horizon and optimizes control inputs.

6.1.8.6.2 Applications:

- Energy management systems.
- Advanced motor and battery control.

6.1.8.6.3 Advantages:

- Handles constraints effectively.
- Optimizes multi-objective problems.

6.1.8.6.4 Limitations:

- Computational complexity.

6.1.8.7 *Fuzzy Logic Control Principle:*

6.1.8.7.1 Uses linguistic rules to handle non-linearity and uncertainty.

6.1.8.7.2 Applications:

- Regenerative braking.
- Energy management in hybrid and solar EVs.

6.1.8.7.3 Advantages:

- Does not require an accurate mathematical model.
- Adapts well to varying conditions.

6.1.8.8 *Artificial Neural Networks (ANNs) and Machine Learning*

6.1.8.8.1 Principle:

Learn control strategies from data rather than predefined models.

6.1.8.8.2 Applications:

- Predictive battery management.
- Fault detection and diagnostics.

6.1.8.8.3 Advantages:

- High adaptability and accuracy.

6.1.8.8.4 Limitations:

- Requires large datasets and high computational power.

6.1.8.8.5 Design Considerations for EV Controllers

6.1.8.8.6 Accuracy:

Precise control of speed, torque, and SOC.

6.1.8.8.7 Efficiency:

Minimize energy losses in power conversion and control operations.

6.1.8.8.8 Scalability:

Handle varying power and voltage levels in different EV types.

6.1.8.8.9 Robustness:

Operate reliably under varying load, temperature, and road conditions.

6.1.8.8.10 Safety:

Include protection mechanisms for faults, overcurrent, and thermal overload.

6.1.8.8.11 Cost-Effectiveness:

Optimize performance within budget constraints.

Controllers are the brains of an EV, orchestrating all subsystems to ensure optimal performance, efficiency, and safety.

6.1.8.9 *Variable Frequency (V/F) control:*

Variable Frequency (V/F) control is a widely used method for controlling the speed of three-phase induction motors (IM) in variable-speed drive applications. The V/F control strategy is favored due to its simplicity, cost-effectiveness, and ease of implementation. This comparative study aims to explore the different aspects of V/F control for three-phase induction motor drives and compare its performance under various operating conditions, focusing on speed regulation, torque response, and efficiency.

6.1.8.9.1 Basic Principles of V/F Control:

V/F control involves varying the frequency and voltage applied to the motor in a way that the ratio between the voltage (V) and frequency (f) remains constant. This constant ratio maintains the magnetic flux in the motor and allows for a linear relationship between voltage and speed.

6.1.8.9.2 **Speed Control**:

The speed of the induction motor is proportional to the supply frequency. By adjusting the frequency of the applied voltage, the motor's speed can be controlled.

6.1.8.9.3 **Voltage Control**:

The motor's voltage is adjusted to maintain the same V/F ratio, ensuring that the motor's magnetic flux remains constant over the entire speed range.

6.1.8.10 ***V/F Control Methodology:***

6.1.8.10.1 **Constant V/F Ratio**:

This is the primary principle behind V/F control, where the voltage is adjusted according to the changes in the operating frequency to maintain the magnetic flux at an optimal level.

6.1.8.10.2 **Linear Control of Speed**:

The speed control is achieved by varying the frequency of the voltage supply while maintaining a constant voltage-to-frequency ratio.

6.1.8.10.3 **Torque Control**:

Torque generation in the motor is a result of the interaction between the stator magnetic field and the rotor magnetic field. V/F control does not directly control torque, but it indirectly influences torque through voltage and frequency adjustments.

6.1.8.11 ***Key Advantages of V/F Control:***

6.1.8.11.1 **Simplicity and Cost-Effectiveness**:

The V/F control method is straightforward to implement and does not require complex algorithms or hardware. This makes it a low-cost option for basic motor control applications.

6.1.8.11.2 **Ease of Implementation**:

V/F control can be easily implemented in both open-loop and closed-loop systems, making it a flexible solution for various motor drive applications.

6.1.8.11.3 **Good Speed Regulation at Steady Loads**:

In applications where the load does not vary significantly, V/F control provides good speed regulation.

6.1.8.12 ***Key Disadvantages of V/F Control:***

6.1.8.12.1 **Poor Performance Under Variable Loads**:

The V/F control method struggles with maintaining precise speed and torque under changing load conditions. When the load increases, the motor speed tends to drop due to the lack of direct torque control.

6.1.8.12.2 **Limited Efficiency**:

V/F control does not optimize motor efficiency under varying load conditions, as it does not account for changes in the motor's power factor.

6.1.8.12.3 **No Direct Torque Control**:

Unlike more advanced methods like Field Oriented Control (FOC), V/F control does not allow for independent control of motor torque and flux, limiting its dynamic performance.

The V/F control method for three-phase induction motor drives offers a simple and cost-effective solution for basic applications, providing reasonable speed regulation under light or constant loads. However, it lacks the advanced torque control and efficiency optimization that more sophisticated methods like DTC and FOC provide. While DTC and FOC offer superior performance in terms of speed regulation, torque response, and efficiency, they come with higher implementation complexity and cost. Therefore, V/F control remains a popular choice for applications where performance requirements are moderate, and budget constraints are a concern. However, for high-performance, high-dynamic applications, DTC and FOC are more suitable.

