PERFORMANCE ANALYSIS OF HYBRID MICROGRID UNDER ISLANDING MODE

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2024

CERTIFICATE

This is to certify that the work reported in the Ph.D. thesis entitled "**PERFORMANCE ANALYSIS OF HYBRID MICROGRID UNDER ISLANDING MODE**" submitted in fulfillment of the requirement for the reward of degree of **Doctor of Philosophy (Ph.D.)** in the Department of Electrical Engineering, is a research work carried out by Kulkarni Mangesh Subhash 42000179, 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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DECLARATION

I, hereby declare that the presented work in the thesis entitled "**PERFORMANCE ANALYSIS OF HYBRID MICROGRID UNDER ISLANDING MODE**" in fulfilment of the degree of **Doctor of Philosophy (Ph. D.)** is an outcome of research work carried out by me under the supervision of Dr. Sachin Mishra, working as Professor, in the School of Electronics and Electrical Engineering of Lovely Professional University, Punjab, India and under the Co-supervision of Dr. Suresh Kumar Sudabattula, working as Associate Professor, in the School of Electronics and Electrical Engineering of Lovely Professional University, Punjab, India. In keeping with general practice of reporting scientific observations, due acknowledgements have been made whenever work described here has been based on findings of other investigator. This work has not been submitted in part or full to any other University or Institute for the award of any degree.

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Abbreviations

Renewable Energy Sources	RES
Islanding Detection Method	IDM
Rate of Change of Phase Angle Difference	ROCPAD
Intermittent-Bilateral Reactive Power Variation	IB-RPV
Hybrid Microgrid	HMG
Utility Grid	UG
Non-Detection Zone	NDZ
Distributed Generation	DG
Voltage Vector Shift	VVF
Rate of Change of Frequency	ROCOF
Dynamic Thermal Rating	DTR
Dynamic Line Rating	DLR
System Integrity Protection Schemes	SIPS
Rate of Change Voltage	ROCOV
rate of change of reactive power	ROCORP
Machine Learning	ML
Artificial Intelligence	AI
artificial neural networks	ANN
Support Vector Machine	SVM
Slip-Mode Frequency Shift	SMS
Active Frequency Drift	AFD
Sandia Frequency Shift	SFS
Reactive Power Variation	RPV
Microgrid	MG
Power Line Carrier	PLC
Low-Voltage	LV
Phasor Measurement Unit	PMU
Power Quality	PQ
Point of Common Coupling	PCC
Reactive Power	RP
Reactive Power Amplitude	Q_{dis} / $-Q_{dis}$
Resonance Frequency	f_0
Quality Factor	Q_f
Circuit Breaker	CB
Total Harmonic Distortion	THD
Transient Response Time	t_s
Islanding	IS
Intentional Islanding	I_i
Unintentional Islanding	U_i

Detection Time	T_D
Islanding Detection Methods	IDM
Distributed Energy Resources	DERs
Electrical Power System	EPS
Machine Learning	ML
Deep Learning	DL
Signal Processing	SP
Power Quality	PQ
Fuzzy Logic	FL
Kalman Filter	KF
Wavelet Transform	WT
Change of Angle Difference Method	CADM
Frequency Difference Method	FDM
Harmonic Injection	HI
Second Order General Integrator	SOGI
Rate of Change of Voltage	ROCOV
Rate of Change of frequency over Power	ROCOFoP
Rate of Change of Voltage over Power	ROCOVoP
Adaptive Neuro-Fuzzy Inference System	ANFIS
Micro Phasor Measurement Unit	MPMU
Power Line Carrier Communication	PLCC
Supervisory Control And Data Acquisition	SCADA
Over /Under Voltage	OUV
Over / Under Frequency	OUF
Modified Sandia Voltage Shift	MSVS
High Voltage Direct Current	HVDC
Pulse Width Modulation	PWM
Total Harmonic Distortion of Voltage	THDv
Total Harmonic Distortion of current	THDi
Slip Mode Shift	SMS
Slip Mode Frequency Shift	SFS
Automatic Phase Shift	APS
Fourier Transform	FT
Discrete Fourier Transform	DFT
Stockwell Transform	ST
Phaselet Transform	PT
Time Time Transform	TTT
Variation Mode Decomposition	VMD
Empirical Mode Decomposition	EMD
Direct Transfer Trip	DTT
Decision Trees	DT
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Empirical Mode Composition	EMC
Hilbert Transform	HT
Hilbert-Huang Transform	HHT
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Adaptive Particle Swarm Optimization	APSO
Real Power Shift	RPS
K-Nearest Neighbors	KNN
Feedforward Neural Network	FNN
Tunable Q factor Wavelet Transform	TQWT
Deep Neural Network	DNN
Singular Value Decomposition	SVD
Wavelet Singular Entropy	WSE
Wavelet Packet Transform	WPT
Mathematical Morphology Ratio Index	MMRI
Dilation-Erosion Differential	DED
Median-based Islanding Recognition Factor	MIRF
Current-based Islanding Recognition Factor	CIRFC
Root Mean Square	RMS
Subspace-K-Nearest Neighbor	SSKNN
Synchronous Generator Based Microgrid	SGBMG
Inverter Based Microgrid	IBMG
Small Scale Synchronous Generator	SSSG

Abstract

Hybrid microgrids (HMG), which combine AC and DC power networks, are a cornerstone of modern energy systems because they integrate renewable energy sources (RES) and ensure reliable and flexible power supply. However, detecting islanding, a condition where part of the grid continues to operate autonomously after being disconnected from the utility grid (UG), remains a significant challenge. Islanding poses serious risks, including equipment damage, safety hazards for utility workers, and disruption of power quality (PQ). Hence, an effective islanding detection mechanism is crucial for maintaining the stability and safety of HMG operations.

The core objective of this thesis is to propose and validate a new hybrid IDM that combines the strengths of two existing approaches: The Rate of Change of Phase Angle Difference (ROCPAD) and the Intermittent-Bilateral Reactive Power Variation (IB-RPV). By integrating these two methods, the hybrid IDM aims to eliminate the limitations of standalone passive and active detection methods. The ROCPAD method, a passive technique, continuously monitors the phase angle between voltage and current at the Point of Common Coupling (PCC), providing sensitive detection of grid disturbances. However, it is prone to large Non-Detection Zones (NDZ) and nuisance tripping under conditions such as high load variability. The IB-RPV, an active technique, introduces controlled reactive power perturbations to induce measurable changes in system parameters during islanding. This active method is highly effective in reducing the NDZ but can degrade PQ if applied continuously. The proposed hybrid IDM has the potential to improve the reliability and safety of HMG operations significantly.

The hybrid IDM proposed in this research simulated using MATLAB Simulink, which operates in a two-stage process. The initial stage involves the passive ROCPAD method, which continuously monitors key grid parameters for abnormalities that could indicate islanding. When deviations in phase angle exceed a defined threshold, the second stage is initiated. This stage involves the active IB-RPV method, which is triggered to inject small reactive power perturbations, thereby confirming the presence of islanding. This two-stage approach leverages the sensitivity of the ROCPAD method while minimizing its

susceptibility to false positives by validating potential islanding events through the active IB-RPV method. Notably, the active method is only engaged when the passive method detects an abnormality, thereby significantly reducing the impact on PQ and avoiding unnecessary disturbances during regular operation.

This thesis presents a detailed design methodology for implementing the hybrid IDM, including optimal parameter tuning for ROCPAD and IB-RPV, ensuring IEEE 1547 compliance for grid-connected inverters. The design framework also considers the dynamic nature of HMGs, which include inverter-based DERs and synchronous generators, providing the hybrid IDM can be universally applied across different MG configurations. Key performance metrics such as NDZ, detection time, and PQ impact are rigorously analyzed in various HMG scenarios, including grid-connected and islanded operation modes.

The hybrid IDM's performance is evaluated through comprehensive simulations under various operating conditions, including load profiles, grid disturbances such as voltage sags, and significant load changes. Key findings of the research include:

Non-Detection Zone (NDZ): The proposed hybrid IDM achieves zero NDZ, including cases where load-generation matching occurs as a significant weakness in many passive methods.

Detection Time: The total detection time is reduced to under 93 ms from the initial detection of phase angle deviation to the activation of the islanding breaker. This rapid detection time is essential to ensure grid stability and operational safety, especially in systems with high levels of intermittent renewable energy.

Power Quality (PQ) Impact: The hybrid IDM minimizes the impact on PQ by activating the IB-RPV method only when the ROCPAD method detects a potential islanding condition. This ensures that the grid remains stable and free from unnecessary disturbances during regular operation, avoiding the common issue of PQ degradation associated with continuous active detection methods.