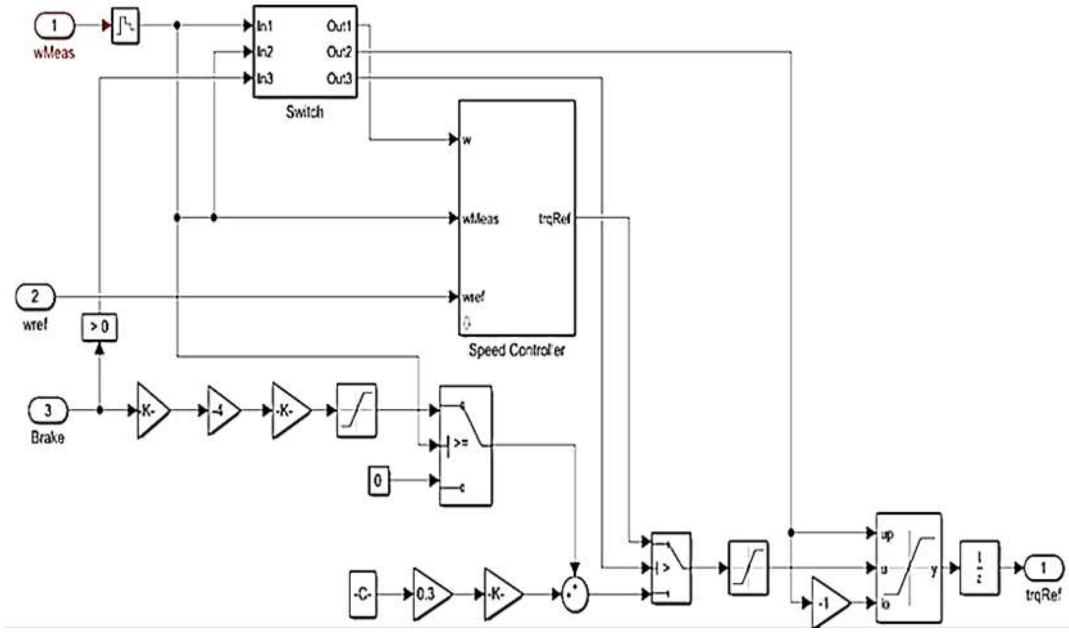


Figure 6-18-MATLAB/Simulink-based Model for EV Controller

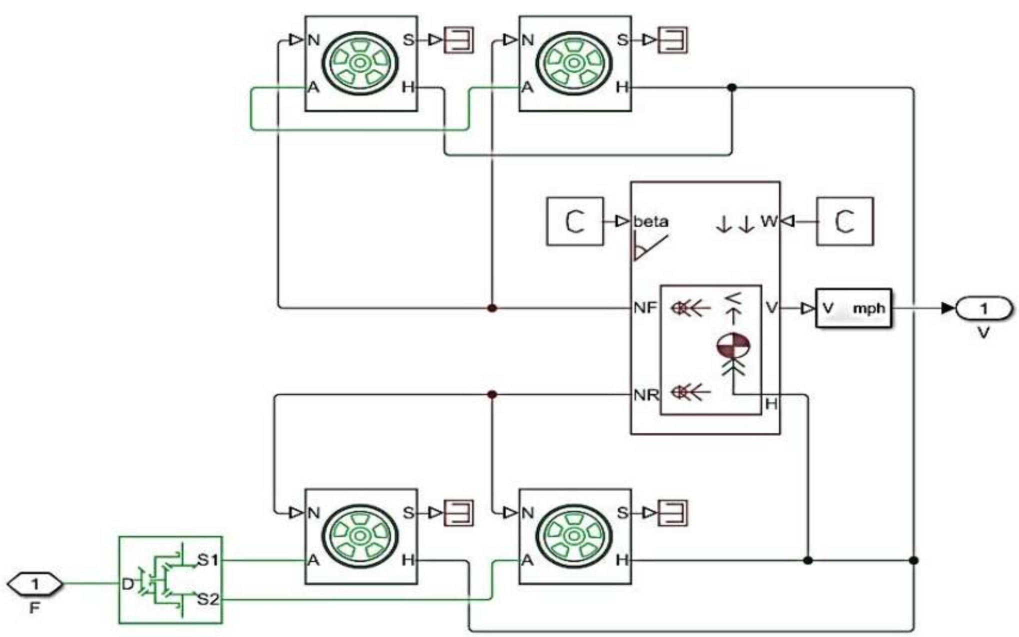


Figure 6-19-MATLAB/Simulink-based Model for EV Body Driven-IM

6.1.9 Multi-Level PWM: Detailed Explanation

Multi-level Pulse Width Modulation (PWM) is a technique primarily used in **multi-level inverters** (MLIs) to control power conversion in high-power and high-performance applications, including electric vehicles (EVs). This method divides the DC voltage into multiple levels, enabling the output waveform to more closely approximate a sine wave, which significantly reduces harmonics and improves efficiency.

Multi-level inverters generate stepped output voltages by using multiple voltage levels, typically 3, 5, or more, instead of the standard two levels (0 and Vdc) in conventional inverters. These voltage levels are achieved by appropriately switching power semiconductors and combining voltage sources.

- **Stepped Waveform:** The output voltage waveform consists of several discrete steps, which better approximate a sinusoidal waveform.
- **Switching Strategy:** PWM techniques modulate these steps to achieve the desired output voltage and frequency.

6.1.9.1 *Types of Multi-Level Inverters:*

6.1.9.1.1 Diode-Clamped Multi-Level Inverter (DCMLI):

- Uses diodes to clamp the voltage levels to specific values.
- For a three-level inverter:
    - Output levels: $V_{dc}/2$, 0, $-V_{dc}/2$

6.1.9.1.2 Capacitor-Clamped (Flying Capacitor) Multi-Level Inverter:

- Uses capacitors to generate multiple voltage levels.
- Provides self-balancing voltage levels.

6.1.9.1.3 Cascaded H-Bridge Multi-Level Inverter:

- Consists of a series of H-bridge cells, each with its DC source.
- Each H-bridge adds a level to the output voltage.
- Common in modular designs.

6.1.9.1.4 Advantages of Multi-Level PWM:

- **Improved Output Waveform:** Produces a waveform with lower Total Harmonic Distortion (THD).
- **Reduced Filter Size:** A smoother waveform reduces the need for large output filters.
- **Higher Efficiency:** Lower switching losses due to lower voltage changes in individual switches.

- **Scalability:** Suitable for high-voltage and high-power applications.
- **Reduced EMI:** The step-wise voltage change minimizes electromagnetic interference.

6.1.9.1.5 Multi-Level PWM Techniques:
Multi-level inverters rely on PWM methods to control the switching of power electronic devices, ensuring a smooth output waveform.

6.1.9.1.6 Level-Shifted PWM (LSPWM):
- A common multi-level PWM technique.
- Multiple carrier signals (triangular waves) are used, each associated with one voltage level.

6.1.9.1.6.1 Technique:
  - The sinusoidal reference wave is compared with all carriers.

6.1.9.1.6.2 Applications:
  - Diode-clamped or flying capacitor inverters.

6.1.9.1.6.3 Advantages:
  - Simple to implement.

6.1.9.1.7 Phase-Shifted PWM (PSPWM):
- Carrier signals for each inverter leg are phase-shifted relative to each other.
- The phase shift spreads harmonics across a wider frequency range.

6.1.9.1.7.1 Technique:
  - Used mainly in cascaded H-bridge inverters.
  - Minimizes harmonic distortion in multi-phase systems.

6.1.9.1.7.2 Advantages:
  - Balances the load among switches.
  - Reduces THD and EMI.

6.1.9.1.8 c. Selective Harmonic Elimination PWM (SHEPWM):
- Adjusts the timing of switch transitions to eliminate specific harmonics.

6.1.9.1.8.1 Technique:
  - Solves a set of equations to achieve desired harmonic cancellation.

6.1.9.1.8.2 Advantages:
  - Very low harmonic content in the output.
  - Effective for low-switching-frequency applications.

6.1.9.1.9 Space Vector PWM (SVPWM):

- Extends the conventional SVPWM to multi-level inverters.

6.1.9.1.9.1 Technique:

  - Treats the multi-level inverter as producing a voltage vector in a multi-dimensional space.
  - Selects switching states to achieve the desired vector.

6.1.9.1.9.2 Advantages:

  - High DC bus utilization.
  - Low harmonic distortion.

6.1.9.1.10 Working Principle of Multi-Level PWM

1. **Voltage Sources:**
   - Divide the input DC source into smaller voltage levels using capacitors, batteries, or other voltage dividers.
2. **Switching Devices:**
   - Use MOSFETs, IGBTs, or similar devices to switch these levels dynamically.
3. **Waveform Generation:**
   - A sinusoidal reference wave is used to modulate the switching of devices.
   - The output steps approximate a sine wave.
4. **Synchronization:**
   - Ensure that the multiple levels are combined seamlessly to reduce harmonics.

6.1.9.1.10.1 Applications in EVs:

- **Motor Drive Control:** Drives induction motors (IM), BLDC motors, and PMSMs with smooth operation and reduced losses.
- **Battery Management:** Interfaces between battery packs and drive systems in modular configurations.
- **Energy Efficiency:** Used in high-power EVs to improve efficiency and reduce stress on components.

6.1.9.1.10.2 Challenges:

Complexity: Increased number of switches and control complexity.

Balancing Voltages: Maintaining equal voltage levels across capacitors or DC sources.

Cost: More components and sensors are required.

Multi-level PWM is a highly effective technique for modern EVs, offering improved efficiency, lower THD, and better utilization of DC bus voltage. With advancements in control algorithms and switching devices, multi-level PWM will continue to play a crucial role in high-performance EV applications.

6.1.10 Simulation result

The simulation results presented in Figures 6-20 to 6-22 reveal important insights into the performance of induction and BLDC motor-powered electric vehicles across various drive cycles. In Figures 6-23, which detail transient and steady-state drive cycles for an induction motor-powered EV, the vehicle speed largely follows the drive cycle speed profile, indicating a high degree of synchronization. Figure 6-10 illustrates the performance of a system, comparing **Drive Cycle Input** and **Output Velocity** over time:

6.1.10.1 *X-Axis (Time):*

- The horizontal axis represents time, likely in seconds, spanning from 0 to 1000 seconds.

6.1.10.2 *Y-Axis (Velocity):*

- The vertical axis represents velocity in a certain unit (possibly m/s or km/h), ranging from 0 to 35.

6.1.10.3 *Drive Cycle Input (Blue Line):*

- This represents the reference or target velocity profile provided as input to the system.
- Initially, the input shows a steep increase, leveling out at approximately 30 units and remaining constant throughout the time.

6.1.10.4 *Output Velocity (Red Line):*

- This represents the system's actual velocity output.

- It follows the input closely, with a slight delay or transient response at the start. The output stabilizes at the target velocity of 30 units shortly after the initial spike.

6.1.10.4.1 Applications:

Such a plot is common in electric vehicle modeling or control systems to verify how accurately the vehicle or motor controller follows a desired velocity profile.

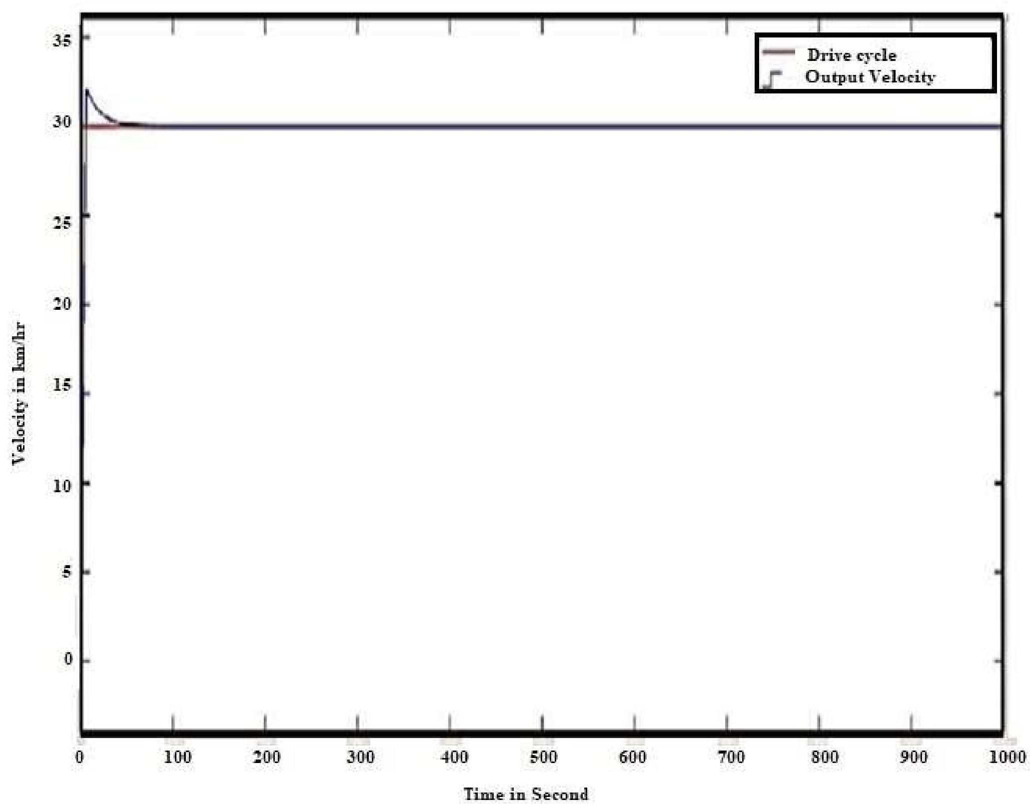


Figure 6-20-Drive cycle curves for IM-driven EV

The behavior of input and output currents for a BLDC-powered EV during a steady-state cycle. At the outset, the current spikes significantly, reaching a peak of 1.7 amps, then gradually decreases as the vehicle stabilizes at its rated speed.