To further validate the robustness of the proposed hybrid IDM, a detailed analysis is performed using the IEEE-13 bus system, simulating the HMG under various real-world conditions. The performance is compared against existing IDMs, showing that the hybrid method eliminates NDZ and provides faster and more reliable detection than traditional active and passive approaches. The results demonstrate that the hybrid IDM is well-suited for modern HMGs, including those integrating both inverter-based and synchronous generation sources.

This thesis also includes a comprehensive comparative analysis of the hybrid IDM against state-of-the-art islanding detection techniques, highlighting its superior performance. This combination of techniques ensures fast, accurate, and non-intrusive islanding detection, making it highly effective for grid-connected and islanded operations.

This research has significant implications for the future of MG technology and renewable energy integration. The hybrid IDM addresses the technical challenges of islanding detection in complex hybrid AC-DC MGs and offers a scalable and adaptable solution for diverse energy systems. The method's ability to eliminate NDZ, reduce detection time, and preserve PQ aligns with the growing demands for high efficiency.

CHAPTER I I

NTRODUCTION

1.1 Introduction

The extensive use of conventional energy resources, such as coal, natural gas, and oil, has raised growing concerns about their negative environmental impact. The emission of greenhouse gases, air pollution, and the depletion of finite fossil fuel reserves have become central issues in global energy policy. In response to these challenges, governments, industries, and environmental groups have taken the lead, inspiring significant advancements in reducing the reliance on fossil fuels for electricity generation in the industrial and residential sectors over the past two decades.

Renewable energy technologies have accelerated development and deployment. These technologies offer clean and sustainable alternatives, not just mitigating but reversing the environmental impact of traditional energy sources. The rapid growth in renewable energy, driven by improved technological efficiency, declining costs, favorable government policies, and rising awareness, is a beacon of hope in the fight against climate change and energy insecurity. Their positive impact on the environment is a reason for optimism in the global energy landscape.

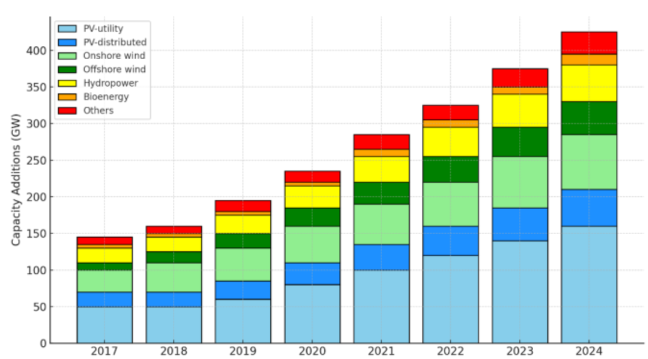


Fig. 1.1 Renewable Energy Expansion

Figure 1.1 illustrates the net renewable electricity capacity additions from 2017 to 2024. According to the International Energy Agency (IEA) report, global renewable energy capacity is projected to increase significantly by 2023, with a net addition of 107 GW. This projected growth is equivalent to more than Germany and Spain's installed power capacity combined, underscoring the rapid pace at which renewable energy is being adopted worldwide. Several key factors are driving this substantial expansion, as shown in Fig.1.2:

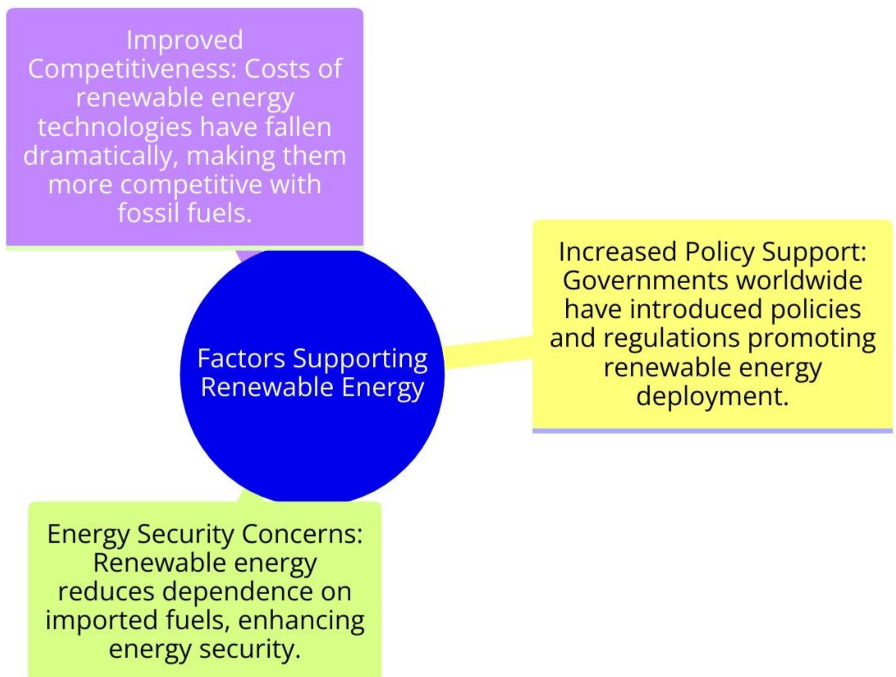


Fig. 1. 2 Driving factors for RE's substantial expansion

As a result of these drivers, the global energy landscape is shifting rapidly, with renewable energy playing an increasingly prominent role in the energy mix. The transition toward cleaner energy sources are critical for achieving global climate goals, reducing greenhouse gas emissions, and ensuring a sustainable future for energy generation.

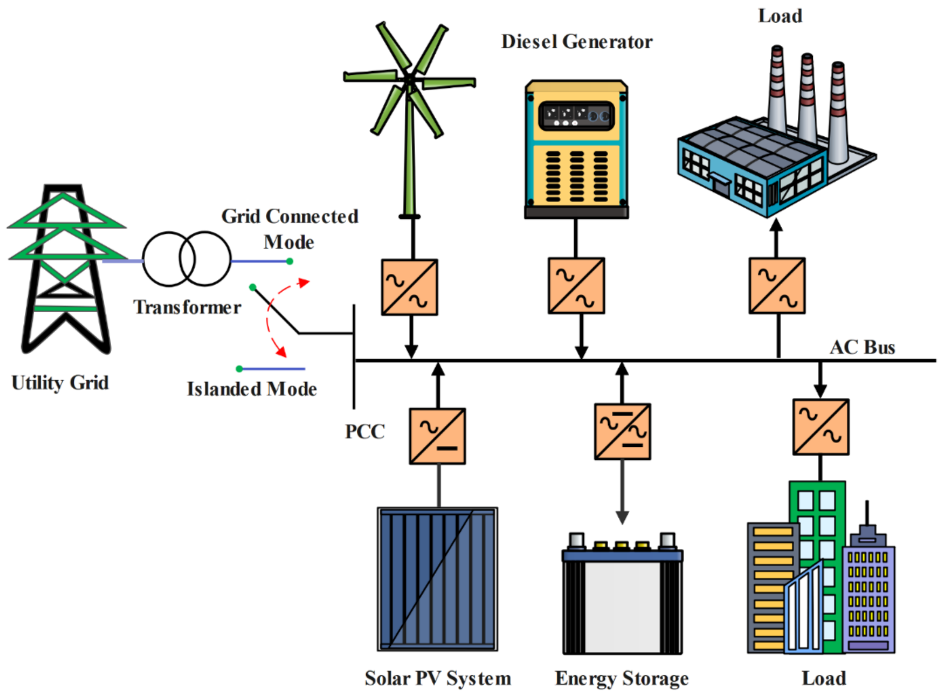


Fig. 1. 3 Hybrid Microgrid

In the global shift towards renewable energy, HMG, as shown in Fig.1.3, is critical in addressing some of the key challenges associated with the widespread adoption of clean energy technologies. As the world seeks to reduce its dependence on fossil fuels and mitigate the environmental impact of conventional power generation, HMG offers a flexible and resilient solution that combines RES with traditional generation and energy storage systems. The significance of HMG in supporting the energy transition, particularly in terms of enhancing energy security, reliability, and the efficient integration of renewable energy, is outlined in Fig. 1.4:

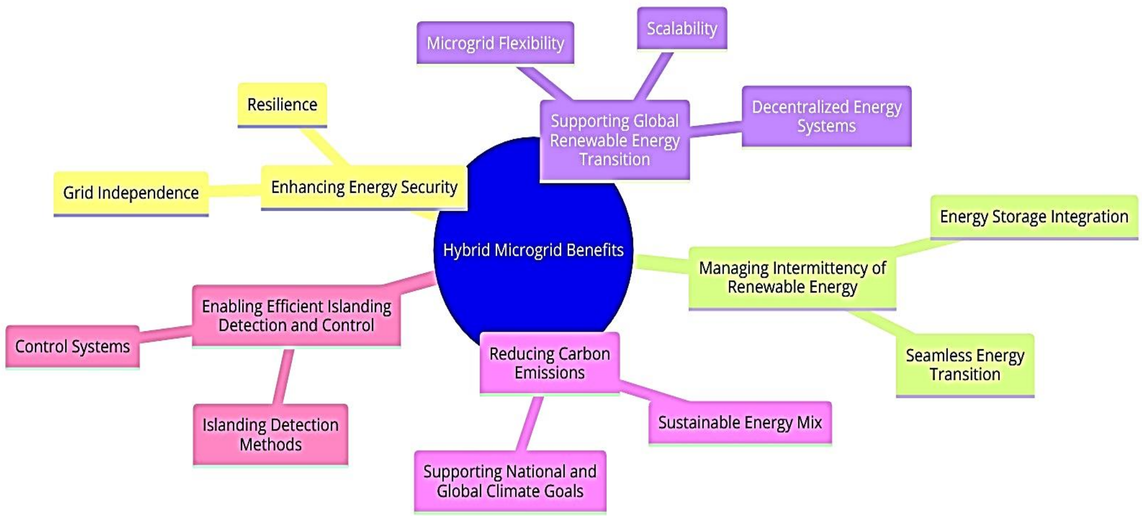


Fig. 1. 4 Merits of Hybrid Microgrid

Therefore, HMG has emerged as a workable alternative in response to the growing demand for clean and renewable energy. These MGs comprise many energy sources, including traditional power plants, generators, and energy storage systems. The increased adaptability of HMGs is one of their main advantages. Combining multiple energy sources allows for more efficient use of resources, resulting in a more consistent and dependable electricity supply. HMGs have the potential to dynamically alter the generation mix in response to changes in demand, the state of the environment, and the current energy supply.

The enhanced flexibility of HMGs in response to RES variability produces a more dependable and durable energy supply. While DG integration offers benefits such as improved reliability, reduced transmission losses, and support for renewable energy goals, it also introduces significant technical and operational challenges. Among these challenges, one of the most critical is islanding, occurs when a section of the power system powered solely by one or more DG is disconnected from the UG, as defined by IEEE Std. 1547 [1]. Islanding can be unintentional, occurring due to unexpected UG disturbances, or intentional, where a portion of the UG is deliberately isolated for reliability or operational flexibility.

Intentional islanding is a pivotal feature that embodies the confluence of de-carbonization, de-centralization, and digitization within the framework of renewable energy scale-up. By enabling MGs to operate autonomously from the UG during disturbances, islanding facilitates the integration of RES, which is crucial for reducing greenhouse gas emissions and achieving de-carbonization targets. It bolsters de-centralization by promoting localized energy generation and consumption, empowering communities to take control of their energy needs. This enhances UG resilience and minimizes transmission losses. Moreover, islanding capitalizes on advanced digital technologies, including smart meters, IoT sensors, and AI-driven algorithms, for precise detection and seamless management of islanding events, ensuring operational stability and continuity. This capability augments the reliability and appeal of RES and propels technological innovations in energy storage, power electronics, and smart grid infrastructure. Additionally, it unlocks new market opportunities by making renewable energy projects more attractive to investors and aligning with regulatory policies that incentivize resilient and sustainable energy solutions. Therefore, integrating islanding with de-carbonization, de-centralization, and digitization is indispensable for achieving a sustainable, resilient, and future-proof energy ecosystem. In unintentional islanding, DG units within the isolated portion of the grid are compelled to continue operating without synchronization with the UG. This scenario can lead to several significant issues, shown in Fig.1.5:

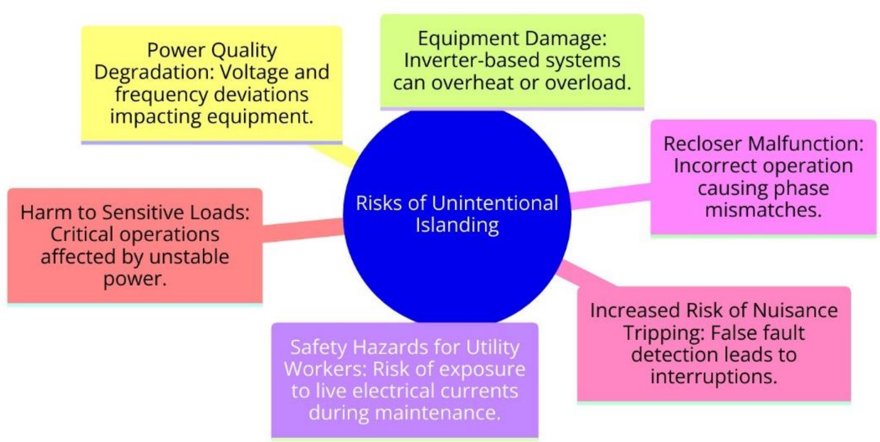


Fig. 1. 5 Issues with unintentional Islanding

Therefore, Unintentional islanding detection is crucial to mitigate these risks. Islanding detection methods (IDMs) ensure that the MG can quickly and accurately identify islanding events and disconnect the DG units from the grid when necessary, preventing potential hazards and maintaining system integrity.

1.2 Standards for Islanding Detection

ID standards are essential in creating standardized and trustworthy procedures for identifying islanding occurrences in DERs. The public and utility personnel may be in danger of injury during islanding incidents. Standardized detection techniques ensure dispersed generating units are quickly disconnected from the UG during such situations, reducing the risk of electrocution and equipment damage. Maintaining grid stability requires quick and precise islanding identification standards, as in Table 1.1, to ensure coordinated and regulated UG disconnections from DER, minimizing interruptions.

Table 1.1 Islanding Standards

Standards	Q_f	T_D (t)	Normal frequency range, f, (nominal frequency f_0)	Normal voltage range, V, (nominal voltage V_0)
IEEE Std. 1547- 2003	1	$t < 2$ s	59.3 Hz $\leq f \leq$ 60.5 Hz	0.88 v $\leq V \leq$ 1.10 v
IEEE Std. 929-2000	2.5	$t < 2$ s	59.3 Hz $\leq f \leq$ 60.5 Hz	0.88 v $\leq V \leq$ 1.10 v
IEC 62116	1	$t < 2$ s	(f_0–1.5 Hz $\leq f \leq f_0$ + 1.5 Hz)	0.85 v $\leq V \leq$ 1.15 v
AS4777.3-2005	1	$t < 2$ s	Set value	Set value
VDE 0126-1-1	2	$t < 0.2$ s	47.5 Hz $\leq f \leq$ 50.2 Hz	0.80 v $\leq V \leq$ 1.15 v
UL 1741	≤1.8	$t < 2$ s	Set value	Set value
Korean standard	1	$t < 0.5$ s	59.3 Hz $\leq f \leq$ 60.5 Hz	0.88 v $\leq V \leq$ 1.10 v
Japanese standard	0 (+ rotating machinery)	Passive: $t < 0.5$ s Active: 0.5 s $< t <$1 s	Set value	Set value

Standards help ensure that ID tools and algorithms work together across various vendors and technologies. Interoperability is essential given the variety of DG technologies, including MGs, solar, and wind. A DG system operator can reduce downtime and possible revenue loss by effectively detecting islanding occurrences and preventing unwanted disconnections. Regulations are frequently based on standards, guaranteeing that all DG systems adhere to operational and safety best practices. The improvement of ID techniques is constantly being researched and developed, spurring industry innovation.

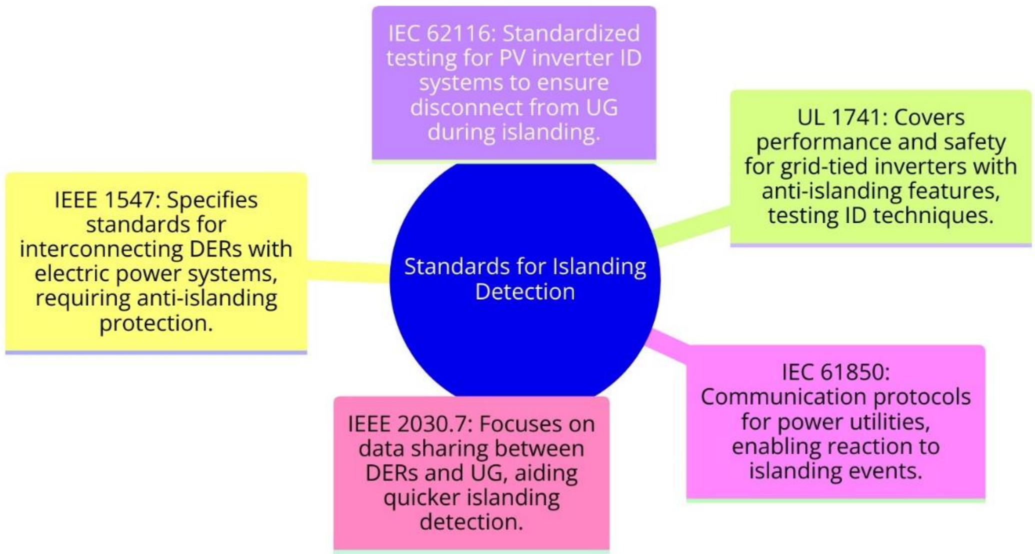


Fig. 1. 6 Standards for Islanding Detection

These standards, shown in Fig. 1.6, contain testing and validation processes to ensure ID systems work as intended. In these methods, inverters or DER systems are exposed to various islanding scenarios in controlled conditions, and their responses are evaluated. This validation method ensures that ID systems meet the criteria and are dependable under multiple operational circumstances.