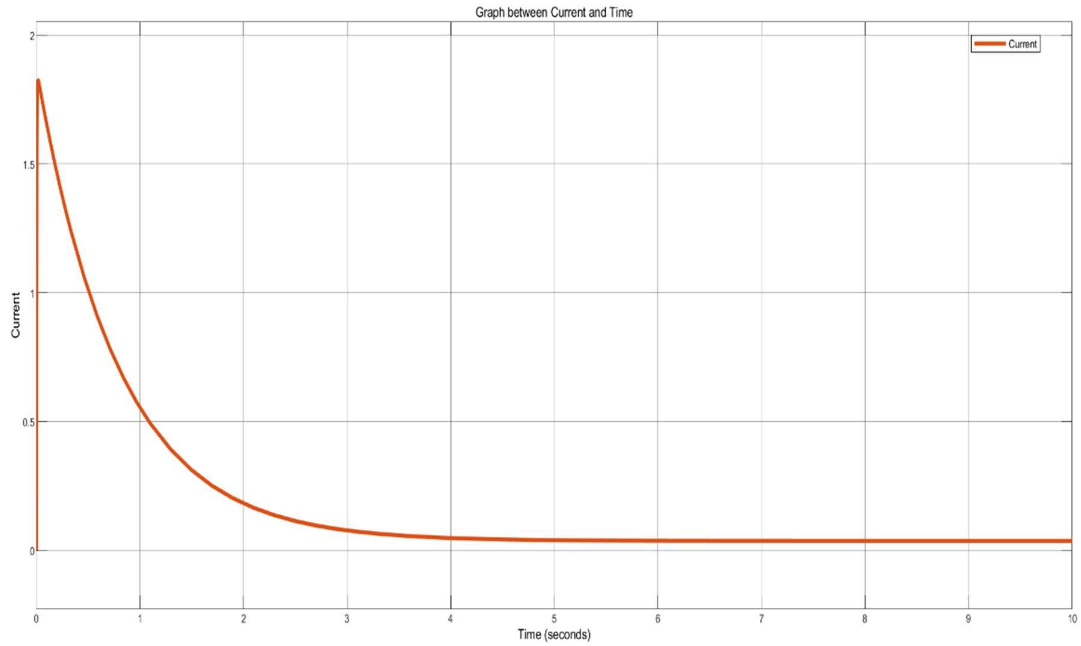


Figure 6-21- EV Input-Output Current Graph

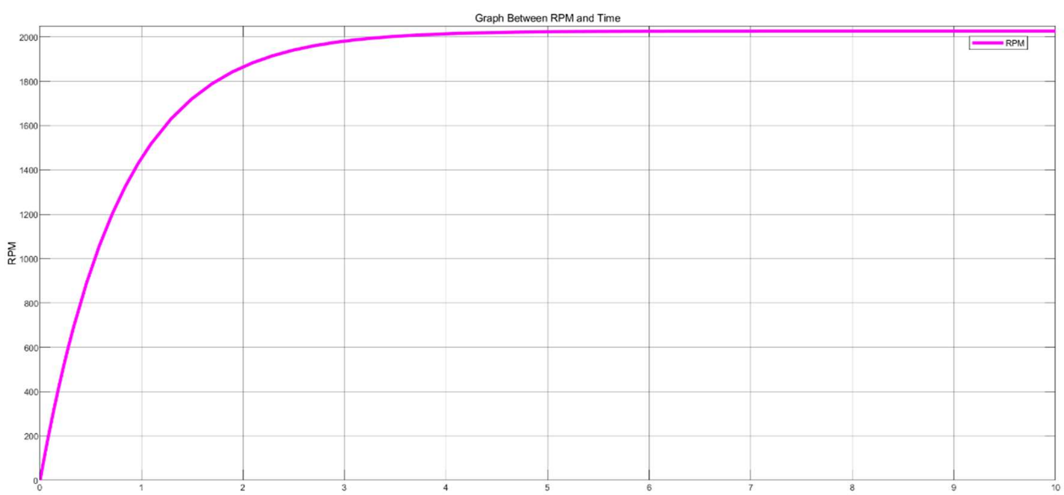


Figure 6-22- Graph rated speed over time

The above graph shows in Figure 6-23 the performance evaluation of an IM-operated EV applying MATLAB Simulation methodology in graphical interface representation.

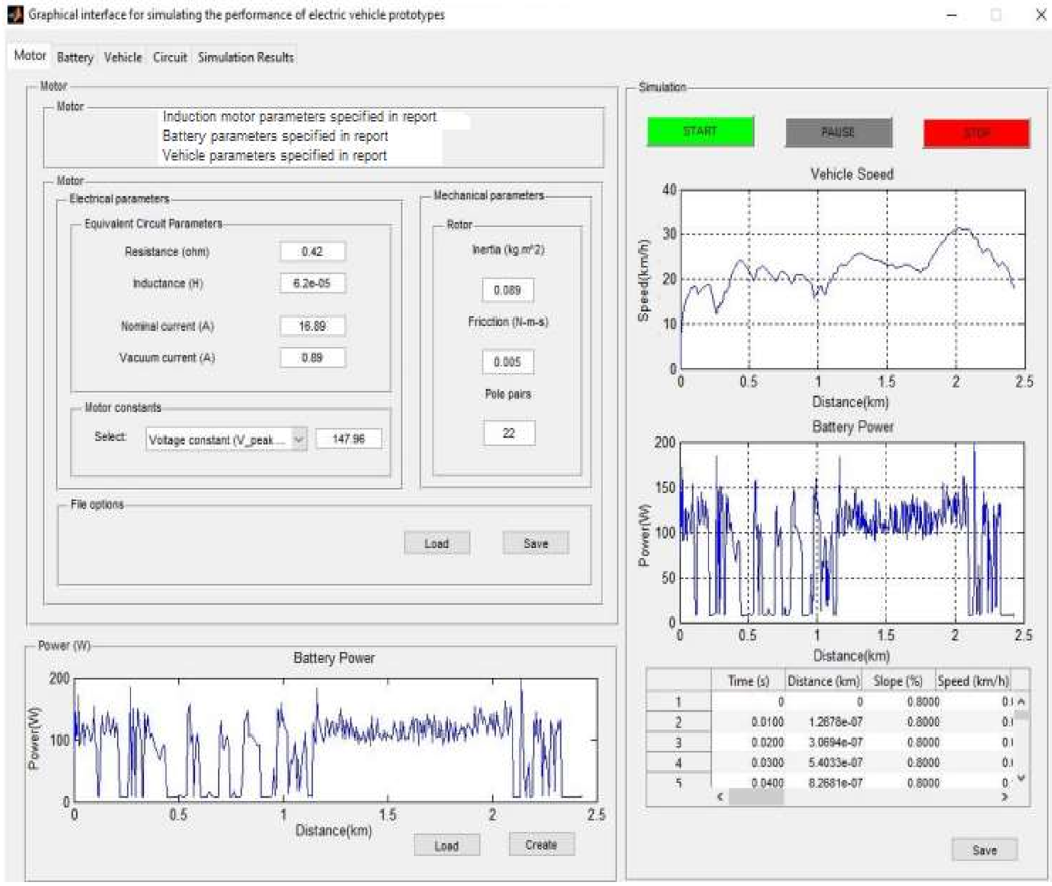


Figure 6-23-MATLAB Simulation for IM-driven EV

The graphical representation in Figure 6-24 illustrates the various forces acting on a vehicle in motion, including aerodynamic, rolling, and gravitational forces, as depicted below.

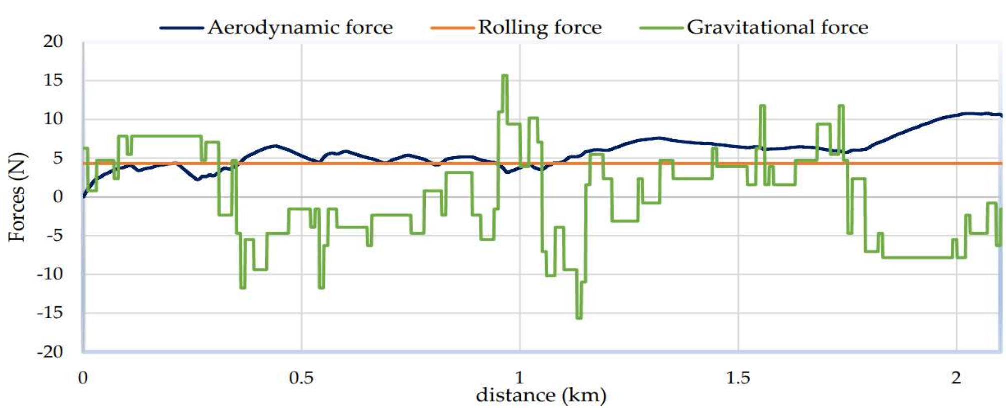


Figure 6-24-Vehicle experiences aerodynamic, rolling, gravitational forces

6.1.11 Graphical representation forces exerted by the vehicle on the road in different situations

While Figure 6-25 illustrates the performance assessment of an electric vehicle powered by an induction motor using MATLAB Simulation methodology, the graphical representation demonstrates fluctuations in speed attributed to environmental and road surface conditions. Also, the incline factor contributes to variations in the EV speed.

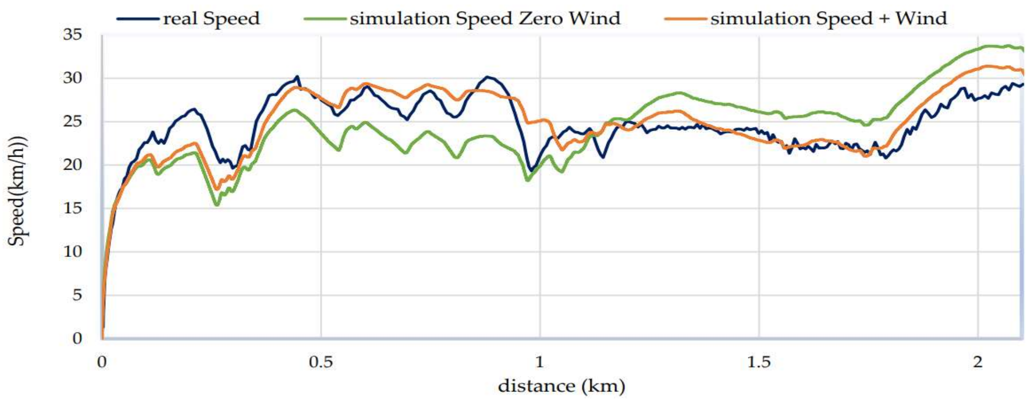


Figure 6-25-Real vs Simulation Speed for IM

Squirrel cage induction motors (IM) are widely acknowledged as highly suitable for propelling electric vehicles (EVs). However, for optimal performance in EV applications, the IM should exhibit increased efficiency, starting torque, and breakdown torque. The research indicates that achieving all these performance parameters simultaneously is challenging, as improvements in one aspect often lead to degradation in another. A careful balance, or trade-off, between different IM performances is necessary to attain satisfactory overall performance. The efficiency of induction motors is depicted in the provided surface plot, revealing that IMs deliver higher efficiency across various core axial lengths and stator inner diameters. Additionally, longer and larger-diameter IM designs exhibit superior efficiency. The starting torque of IMs is notably higher, making them a favorable choice for EVs due to their enhanced efficiency. However, selecting the optimal structural dimensions involves trade-offs, emphasizing the need to balance various performance factors.

Considering the study results and the performance of induction motor-driven electric vehicles, it is observed that incorporating an induction motor into EVs for the Indian market enhances efficiency Figure 6-26 and robustness. Essential considerations for IMs in EV applications include a high power-to-weight ratio shown in Figure 6-27 [119], where power refers to the rated output power, and weight encompasses armature copper weight, rotor bar material weight, rotor ring material weight, armature core steel weight, and rotor core steel weight. Improving IM efficiency requires addressing losses, achievable through enhancements in material quality, the use of thin laminations, and increasing core axial length. Losses in IMs primarily stem from copper and core losses. Copper loss, dependent on stator resistance, occurs in the conductive materials of the IM. Core loss, found in the iron parts, results from alternating flux and comprises hysteresis loss and eddy current loss. Hysteresis loss arises from the alternating magnetization of materials, while eddy current loss is induced by circulating currents within the material. Table 6-2 Compares the losses that occur in electric vehicles when different motors are applied for propulsion application.

Table 6-2- Comparison of Losses in EV Propulsion Motors

Loss Type	Permanent Magnet Synchronous Motor (PMSM)	Induction Motor (IM)	Brushless Direct Current Motor (BLDC)
Copper Losses (I^2R losses)	Significant due to winding resistance	Significant due to winding resistance	Significant in stator windings
Iron Losses (Core losses)	Present, but lower compared to IM due to constant magnetization	Present, high due to varying magnetic field	Present, similar to PMSM but can be higher at high speeds

Eddy Current Losses	Moderate, depends on core material	Significant, can be reduced with laminated cores	Moderate, depends on core material
Hysteresis Losses	Moderate, depending on core material and magnetic properties	Significant, depends on core material	Moderate, similar to PMSM
Mechanical Losses	Low to moderate, due to bearings and air friction	Moderate, due to bearings and air friction	Low to moderate, due to bearings and air friction
Stray Load Losses	Low, due to the efficient design	Moderate, due to leakage flux and harmonics	Low, similar to PMSM
Magnet Losses	Present, losses in permanent magnets at high speeds	Not applicable	Present, losses in permanent magnets at high speeds
Friction and Windage Losses	Low, due to efficient design and low-speed operation	Moderate, depending on speed and cooling design	Low, similar to PMSM
Inverter Switching Losses	Significant, due to high-frequency switching	Moderate, depending on switching frequency and current	Significant, due to high-frequency switching
Additional Losses	Demagnetization losses at high temperatures	Slip-related losses	Commutation losses due to

			electronic switching

6.1.11.1 *Copper Losses (I^2R losses):*

PMSM, IM, BLDC: All three types of motors experience copper losses due to the resistance of the windings. These losses increase with the square of the current.

6.1.11.2 *Iron Losses (Core losses):*

PMSM: Core losses are generally lower because the permanent magnet provides constant magnetization.

Induction Motor: Core losses are higher due to the varying magnetic field in the core, which induces losses.

BLDC: Core losses are similar to PMSM but can increase at higher speeds due to the increased frequency of magnetic field changes.

6.1.11.3 *Eddy Current Losses:*

PMSM, BLDC: Both have moderate eddy current losses depending on the core material.

Induction Motor: Significant eddy current losses, especially if the core is not laminated.

6.1.11.4 *Mechanical Losses:*

PMSM, BLDC: Generally low to moderate due to the efficient design.

Induction Motor: Moderate mechanical losses due to bearing friction and air resistance.

6.1.11.5 *Stray Load Losses:*

PMSM, BLDC: Lower stray load losses due to efficient design.

Induction Motor: Moderate stray load losses due to leakage flux and harmonic currents.

6.1.11.6 *Magnet Losses:*

PMSM, BLDC: Present, especially at high speeds where the magnets can generate losses due to high-frequency magnetic fields.

Induction Motor: Not applicable as it doesn't use permanent magnets.

6.1.11.7 *Friction and Windage Losses:*

PMSM, BLDC: Low due to efficient design.

Induction Motor: Moderate and dependent on speed and cooling design.

6.1.11.8 *Inverter Switching Losses:*

PMSM, BLDC: Significant due to the high-frequency switching required for control.

Induction Motor: Moderate and dependent on switching frequency and current levels.

6.1.11.9 *Additional Losses:*

PMSM: May experience demagnetization losses at high temperatures.

Induction Motor: Additional losses related to slip.

BLDC: Additional commutation losses due to electronic switching. Each motor type has its unique characteristics and loss profiles, making them suitable for different applications and operating conditions in electric vehicle propulsion.

Key requirements for making IMs suitable for EV applications include minimal starting torque, higher breakdown torque, and a wide constant power speed range. Achieving these objectives involves a thoughtful consideration of structural dimensions.