1.3 Islanding Detection Performance Evaluation

The accuracy and general efficiency of the system are primarily determined by several essential performance criteria closely linked to the effectiveness of the ID method. The NDZ is crucial for these variables. NDZ is the portion of a system where anomalies or errors could arise yet go unnoticed, directly endangering the dependability of the entire monitoring and management procedure. Furthermore, the fault detection ratio is an important metric that assesses how well the system can locate and diagnose defects within its operational purview. Moreover, fluctuations or disruptions in PQ can affect the accuracy of fault detection and, consequently, the overall dependability of the system, making PQ a crucial component of IDM performance. The last important statistic is T_D, which shows how quickly IDM detects abnormalities and acts. This directly impacts the system's effectiveness and how quickly it can reduce possible threats. The interaction of these performance traits highlights the necessity of an all-encompassing strategy for IDM, guaranteeing a strong and dependable system that can efficiently manage and preserve IDM's health in various operational contexts.

1.3.1 Non-Detection Zone

When the chosen NDZ operates alone in the energy mismatch space, active and reactive power are the only variables, and the IDM's detection capabilities are limited. The NDZ appears as a range of active and reactive power values in the energy mismatch region where the IDM purposefully chooses not to sound an alarm or indicate an anomaly. This purposeful exclusion is essential to avoid needless interventions during regular system operations or temporary conditions. However, the problem arises if the electricity system or MG only runs inside this NDZ. Under such circumstances, the IDM cannot identify or detect a single operation inside the designated NDZ, possibly ignoring circumstances that call for attention or intervention. This restriction emphasizes the delicate balance that needs to be struck when creating NDZs inside IDM parameters: preventing false alarms while ensuring that actual anomalies, even those that fall inside the designated NDZ, are correctly detected for dependable and efficient system management. This balance must be struck to maximize the IDM's performance and guarantee its flexibility in various operating situations to prevent pointless interventions and omitting essential events in the energy mismatch space.

The power mismatch range P and Q can be defined as follows.

$$\left(\frac{V}{V_{\max}}\right)-1 \leq \frac{\Delta P}{P} \leq \left(\frac{V}{V_{\max}}\right)^2 -1 \qquad \text{…………….. (1.1)}$$

$$Q_f\left[1-\left(\frac{f}{f_{\min}}\right)^2\right]\le\frac{\Delta Q}{P}\le Q_f\left[1+\left(\frac{f}{f_{\min}}\right)^2\right]$$

………..…. (1.2)

The NDZ region becomes zero when the load demand equals the DG output ($\Delta P = \Delta Q = 0$).

1.3.2 Detection Time

In MG islanding terms, T_D is the period between the MG disconnecting from the UG and the IDM, subsequently determining that the MG is in an islanded state. The effectiveness and responsiveness of the ID system are evaluated primarily based on this metric. If the T_D is lower, it indicates that the disconnection event was handled quickly and accurately, reducing the danger of equipment damage or poor PQ, two possible consequences of islanding. The time interval between the MG disconnect event and the point at which the IDM definitively determines and proclaims the islanded state is the mathematical expression for the T_D. This quantitative metric helps assess the ID mechanism's performance in real time and shows how quickly the system can adjust to changes in UG connection. To ensure a switch from grid-connected to islanded operation, the IDM must effectively analyze and understand the dynamic parameters of the power system to achieve a low T_D. It is imperative to optimize TD to improve the dependability and efficiency of MG ID systems in preserving operational stability during UG disruptions.

$$T_D = T_{ID} - T_{CB_{TRIP}}$$

…………. (1.3)

1.3.3 Power Quality

Active IDMs, which purposefully introduce disruptions into the electrical system, are essential to the ID process. This intentional interference is a tactical maneuver to cause observable perturbations in the system's characteristics and facilitate the detection of an islanded condition. However, there is a double-edged effect to this deliberate introduction of disturbances: it may cause the output PQ to deteriorate. A threat to the general stability and dependability of the power supply is the disturbances caused by active IDMs, which can appear as variations in voltage, frequency, or other power-related parameters. Thus, while selecting IDMs for ID, PQ becomes an essential factor. For reliable detection, it is crucial to balance maintaining consistent power production and effectively injecting disturbances. It is necessary to carefully assess and choose IDMs to guarantee that the advantages of precise ID are achieved without jeopardizing the general dependability and performance of the UG.

1.4 Challenges for Unintentional Islanding Detection

Unintentional islanding detection presents several challenges due to the complexities of DG systems and the dynamic nature of MG. These challenges impact IDM's accuracy, speed, and reliability. Critical challenges associated with detecting unintentional islanding in HMG as shown in Fig. 1.7:

Fig. 1. 7 Key Challenges for Islanding Detection

With the increasing significance of HMGs in the global energy transition, the need for robust IDMs cannot be overstated. Opportunities and problems arise from HMGs' ability to function independently in islanding mode, especially when it comes to guaranteeing the stability and dependability of DG. Different IDMs have been developed to ensure safe disconnection and reconnection procedures, as detecting unintentional islanding has become necessary for contemporary power systems. However, the shortcomings of conventional IDM approaches in terms of false alarm rates, detection speed, and NDZ highlight the need for more advanced detection techniques. This demand for innovation and progress intensifies as MGs use more RES. The subsequent chapter will comprehensively review the existing literature, focusing on recent advancements in IDMs.

The introduction chapter explores the pressing challenges posed by conventional energy sources, which contribute to greenhouse gas emissions, air pollution, and the depletion of finite resources, raising global environmental concerns. It emphasizes the growing role of renewable energy technologies, which have seen accelerated development due to technological advancements, decreasing costs, favorable government policies, and increasing awareness of climate change. The chapter introduces HMGs, which combine RES with traditional power generation and energy storage systems to create more resilient, flexible, and sustainable energy solutions. A key feature of HMGs is their ability to perform "islanding," allowing sections of the grid to operate autonomously during disruptions, thereby supporting goals of de-carbonization, decentralization, and enhanced grid reliability. The chapter also focuses on the importance of robust IDMs, ensuring safe and efficient operation during intentional and unintentional islanding events. Performance metrics like NDZ, detection time, and power quality are crucial for evaluating the effectiveness of these systems. The discussion emphasizes the need for continued innovation and standardization in IDMs, given their critical role in ensuring the stability and resilience of HMGs in the global transition toward renewable energy.

1.5 Organization of Thesis

This thesis is organized into seven chapters to progressively present the design, analysis, and comparison of the proposed hybrid IDM for HMGs. The chapters are arranged as follows:

Chapter II: Literature Review

This chapter presents a comprehensive review of existing islanding detection methods and discusses the literature gaps that necessitate the development of a more effective IDM.

Chapter III: Methodology

This chapter details the methodological approach to designing and implementing the proposed hybrid IDM.

Chapter IV: Design and Development of the Hybrid Microgrid

This chapter focuses on the design and development of the HMG, which serves as the test bed for the proposed islanding detection method.

Chapter V: Performance Analysis of the Proposed Islanding Detection Method

This chapter evaluates the proposed hybrid IDM. Detailed simulation results are presented, demonstrating the method's performance.

Chapter VI: Comparative Analysis with Existing Methods Based on Performance Indices

This chapter compares the proposed hybrid IDM and existing islanding detection techniques based on key performance indices.