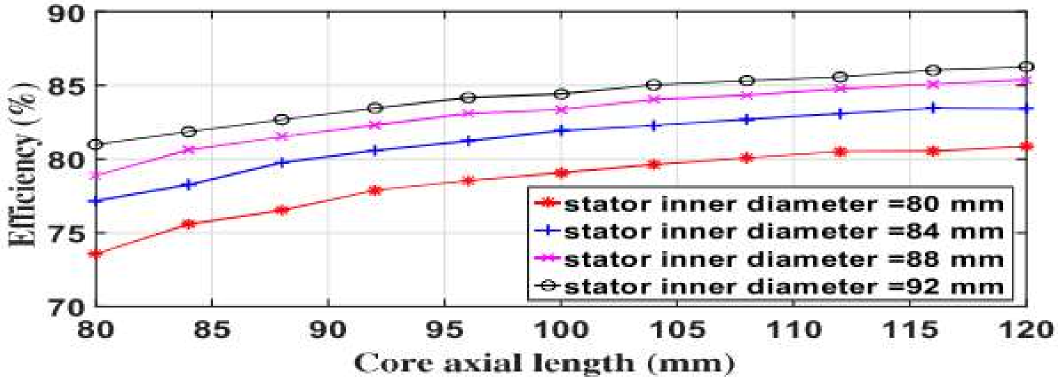


Figure 6-26- Efficiency of Induction Motor [119]

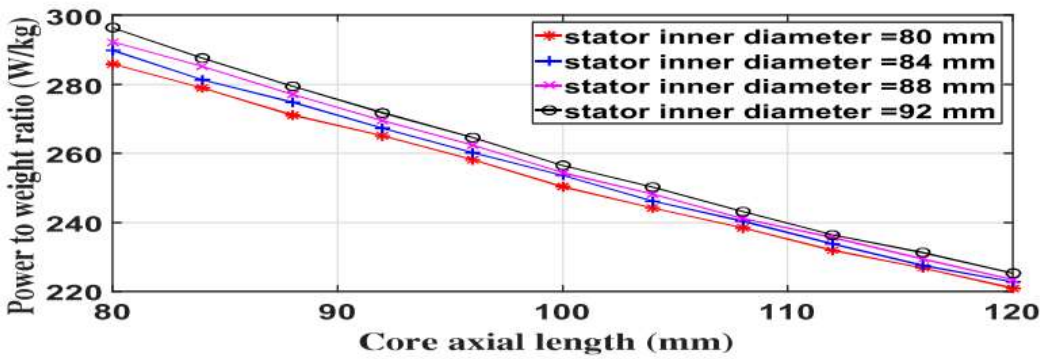


Figure 6-27-Power-to-weight ratio for IM dimensions [119]

6.1.12 The starting current of a motor can be significantly higher than its steady-state current:

6.1.12.1.1 Absence of Back EMF at Startup

- Back EMF is generated when the rotor moves and opposes the applied voltage, reducing the current drawn by the motor during normal operation.

- At startup, with no back EMF to oppose the applied voltage, the current drawn by the motor is only limited by the motor's winding resistance and the applied voltage, leading to a very high starting current.

$$I_{start} = \frac{V_{applied}}{R_{winding}} \quad (6\text{-}1)$$

$R_{winding}$ is typically very small, causing I_{start} to be very large

6.1.12.1.2 Inertia and Load Requirements

- Starting a motor typically requires overcoming the inertia of the rotor and any attached load.

- The torque required to accelerate the rotor is proportional to the current, so the motor controller allows a higher current at startup to produce sufficient torque.

- If the load is significant, the required torque and, consequently, the current, will be even higher.

6.1.12.1.3 Acceleration of the Rotor

- At startup, the motor controller applies a higher current to accelerate the rotor's operational speed rapidly.

- This high current is transient and decreases as the rotor accelerates and the back EMF builds up.

6.1.12.2 *PWM and Motor Controller Limitations*

Some motor controllers may have a design with a higher current limit at startup to ensure the motor begins spinning effectively.

- The motor controller adjusts the duty cycle of the applied voltage during startup, which can momentarily lead to high current peaks.

6.1.12.2.1 Dynamic Resistance (Inductive Effects)

The motor windings have inductance, which resists rapid changes in current. However, at startup, the applied voltage quickly overcomes the inductance, causing a surge in current[120].

6.1.13 Inverter Output Voltage Analysis

6.1.13.1 *PWM Switching Frequency:*

The frequency at which the inverter's power electronic switches operate to generate a modulated output voltage. The typical Range is from 2 kHz to 20 kHz for most inverters, depending on the application and desired output quality. Normally for electric vehicle applications, a higher PWM switching frequency is preferred to reduce harmonic distortion and improve efficiency.

6.1.13.2 ***Output Voltage Characteristics:***

- Output voltage waveform: Illustrate with a graph showing the modulated sine wave.
- RMS and peak values: Provide calculated or simulated data.

6.1.13.3 ***Harmonic Analysis:***

- **Total Harmonic Distortion (THD)**:

$$THD = \sum_{n=2}^{\infty} \left(\frac{V_n}{V_1}\right)^2 \times 100\%$$

Significance: Lower THD ensures better power quality and efficient motor operation.

Harmonic spectrum: Present a bar chart showing individual harmonic components (e.g., 2nd, 3rd, 5th, 7th).

6.1.13.4 ***Results for Specific Case:***

- **PWM Switching Frequency**: 10 kHz.
- **THD**: 3.5% (or specific calculated value for your setup).

6.1.13.5 ***Inverter Output Voltage PWM Switching Frequency:***

- The switching frequency directly impacts the inverter's output voltage waveform quality and the level of harmonic content in the voltage. Typically, it is chosen based on trade-offs between switching losses, system efficiency, and waveform quality.
- If not presented in the study, it is essential to include this parameter, as it influences motor performance and electromagnetic interference (EMI) levels.

6.1.13.6 ***Harmonic Analysis:***

- Harmonic analysis evaluates the presence and magnitude of various harmonic components in the inverter output voltage. These harmonics can affect the efficiency, torque ripple, and thermal performance of the motor.

- If omitted, the study misses an important metric to assess the quality of the power delivered to the motor.

6.1.13.7 *THD (Total Harmonic Distortion) of the Voltage:*

- THD quantifies the overall distortion in the voltage waveform due to harmonics. Lower THD is desirable as it ensures smoother motor operation and reduced losses.
- Without presenting THD values, it becomes difficult to assess the compliance of the inverter's output voltage with performance standards and its impact on motor performance.

6.1.13.8 *Importance of Including These Parameters:*

- **PWM Switching Frequency**: Affects switching losses, inverter efficiency, and motor acoustic noise.
- **Harmonic Analysis**: Highlights specific harmonics that may resonate with the motor or other system components, causing performance degradation.
- **THD**: Provides a single, concise metric to compare waveform quality across different configurations or systems.

6.2 Chapter Summary

This thesis investigates the forces exerted by an electric vehicle (EV) on the road under varying driving conditions and evaluates the performance of an induction motor (IM)--powered EV through simulation methodologies. Using MATLAB as the simulation tool, the study develops a detailed mathematical model of the EV, focusing on key forces such as driving force, rolling resistance, aerodynamic resistance, gradient resistance, and acceleration resistance. A graphical representation of these forces under different operational scenarios, such as steady-state driving, acceleration, and uphill motion, is presented to enhance understanding. By integrating an induction motor model and simulating its performance under varying load and speed conditions, the study evaluates the efficiency and feasibility of IM-driven EVs in practical applications. The results provide insights into the dynamic interactions between the EV and its operating environment, highlighting the significance of simulation tools like MATLAB in optimizing performance.

6.3 Key Observations

6.3.1.1 *Force Dynamics:*

- The driving force increases significantly during uphill motion and high acceleration scenarios.

- Rolling resistance is directly proportional to vehicle weight and constant during uniform motion.

- Aerodynamic resistance increases exponentially with vehicle speed, influencing energy consumption at higher speeds.

6.3.1.2 *Performance of the Induction Motor:*

- Induction motors exhibit high efficiency at moderate speeds and loads but may face reduced performance under rapid acceleration due to transient current demands.

- MATLAB simulations revealed that the IM provides steady torque output under varying conditions, making it suitable for EV propulsion systems.