Chapter VII: Conclusion and Future Work

The final chapter summarizes the contributions of the thesis and provides concluding remarks. Suggestions for future research directions are also discussed.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

One of the most critical challenges in maintaining the steady and dependable operation of modern power systems is the identification of islanding occurrences in HMGs. Effective ID becomes increasingly tricky when HMGs integrate multiple DERs, including RES, adding to the system's complexity. Although conventional IDMs, both passive and active, have been widely used, they frequently have serious drawbacks, including NDZs, delayed detection periods, and a high risk of false alarms, especially in systems with a high intermittent generation penetration rate. These restrictions may result in possible safety risks as well as operational inefficiencies. More sophisticated IDMs have been created recently, providing improved durability, sensitivity, and detection speed across various grid conditions**.** This chapter provides an extensive overview of current IDMs, assessing their applicability for HMG with intricate energy architectures and assessing how well they work in both grid-connected and islanding modes.

IDMs can broadly be classified into remote and local methods, each with distinct operational mechanisms and use cases [3]. Remote IDMs involve communication between the utility grid and DG units, typically relying on advanced infrastructure such as SCADA systems, PMUs, or other forms of centralized control. These methods, such as Supervisory Tripping and PLCC, offer high reliability and accuracy but come at the cost of increased infrastructure complexity and communication overhead.

On the other hand, local IDMs operate independently at the DG unit or MG level, monitoring electrical parameters such as voltage, frequency, and harmonic distortion to identify islanding events. Local methods are typically divided into passive, active, and hybrid techniques, but recent advancements have also introduced intelligent and signal-processing-based methods. Passive methods rely on detecting anomalies in system parameters without introducing any disturbances, whereas active methods deliberately inject minor disturbances into the system to provoke measurable changes. Hybrid methods combine both approaches to enhance detection sensitivity and reduce NDZs.

In addition, intelligent IDMs utilize advanced data processing techniques, such as pattern recognition and clustering, to enhance the accuracy and speed of detection. These adaptive methods can improve performance under varying operational conditions in MGs. Signal processing-based methods employ techniques like wavelet transforms, Fourier analysis, and other frequency domain analyses to extract useful features from electrical signals, which are then used to detect islanding events with high precision. While remote methods are typically more reliable, local methods, especially intelligent and signal processing-based approaches, are gaining popularity due to their flexibility, lower implementation costs, and high suitability for modern HMGs with decentralized architecture. This classification forms the foundation for a deeper exploration of IDMs in the following literature review.

2.2 Islanding Detection Methods

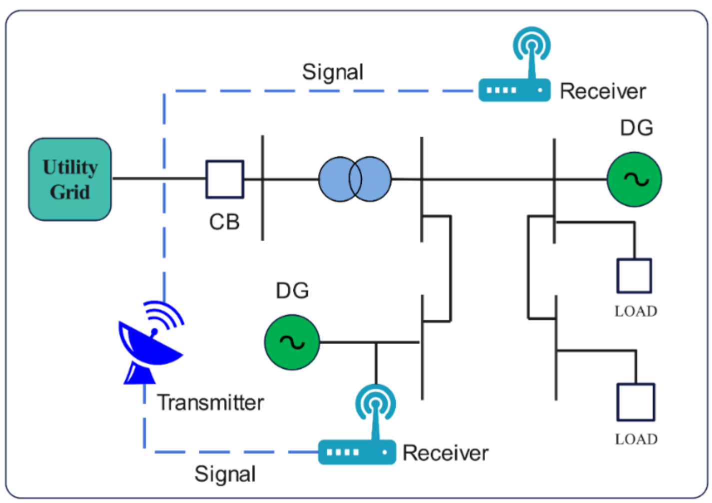


Fig. 2. 1 Remote IDM

2.2.1 Remote Techniques

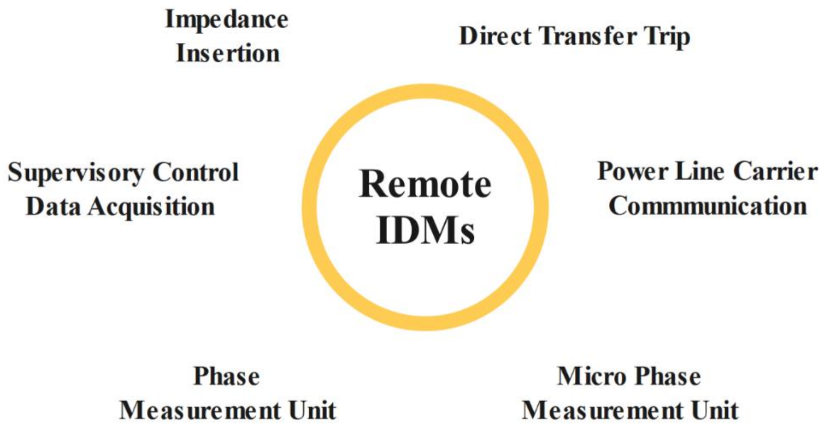


Fig. 2.2 Remote IDMs

Remote or grid-resident IDMs use communication or SP technologies to identify IS events. The use of remote IDMs is recommended because it can avoid several issues related to local IDMs, including reduced efficacy when there are several DG units, negative impacts on PQ, and the existence of NDZs. However, small and medium-sized DG systems cannot afford the high price and complicated implementation associated with remote IS detection. Fig. 2.1 describes how remote IDMs work, and Fig. 2.2 lists different remote IDMs. ECS, DTT, and PLCC are a few well-known methods of remote techniques [5].

2.2.1.1 Impedance Insertion

The PCC voltage and frequency are altered beyond the allowable operating range by activating a specific impedance element, usually a bank of capacitors, using the Impedance Insertion method. This creates a reactive power imbalance. Nevertheless, this approach has several shortcomings, such as the expense of the capacitor bank, sluggish reaction times, and the possibility of running into NDZs [6]. However, its broader use has been hindered by the need for an additional device attached to the PCC and the ensuing expensive implementation costs.

2.2.1.2 Direct Transfer Trip

The central control unit of an IDM based on DTT keeps track of all circuit breakers that can isolate the DGs and determines which areas are islanded. This method has excellent effectiveness and precision, just like other remote IDM systems; however, it has drawbacks due to expensive costs and complicated implementation. This is due to its reliance on a supervisory system and communication infrastructure, which includes radio, dedicated fiber, and leased phone lines [8]. In a study published in [66], three naturally occurring IS events were examined in a power plant with different generators that used the DTT strategy to prevent islanding. The analysis suggests that the DTT technique should not be used in systems that can perform load shedding to avoid extended detection periods. Furthermore, the existence of reactive compensators may substantially affect the scheme's performance.

2.2.1.3 Power Line Carrier Communication

The power line infrastructure serves as the communication channel for a PLCC system. UG interruption detection happens if the IS signal stops during its four conduction cycles, which is how it is usually conveyed [67]. For communication lines longer than 15 km, repeaters are required for PLCC-based IDMs to prevent signal attenuation [5]. However, there haven't been many articles on this method because of its high complexity and implementation expense. Paper [7] provided an overview of the original proposal for using PLCC for IS detection. In particular, for smaller generation systems, it emphasizes that high-frequency signals should be avoided due to their propensity to be attenuated by the series inductors found in distribution transformers. In addition, to reduce complexity, the information must be conveyed purposefully and slowly. The study combines a low-cost receiver with a commercial automatic meter reading device to minimize extra implementation costs. In addition, it lists several conditions that must be met for an IDM based on PLCC to be economically viable. A study that evaluates a PLCC-based IDM used for absolute DG configuration is presented in [68]. Numerous findings on the signal attenuation brought about by the transmission line's inherent qualities and local load characteristics are drawn from this research. An analysis of the signal attenuation caused by a medium voltage transformer is presented in [69], along with a mathematical equation that characterizes this attenuation. Finally, a sensitivity analysis of a PLCC-based IDM is carried out [70].

2.2.1.4 Supervisory Control Data Acquisition Method

This system is appropriate for IS detection since it manages a variety of circuit breakers, including those that link DG to the UG. This method has benefits and drawbacks that are comparable to those of remote approaches. As a result, it may remove NDZs without sacrificing PQ. However, SCADA-based IDMs [11] are impractical for small or medium-sized DG systems because of their high cost, complexity, and need for remote operators [71].

2.2.1.5 Phase Measurement Unit (PMU) Method

PMU gives real-time information about the electrical phasor's phase and magnitude in the electrical system [72]. PMUs are used in many aspects of power systems, including monitoring, synchronization, purposeful islanding, and transmission voltage level detection of inadvertent UG outages. Regarding intentional IS operations, [73] carried out a thorough analysis of intentional IS. The results disclosed that the PMU device successfully reconstructed the evaluated signals with little amplitude and phase error. Furthermore, the study found that PMU devices provide a more reliable depiction of electrical parameters than SCADA systems. On the other hand, PMU is also used for inadvertent IS detection. Two different PMU IDMs, the CADM and the FDM, are proposed in [74]. Whereas the latter takes advantage of the phase difference between two buses, the former compares the observed frequency with a predetermined threshold to identify loss of mains. The outcomes show that both approaches successfully identify IS in three distinct circumstances. Additionally, it is seen that the FDM and CADM combination is sufficiently selective to avoid falsely tripping the DG during six non-IS incidents. A new IDM is presented in [75], which consists of a PMU system that uses an intelligent tree algorithm to detect IS. Systematic Principal Component Analysis (SPCA) is used in [9] to create the Synchro-phasor IDM, which performs well even when training data is updated. [76] Suggests a remote solution that combines PMU and SCADA techniques to produce accurate IS detection with no instances of misclassification. Additionally, [77] and [78] provide descriptions of other practical PMU-based accidental IS detection approaches.