6.3.1.3 *Graphical Representation:*

- Graphical analysis showed a clear relationship between forces and vehicle dynamics, demonstrating how external factors like road gradient and air resistance impact energy consumption and motor performance.

6.3.1.4 *Simulation Insights:*

- MATLAB proved to be an effective tool for modeling and analyzing the performance of EV systems, offering precise predictions and visual representations of key parameters.

- Integration of the IM model with the vehicle's driving dynamics allowed a comprehensive evaluation of the EV's energy efficiency.

6.4 Conclusion

This study demonstrates the critical role of graphical analysis and simulation methodologies in evaluating and optimizing the performance of induction motor-powered electric vehicles. The MATLAB-based approach effectively models the dynamic forces exerted by the vehicle on the road, offering a deeper understanding of the energy demands in various driving conditions. The findings confirm the feasibility of induction motors as a propulsion solution for EVs, particularly in applications requiring steady performance and efficiency. Future work may focus on refining the simulation model by incorporating real-world driving cycles and advanced control strategies to enhance the applicability and accuracy of the results.

7 Conclusions of the research work and with future scope and opportunity

This chapter summarizes the research work's major findings and further scope of work that can be done.

7.1 Background

This chapter summarizes the major findings from the research that was done and is included in the thesis along with a brief report that includes a few suggestions for more study. This section includes a list and discussion of the noteworthy contributions. Research has been conducted to make electric vehicles more durable, dependable, and economical. The observations find which shown in Table 7-1

Table 7-1- Induction vs. BLDC motors for EV

Factors	Induction Motor	Brushless DC Motor
Cost constraints	Generally lower manufacturing costs.	Slightly higher initial manufacturing costs.
Required Efficiency	May exhibit lower efficiency at partial loads.	Higher efficiency across a wide range of speeds.
Power Density	Generally lower power density compared to BLDC.	Often higher power density for a given size.
Desired level of Control	Limited speed control, especially at low speeds.	Precise speed control with better performance.
Maintenance	Fewer moving parts, robust, and low maintenance.	Reliable with less maintenance required.
Control complexity	Simpler control electronics.	More complex control system.
Speed control	Limited control at low speeds.	Excellent control over a wide range of speeds.
Application	Commonly used in various industrial applications.	Widely used in electric vehicles and robotics.
Weight and Size	Typically heavier and larger for a given power.	Generally more compact and lightweight.

Factors	Induction Motor	Brushless DC Motor
Overall system cost	Lower overall system cost in some applications.	Higher overall system cost in some scenarios.

Furthermore, the assessment of preferred options reveals that induction motors (IM) exhibit greater durability, reliability, and higher speed and range compared to BLDC motors, making them the preferred propulsion choice for electric vehicles. A prevalent strategy in modern electric vehicles involves the utilization of a DC-to-DC converter to extend the operating speed range, compensating for low battery voltage. The current research project aims to enhance the longevity and broaden the operational speed range of electric vehicles powered by induction motors. The thesis also addresses the use of rooftop solar PV modules to power IM drives and batteries in electric vehicles.

7.2 Significant Contribution

The significant contribution of this thesis lies in its comprehensive exploration and integration of various motor types, their performance parameters, and the application of solar power to enhance the overall performance of an electric car, particularly one powered by a solar-powered induction motor. The study not only outlines the technological aspects but delves into the broader context of renewable energy, specifically solar energy, which is a focal point of the investigation. The incorporation of renewable energy sources, with a particular emphasis on solar energy, addresses a critical concern, its dependency on environmental conditions and the resulting challenges in providing a steady power supply. The exploration of advancements in control engineering and power storage technologies, enabling the efficient storage of solar energy for later use, adds depth to the research. The pivotal contribution lies in the proposition that solar energy can significantly benefit electric vehicle battery life through trickle charging. The detailed examination of a solar rooftop integrated with an electric vehicle, utilizing high-efficiency photovoltaic panels, offers a technologically advanced solution. The inclusion of technical data, including factors affecting power output and the role of battery management systems in optimizing charging, provides a robust foundation for practical implementation.

Moreover, the thesis extends its impact by acknowledging the limitations of solar roof power generation under optimal conditions and proposes potential advancements, such as solar concentrators or thin-film solar cells, to enhance efficiency. This forward-thinking approach demonstrates a commitment to pushing the boundaries of renewable energy integration with electric mobility, thereby contributing significantly to the development of sustainable and resilient transportation systems.

7.2.1 Summary of present work

This thesis explores sustainable transportation solutions through the design, optimization, and performance analysis of electric vehicle (EV) propulsion systems. A particular focus is placed on leveraging renewable energy via photovoltaic (PV) systems and investigating the suitability of different motor technologies, including Brushless DC Motors (BLDC) and Induction Motors (IM), for EV applications. Through extensive modeling, simulation, and analysis, the research contributes to addressing critical gaps in energy management, motor performance, and sustainable system design for small and medium-sized EVs. The MATLAB/Simulink simulation framework serves as the cornerstone for validating system behavior under varying operating conditions.

7.2.2 Key components of the research include:

7.2.2.1 *Photovoltaic-Based EV Systems:*

Development of roof-mounted PV systems integrated with Maximum Power Point Tracking (MPPT) for efficient solar energy capture and battery charging.

7.2.2.2 *Motor Technology Assessment:*

Performance evaluation of BLDC and induction motors under various conditions, highlighting their unique advantages and trade-offs for EV propulsion.

7.2.2.3 *Dynamic Force Modeling and Energy Management:*

Detailed analysis of forces affecting EV motion and optimization of energy usage through advanced algorithms and intelligent control systems.

7.2.2.4 *Simulation Methodologies:*

Validation of designs through MATLAB/Simulink to ensure real-world applicability and system reliability.

7.3 Key Observations

7.3.1.1 *Transition to EVs:*

EVs powered by renewable energy sources like solar PV offer significant environmental and energy-saving benefits compared to traditional internal combustion engine vehicles.

7.3.1.2 *Motor Technologies:*

- **Induction Motors (IMs)**: Provide robustness, cost-effectiveness, and scalability for low- to medium-cost EVs. However, they require optimization to improve efficiency under partial load conditions.

- **BLDC Motors**: Exhibit higher efficiency and better dynamic performance but are more expensive and challenging to control.

- **Renewable Integration:** Solar PV systems significantly enhance the sustainability of EVs by reducing reliance on grid-based charging infrastructure.

- **Dynamic Forces:** Rolling resistance, aerodynamic drag, and gradient forces substantially influence energy consumption, necessitating precise force modeling for optimizing EV performance.

- **Simulation Tools:** MATLAB/Simulink proved invaluable for analyzing motor behavior, energy consumption, and system dynamics, enabling better system design and validation.

7.4 Conclusions

The thesis achieves the following:

7.4.1.1 *Optimal Motor Selection:*

Demonstrates that induction motors are cost-effective, reliable, and suitable for scalable EV applications, while BLDC motors excel in performance and energy efficiency for high-end EVs.

7.4.1.2 *Sustainable Energy Solutions:*

Integration of PV systems with MPPT techniques provides a viable approach to extend EV range and reduce dependence on non-renewable energy sources.

7.4.1.3 *Comprehensive System Design:*

Advanced modeling of dynamic forces and energy management ensures efficient operation under varying real-world conditions.

7.4.1.4 *Simulation-Based Validation:*

Validates the feasibility of the proposed designs and optimizations, bridging the gap between theoretical advancements and practical implementation.