2.2.1.6 Micro Phase Measurement Unit (MPMU)

The MPMU was first proposed in [79]. These units are specifically designed to handle the unique characteristics of distribution lines [80]. The main aspects monitored by the IDM based on MPMU in [10] are the Cumulative Sum of Frequency Difference and the Phase Angle Difference. This plan takes advantage of the phase's effect on frequency once sources are lost. IS event detection is achieved by using a Pearson correlation coefficient. Findings show that the system can reliably identify IS in 0.25 sec. Moreover, it can reliably detect non-IS scenarios and is robust against measurement noise. A unique IDM using four MPMU devices coupled to various electrical system busses [81] is based on MPMU. Electrical parameters are used to detect UG interruptions. The central controller is made up of logic gate arrays. The outcomes show how selective the system is to non-IS occurrences and how well it can identify IS when there is a power balance. A notable drawback of IDMs based on MPMUs is their vulnerability to assaults originating from communication networks and internet-based data transfers. This problem is addressed in [82], which promotes the establishment of a specific sub-channel for the sole purpose of detecting islanding. This technique protects against many cyberattacks, such as physical cable blockage, data replication, injecting fake data, and disrupting network traffic.

2.2.2 Local Passive Techniques

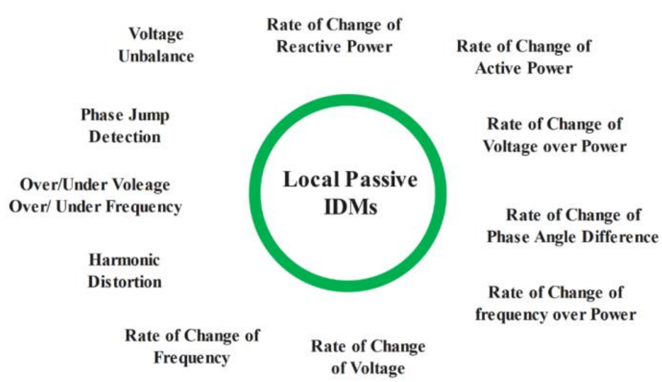


Fig. 2.3 Local Passive IDMs

As shown in Fig. 2.3, a wide variety of IDMs that only depend on tracking specific PCC variables are included in Passive IS Detection. Since passive methods don't cause any disruptions or degrade PQ, their main benefit is that they are non-intrusive. Nevertheless, passive methods have many unreliability issues, primarily because of their enormous NDZ and sluggish detection performance. OUV or OUF detection, PJD, HD detection, ROCOF, ROCOV, ROCPAD, ROCOP, and ROCORP are crucial examples under this category [37].

2.2.2.1 Over/Under Voltage (O/UV) and Frequency (O/UF)

As part of the OUV and OUF schemes, real-time voltage magnitude and frequency readings are monitored and compared to predetermined thresholds. The inverter turns off if it notices an abnormality within a set time window. With frequency and voltage relays being standard components in most commercial inverters, this approach is among the simplest passive methods.

2.2.2.2 Phase Jump Detection (PJD)

Since changes in phase dynamics can sometimes happen more quickly than changes in frequency, this method responds more rapidly than the OUV or OUF method [16]. But it's important to remember that contemporary PLL algorithms have improved the synchronization between the inverter current and PCC voltage, enabling quick absorption of phase jumps and possibly avoiding the detection of islanding. Choosing a suitable threshold to detect grid disconnections presents another implementation challenge. Unlike voltage frequency and magnitude, the phase jump threshold is not specified [12]. Moreover, the PJD method may result in erroneous tripping since motor starts or capacitor bank switching might generate brief variations in the PCC voltage phase that unintentionally cause detection. [84]

2.2.2.3 Harmonic Distortion (HD)

Nevertheless, the load impedance could be substantially greater than the grid impedance, and the harmonic components of the inverter output current impact the THDv after a grid outage [84]. This method's main benefit is that it is not affected by power imbalances between generated and consumed power [47]. Setting protective relay parameters is a hurdle with its implementation, though. A smaller IS threshold could cause the inverter to trip unintentionally, whereas a more significant threshold could cause the NDZ to grow. It's also critical to recognize that the algorithm is not very selective because some non-IS circumstances can potentially raise THDv [85]. In addition, the method's effectiveness is impacted by background distortion in the grid [87] and non-linear loads [86]. HD-based IDMs have been presented in some research to address the issues above and improve selectivity, robustness, and efficiency. Some techniques combine HD with other passive characteristics to increase selectivity. For instance, passive IDMs that integrate harmonic measurement with an unbalanced phase voltage relay are presented in [88], [89], and [90]. The outcomes show that this combined method successfully distinguishes between IS and non-IS events and delivers accurate IS identification under both balanced and unbalanced load scenarios. Furthermore, [91] suggests a hybrid approach that uses THDv and the Gibbs phenomenon. Experimental tests validate the solution's ability to identify IS development in multi-DG systems. It exhibits a lower harmonic content and a lowered NDZ compared to passive HD versions and active IDMs. Other methods identify IS by concentrating on particular harmonic components. A technique for HD is presented in [92] that determines the third and fifty-fifth harmonic components' energy densities using a KF and presents an IDM based on the inverter's PWM harmonic signature [93]. Additionally, [94] offers a passive IS detection technique based on the PCC voltage's even harmonic components. The results show how well this approach works in a multi-DG system to identify grid outages. Finally, IS detection is accomplished in [95] by extracting the second harmonic component of both voltage and current using a DFT.

2.2.2.4 Rate of Change of Frequency

ROCOF depends on several factors, including inertia, nominal frequency, rated power, and the amount of active power supplied by the UG at the moment of islanding. The method can be used using a PLL [98], ZCD [97], a Fast FT [98], an Interpolated DFT and a KF [33], or PMU [99]. Choosing the right measurement window for ROCOF computation and setting the suitable threshold for IS detection are two of the main challenges with ROCOF-based IDM. As per reference [96], the measuring period must be between 0.3 and 0.7 sec, with a detection threshold of 0.3 Hz/s. In addition, a method for building ROCOF relays based on field observations at a biomass production facility is described in [100]. The intricacy of integrating ROCOF relays with other frequency protection devices presents another obstacle to the successful application of this technique. In response to this problem, [14] suggests a graphical design method to guarantee communication between ROCOF and O/UF relays. The susceptibility of ROCOF to annoying journeys after non-IS events is another major disadvantage. As a result, by measuring another electrical variable in addition to ROCOF, various research has tried to address this problem. An under-voltage interlock feature is suggested in [97] to distinguish between temporary events like voltage dips and grid disruptions. According to [101], the THD_i value is the lock that activates the ROCOF safeguard. [102] presents the integration of grid impedance estimate with ROCOF. Finally, an improved ROCOF relay utilizing the adaptive KM estimate technique is given in [103]. This method lessens the susceptibility of the relay to non-IS faults, allowing it to differentiate between grid outages and other electrical emergencies. However, the ROCOF method has a lot of different benefits as well. Adaptability is one of these advantages; the scheme can be precisely adapted to a variety of systems, including synchronous generator-based systems [102], PV systems [104], and other types of MGs [105]. In addition, some active IDMs that use the ROCOF relay have been created to speed up the detection of grid interruptions: IDM based on RPV implemented with ROCOF relay is introduced in [107]; [19] proposes a hybrid technique that combines SFS and ROCOF; and [106] offers a blend of ROCOF and SMS. Furthermore, in [108], an active ROCOF relay is suggested.

In contrast to other passive solutions, the ROCOF strategy's NDZ has yet to be analytically determined in the literature. Nonetheless, several investigations have tried to define the NDZ's limits using computational or experimental evaluations. For example, computational research was proposed in [109] to map the NDZ for PV systems with varied inertial constants and across different RLC loads, spanning different quality factor values. On the other hand, in [13], the ROCOF and ROCOV relay blend produced a lesser NDZ than the OUF and OUV combined. Moreover, a comprehensive computational analysis was carried out in [110] to regulate the upper bound of the ROCOFs NDZ.

2.2.2.5 Rate of Change of Voltage

This approach relies on the ROCOV since grid interruptions may cause a momentary divergence in the PCC voltage [15]. ROCOV can be used for various tasks, such as identifying electrical emergencies or IS occurrences. In HVDC systems [111], [112], and DC MGs [113], this technique is frequently used for fault detection. Further, as [114] reports, ROCOV can be applied to AC MGs to detect UG loss. Additionally, different IDMs can be combined with ROCOV. One hybrid approach that can identify IS in a multi-DG system is suggested in [115], which combines ROCOV monitoring with ROCOP. ROCOV relays are considered more dependable and selective than conventional current and voltage protection devices, as stated in [116]. Furthermore, a coordinating system based on ROCOV assessment for MGs is proposed in [117].

2.2.2.6 Rate of Change of Phase Angle Difference (ROCPAD)

This technique, first presented in [118], entails constantly tracking the ROCPAD between the inverter's voltage and current output and examining the rate at which this parameter changes over time. To reduce NDZ, a passive IDM that blends ROCOF, ROCOV, and ROCPAD is proposed in [119].

2.2.2.7 Other Rate of Change Based-Methods

As previously noted, the IS occurrence might result in rapid and brief departure of multiple electrical variables. Since voltage and frequency are the most frequently occurring, they have their part in this section. Some rate-of-change-based relays, such as ROCOP [120], ROCORP [121], ROCOFoP [122], and ROCOVoP [22], have been reported in the literature, though. Moreover, a combination of ROCOP and ROCORP is suggested in [123].

2.2.2.8 Voltage Unbalance

A three-phase system may encounter phase delays or voltage amplitudes that deviate from 120 degrees, leading to a phenomenon known as voltage unbalance. The loads in each phase of an IS operation may also have varying magnitudes or impedances, which might result in voltage imbalance. For instance, as was previously indicated in [88], the voltage imbalance is utilized to interlock the IS analysis with the harmonic measurement. A comparable method was suggested in [89]. In order to improve the capacity to distinguish between islanding and non-islanding events, it monitors the voltage imbalance using the fifteenth-order harmonic. Furthermore, a few hybrid techniques operated using the voltage imbalance as a passive stage. These methods will be further examined in the subsection on hybrid methods.

2.2.3 Local Active Techniques

As previously stated, when there is a balance between the power produced by DG and the power required by local loads, passive IDM shows unreliability. Consequently, active IDMs were developed in response to the requirement to overcome NDZ difficulties with passive IDMs. These strategies entail producing perturbations in the inverter operation to alter the operating point outside the established standard's thresholds. Although active solutions inevitably lead to a decline in PQ, their use is warranted by reducing NDZ [18].

2.2.3.1 Active Frequency Drift (AFD)

The main benefit of the AFD solution is easy to implement. It's crucial to remember that this algorithm has several shortcomings, such as high levels of THD_i, inefficiency in multi-DG IS circumstances, serious NDZ problems, and impact on PQ due to frequency perturbation. An additional constraint related to the fixed value of C_f is present. As a result, there is an issue with the load-induced frequency wandering propensity. More inductive loads tend to cause the frequency to drift below the grid frequency, whereas when C_f is positive, the frequency tends to drift to values more significant than the UG frequency. The IDM's imposed frequency deviation may be countered by this load-induced frequency drifting tendency, which could lead to a failure to identify grid outages.

2.2.3.2 Improved Active Frequency Drift (IAFD)

The IAFD algorithm was proposed by [125] to address the THD_i issue with the Classic AFD. During the odds quarter-cycles of current, IAFD substitutes a step on the current magnitude for the dead time. The detecting capability will increase with increasing K, but the output current's harmonic content will also increase with increasing K, impacting PQ.

2.2.3.3 AFD with Pulsating Chopping Factor (AFDPCF)

As stated, the Classic AFD cannot adjust to the frequency drifting brought on by local loads. To overcome this restriction, [127] created the AFDPCF, which substitutes a pulsing signal between positive, zero, and negative values for the fixed value of C_f. This method's main advantage is that it reduces the THD_i injected during the conduction periods when C_f equals zero. As demonstrated in [46], the AFDPCF algorithm eliminates the NDZ for various values. The AFDPCF design process, which computes $C_{f\,max}$ and $C_{f\,min}$ values to eradicate a specific range of quality factor values, was also introduced by [46]. The algorithm's main drawback is that it takes longer to detect ID than other approaches. As explained in [46], the C_f value and grid disruption change do not co-occur. This means the approach can only start frequency drift after the C_f value changes if IS occurs when C_f equals zero. [128] discusses an alternate version of the AFDPCF.

2.2.3.4 Sandia Frequency Shift (SFS)

The SFS method was put forth by [124] to fix the Classic AFD algorithm's operational issues by using a variable chopping factor connected to the detected frequency inaccuracy. The distortion introduced into the inverter output current phase discrepancy concerning the PCC voltage is produced by the output current of the inverter. THD_i rates and T_D are reduced, which is the main benefit of the SFS method. In contrast, the frequency differs from the nominal value during a UG outage, which causes C_f to rise. This frequency variance intensifies C_f, even more, resulting in a feedback loop that shortens the T_D. C_{fo} and the accelerating gain K are the two parameters that determine the SFS design. The gain K establishes the NDZ size, while the C_{fo} influences the THDi rate [129]. Therefore, the application of SFS aims to achieve the most significant NDZ reduction with the least THDi injected. Numerous design techniques have been suggested for this situation. However, the amount of inverters linked to the same PAC can affect the SFS algorithm's NDZ, reducing the algorithm's detection capacity. To solve this issue and ensure the best possible tuning of the SFS, even in multi-DG cases, [130] suggested a new design technique for the SFS scheme. Although computational models were completed, no experimental validation was given.

A dynamic analysis was conducted on the NDZ problem by [131] to investigate the impact of the accelerating gain K and the parameters C_{fo} on the NDZ mapping and size. The range of Q_f

values for which the NDZ is eliminated was found to be directly impacted by K; an increase in K results in a smaller NDZ. Conversely, C_{fo} establishes the Cnorm's value at the NDZ's starting point. In this way, a rise in C_{fo} corresponds to an increase in the norm. However, the stability analysis in [54] has proven that high K values can impact the converter's stability and cause incorrect tripping, especially for large-scale DGs or weak grids. In this case, [132] suggested an SFS variant that is comparable to the AFDPCF algorithm and is based on the idea of the pulsing C_{fo}.

A different parametrization method involves selecting C_{fo} and K correctly by applying ML and artificial intelligence techniques. An adaptive FL-based approach, for example, estimates the local load parameters in [133] and uses the estimated parameters to find the lowest K value, eliminating the NDZ. This process follows SFS parametrization guidelines. However, an ML method based on the immune system makes the parametrization in [134]. THD_i and T_D in a PV and wind power DG system were better in the experimental realization.

2.2.3.5 Slip Mode Shift (SMS)

The Slip Mode Frequency Shift is achieved by inserting a tiny disturbance through a frequency positive feedback loop into the PLL-predicted phase. The primary benefits of this IDM are its capacity to follow the frequency variation of the load applied to it, its digital implementation's ease, and the removal of the NDZ for a particular factor of Q_f [106]. A comparative analysis of how multi-DG IS affects the SMS strategy's NDZ is suggested in reference [49]. The study discovered that multi-DG operation increases its NDZ and negatively impacts performance. The novel APS technique is proposed in [135] and introduces an initial fixed perturbation. A modified APS is suggested in [136], where the parameter values change based on the local load's estimated impedance. Reducing the T_D involves combining the SMS with the ROCOF algorithm, as suggested in [137]. The hybrid IDM presented in [138] is based on combining the SMS with the Q-f droop curve; the following subsection will go into great depth about this method. In an experimental comparative analysis, [139] shows that, in comparison to the SFS scheme, the SMS achieved faster IS detection.

2.2.3.6 Reactive Power Variation (RPV)

A novel IDM is put forth in [142] that involves tampering with the reactive power reference to produce an imbalance in reactive power between the local load and the inverter. Using a Q-f droop curve, an IDM is suggested in [143]. Active techniques to differ the frequency outside the permitted range are proposed in [144] and [145], whereby the q-axis current control is perturbed. [144] employs an intelligent control to ensure quicker ID, [145] put forth a method based on the dq reference frame perturbation that may ensure selectivity. A hybrid IDM with four passive criteria is presented in [146] to help choose when to inject the RPV disturbance. A novel hybrid IDM in [90] combines an active bilateral RPV with two passive features: voltage imbalance and THD_i. This approach represents a significant advancement over [146], as it accurately detects IS while requiring less computing power due to its two-variable measurement requirement. Finally, an altered Q-f droop curve-based IDM is put out in [147]. The experimental validation results demonstrated that the NDZ could be eliminated for various Q_f values. A bidirectional intermittent RPV-based IDM is proposed in [148]. A new RBV-based algorithm is proposed in [149], and its parametrization is related to the frequency resonance of the load. Furthermore, non-unitary power factor inverters are incompatible with any approach. A unique RPV-based IDM with the addition of two sets of RPVs was presented by [150] in this scenario. The outcomes demonstrate that this approach can identify grid outages for power factor inverters with unity and those without in both single and multi-DG systems.