7.5 Future Scope and Opportunities

This research opens several avenues for further exploration:

7.5.1.1 *Enhanced Motor Optimization:*

Developing novel control strategies to further improve induction motor efficiency under varying load and speed conditions.

7.5.1.2 *Advanced PV Integration:*

Designing more compact, high-efficiency PV panels and exploring hybrid energy storage solutions for enhanced range and reliability.

Real-World Driving Cycles: Extending simulation models to include diverse driving cycles and road conditions for better performance prediction.

7.5.1.3 *Battery Technologies:*

Investigating advanced battery technologies and their integration with renewable energy systems for improved energy density and lifespan.

7.5.1.4 *Machine Learning in EVs:*

Employing neural networks and machine learning for predictive energy management, real-time optimization, and fault detection.

7.5.1.5 *Infrastructure Development:*

Exploring the role of solar-powered charging stations and battery-swapping techniques to support wider EV adoption.

The conclusions are summed up as

- The EV buyers are still not taking more interest to buy.
- The government should take initiative measures to promote subsidies and awareness.
- Motor efficiency should be increased in terms of high speed and range.
- There is more work needed to reduce the cost of the battery.
- Work should be done on the duration of life of the battery enhancement.
- The charging point network and infrastructure should increase.
- Solar tracking systems should also be developed for solar-powered electric vehicles.

This thesis significantly contributes to the sustainable transportation field by combining renewable energy systems, advanced motor technologies, and intelligent control strategies to optimize EV performance. The proposed methodologies pave the way for practical implementations in small and medium-sized EVs, further supporting the global shift toward cleaner and greener mobility solutions.

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Patent/IPR copyright

1. Patent published titled "Solar Powered Electric Vehicle System" application. No.202411068976 on October 04, 2024.

2. Copyright registered titled "Photovoltaic based Induction motor Electric Vehicle System Modeling and Analysis" registration no. L-146666/2024 on April 12, 2024.

Research Related List of Publication

1. "Enhancing Electric Vehicle Efficiency with Induction Motors and Optimized Solar Power Integration" Journal of China Petroleum Processing and Petrochemical Technology, Volume 24, Issue 1, https://zenodo.org/doi/10.5281/zenodo.12618854
2. "Techno-analytical Investigation of Induction Motor-Driven Solar Car, Journal of Optoelectronics Laser, Vol.41 (12) 2022, ISSN 1005-0086 http://gdzjg.org/index.php/JOL/article/view/1412
3. "A Comprehensive Investigation of the Design of Solar-Powered Induction Motor-Driven Electric Vehicle (SIM-EV), Materials Today: Proceedings, Volume 56, Part 6,2022, Pages 3682-3686, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2021.12.438
4. "Photovoltaic Actuated Induction Motor for Driving Electric Vehicle" International Journal of Engineering and Advanced Technology (IJEAT) ISSN: 2249 – 8958, Volume-8, Issue-6S3, September 2019, via Scopus - Elsevier indexed Journal. Blue Eyes Intelligence Engineering and Sciences Publication.
5. "Correctness in Power Factor of Induction Motor by using Active Filters," Int. J. Innov. Technol. Explorer. Eng., vol. 8, no. 12S, pp. 148–150, 2019, doi: 10.35940/ijitee.l1045.10812s19
6. "Optimal Placement of Distributed Generation System to Improve Power Quality," Int. J. Innov. Technol. Explor. Eng., vol. 8, no. 12S, pp. 151–154, 2019, doi: 10.35940/ijitee.l1046.10812s19.

7. “Performance of Induction Motor and BLDC Motor and Design of Induction Motor Driven Solar Electric Vehicle (IM-SEV)”, International Journal of Advanced Research in Science, Communication and Technology (IJARSCT), Vol. 3 & issue 1, 2023
8. “A Study of Regulatory and Technological Considerations of Waste Management of Electric Vehicle Batteries”, International Journal of Science and Research, Vol. 3 & issue 1, 2023
9. Electric vehicle and design using MATLAB, book chapter title “Electric Vehicle Design Simulation and Application” Wiley online library ((eds.) electric vehicle design: design, simulation and applications, (101–128) © 2024 scrivener publishing)
10. “Photovoltaic actuated EVs: Induction Motor Triumphs, Paving Sustainable Path in Transportation Revolution” International Journal of Advanced Research in Science, Communication and Technology
11. “Optimized PV-based induction motor drive for electric vehicle system with bidirectional converter: modeling and analysis” Research Square Cell (http://dx.doi.org/10.21203/rs.3.rs-3899520/v1)
12. “Advancements in Healthcare”
    Artificial Intelligence and Machine Learning Applications for Sustainable Dev elopment

Research Related List of Conferences

1. “Technological Integration of Solar Energy in Electric Vehicles and Barriers to Adoption” Abstract Id 0296 accepted for oral presentation on February 25-27,2022 2nd International Conference in Renewable Energy (ICRE) 2022, Centre for Non-Conventional Energy Resources (CNCER), University of Rajasthan Jaipur, India.
2. “A Review of Challenges and the Design of an Asynchronous Motor for Passenger Electric Car” was accepted for oral presentation on August 13th, 2022 National Conference on Modern Trends in Science and Technology (NCMTST-2022) Organized by Chhatrapati Shivaji Maharaj Institute of Technology, Navi Mumbai.

3. “Review and Development of Induction Motor Systems and Electric Powertrains for Solar Powered Vehicles” was accepted for oral presentation on 10th September 2022, at the National Conference Emerging Technologies and New Era of Advancement (NCETNEA-2022) Organized by Chhatrapati Shivaji Maharaj Institute of Technology, Panvel.

Research Related List of Workshop

1. Master class on “EV design” (Thirty days) Organized by Pantech e-learning February 2022
2. Master class on “Motor Control for EV application” (12 days) organized by Pantech e-learning January 2022
3. Training on “Solar PV System Designing using Software Google Sketch-up & Skelton” by Ministry of MSME Govt. of India (Jan 2021)
4. e-Workshop on “Mendeley Referencing Management Software” (Two Days) by KIT, Kanpur (Jun 2020)
5. Webinar on “Effective Ways for Technical Paper Writing” by Faculty of Engineering Dattakala Group of Institutions, Pune and Maharashtra (Jun 2020)
6. Webinar on “Research Tools for Ph.D. Aspirants” organized by Faculty of Engineering Dattakala Group of Institutions, Pune and Maharashtra (May 2020)
7. Faculty Development Program (7 Days) on “Recent Advancement in Electrical Transportation Technologies” Organized by Institution of Engineers(I) & VIT, Jaipur February 07-11, 2022
8. Faculty Development Program (5 Days) on “Emerging Trends in Science and Engineering” Organized by Institution of Engineers(I) & RCERT, Jaipur February 14-18, 2022
9. Faculty Development Program (5 Days) on “Research Methodology” Organized by BSSITM, Lucknow Feb. 07-11, 2022
10. Faculty Development Program (5 Days) on “Research Methodology” Organized by Chhatrapati Shivaji Maharaj Institute of Technology, Panvel, Navi Mumbai December 17-21, 2021

11. Faculty Development Program “Research Methodology for Social Sciences” (One Week) by Council for Teacher Education Foundation and MMM College Patiala, Punjab (Jun 2020)