2.2.3.7 Harmonic Injection

This method's principal benefit is its independence from the balance between electricity consumed and generated [47]. Nevertheless, choosing a safe threshold to identify IS is one of the primary disadvantages. Furthermore, this approach may encounter NDZ for loads with high filtering capabilities. In addition, backdrop distortion may cause annoying excursions, instrumentation noise, or other non-IS events.

A new PLL method based on the SOGI was presented in the publication [151] for this particular circumstance. The same authors suggested an IDM in [17] that relies on injecting a harmonic signal that a double-frequency oscillation can roughly represent. IDM inserting a very comparable disturbance is proposed in [60]. However, GA lowers the number of operations and, as a result, measures the second harmonic order disturbance. Although the GA is also utilized in [152], the suggested approach is predicated on adding the ninth harmonic component. The experimental findings demonstrated a strong performance in IS detection.

An IDM designed for three-phase inverters is proposed to assess the grid impedance [153]. It involves inserting two non-characteristic current harmonics. A digital processing algorithm is used in this strategy to address the issue of instrumentation noise-induced nuisance trips. Additionally, it can identify IS even when there is a power balance. To prevent disruption filtered by capacitive loads, the authors of [154] employ a subharmonic injection. Additionally, it uses a binary tree classification technique to control the inverter from false tripping. In [156] and [157], the compatibility problems of HI techniques in multi-DG systems are also examined.

Another issue with the HI process is obtaining precise harmonic information. Strategies that require intricate mathematical processes, like the GA above, DFT, or ML approaches, are typically used. However, other authors have proposed a cross-correlation-based strategy to reduce the computational complexity.

Although this technique works well, it does not analyze the effects of the grid characteristics and may cause flicker issues or interfere with the DC voltage management. Lastly, a new IDM is proposed in [159] that uses a cross-correlation technique to extract the signal and adds a second-harmonic current component. Because the correlation examines features of the natural grid, it ignores the need to monitor the injected current. Furthermore, even with pseudo link DC, this technique is appropriate for Module Integrated Converters (MIC) and has a modest NDZ.

2.2.3.8 Negative-Sequence Current Injection

This method creates a voltage imbalance between the system's phases following an IS event by injecting a negative-sequence current into the inverter output. Since this method can only be used in three-phase DGs, its principal disadvantages are portability. Additionally, it was determined in [160] that the scheme is vulnerable to nuisance trips due to load fluctuations, rotating machine switches, and other non-IS occurrences. An IDM is presented in [160] that measures the negative-sequence voltage at the PCC to diagnose islanding. The provided results pertain solely to computational simulation and demonstrate the ability to identify IS within 60 ms. Considering the IDM testing criteria, the approach has been proven insensitive to load characteristic variations.

The NDZ of the suggested solution in [160] is found in [161]. Furthermore, a modified approach that can exclude non-detectable situations is proposed in the research, raising the disturbance magnitude to 5%. Current injection method in a multi-DG setting that can identify islanding. A sequential negative current injection approach that can identify IS in a multi-DG setting is presented in [162]. The collected findings show that the method does not depend on Q_f influence, operates in varied grid situations without the need for parametrization modifications, and decreases PQ degradation compared to previous negative sequence-based IDM approaches. Conversely, the low TD and the heavy computing load are the most significant disadvantages. Lastly, [164] and [165] offer additional methods based on harmful sequence injections. However, a high penetration rate of PV inverters can negatively impact their performance, and in weak grid situations, they are susceptible to trips from annoyances.

2.2.3.9 Modern Positive Feedback Methods

A novel active IDM known as APJPF is presented in [129]. It links the inserted distortion with the frequency error [35], combining the distortion suggested in [126] with a frequency positive feedback. On the other hand, a comparison of the solution suggested in [129] and other schemes is conducted in [46]. Additionally, the study indicates a parametrization approach to determine the lowest K gain required to ensure the NDZ is eliminated for a particular range of Q_f.

A novel approach to IS detection utilizing phase-shifted feed-forward voltage is presented in [166]. Its working concept is comparable to that of the SMS algorithm. The experimental findings confirmed the IDM's effectiveness for several quality criteria in both scenarios. The primary objective is to alter the frequency beyond the permitted operational value range to ensure proper inverter shutdown following the occurrence of islanding. The plan passed every test under 90 distinct load situations (varying power levels, normalized capacitance values, and quality factor values) and achieved accurate identification in every scenario. Nevertheless, more research is required to evaluate the method's effectiveness in multi-DG systems.

2.2.4 Local Hybrid Techniques

Compiling the average benefits and drawbacks of both passive and active techniques, the local hybrid IDM. In this way, when compared to active schemes, they can lessen PQ degradation, and when compared to passive schemes, they can diminish NDZ. The principal shortcomings, therefore, are the lengthening T_D and the rise in complexity. Their method of operation is split into two phases. The passive approach is the first when an electrical variable is the only thing being monitored. If not, the active phase is turned off. The evolution of the primary hybrid IDMs' timeline is discussed in this subsection.

2.2.4.1 SFS-Based Hybrid Methods

A hybrid method in [19], wherein the ROCOF monitoring causes the SFS disruption. Since ROCOF's dynamics are faster than frequency, it can help improve the T_D, which is one of the critical shortcomings of hybrid systems. The results show that the technique can detect load islanding with $Qf \leq 5$. Furthermore, the approach demonstrated strong performance in multi-DG contexts and weak grid situations, with the ability to differentiate between IS and non-IS eventualities. A hybrid approach is presented in [169], wherein reactive power monitoring triggers the SFS disturbance. Furthermore, it uses APSO to determine the ideal gain K value to minimize stability implications and ensure accurate IS identification with the lowest possible THD_i. Computing outcomes suggest that IS may be identified under power mismatch load circumstances and $Q_f = 2.5$. Nonetheless, further testing is required to validate the algorithm's capabilities.

2.2.4.2 SMS-Based Hybrid Methods

A novel hybrid IDM is proposed in [170], wherein the active stage introduces the same phase disturbance as the SMS algorithm. The frequency estimation that a droop control performs, in turn, activates the passive stage. The suggested algorithm was evaluated under the UL1741 Standard using a computer simulation. It detected IS for single- and multi-DG systems at various quality factor levels.

2.2.4.3 Voltage Unbalance Methods

As previously mentioned, voltage imbalance can result from the IS phenomenon in a three-phase system. Certain writers employ voltage imbalance as the passive phase in various IDMs. Reference [20] suggests an IDM that combines frequency perturbation and voltage unbalance monitoring. Three passive variations are monitored passively in [146]: voltage imbalance, ROCOF, and voltage variation. IS is recognized as occurring when the frequency variation and the introduced perturbation no longer go below a predetermined threshold. With no requirement for inter-inverter communication, the computational findings show efficacy for a range of load scenarios and IS detection capabilities in a multi-DG context. An IDM is proposed in [90] that combines active bidirectional RPV with passive voltage imbalance and active THD detection techniques. It also offers a precise process for appropriately selecting the harmonic detection threshold using circuit analysis. The outcomes demonstrate excellent performance in multi-DG situations and compliance with the [2] and [42] criteria.

2.2.4.4 ROCOF-Based Methods

The passive stage of hybrid IDM can be effectively implemented using ROCOF monitoring, a potent tool for passive IS identification. Apart from the previously discussed references [19] and [173], wherein the ROCOF functions concurrently with the SFS and SMS, respectively, [172] suggests a hybrid approach consisting of passive ROCOF monitoring and active manipulation of the inverter's reactive power output. Results show that this method detects IS more quickly than previous methods mentioned in [149] and [108].

A novel hybrid IDM based on ROCOF is proposed in [173] to detect IS in a DG system. The suggested approach integrates the elements of the ROCOF passive monitoring system with the perturbation suggested in reference [108]. The proposed method was implemented using the MATLAB/Simulink environment. Tests are still required to confirm the strategy even though the simulation results show that the technique can identify imbalanced IS in less than 100 ms and zero-power mismatch IS in 200 ms.

2.2.4.5 Other ROC-Based Methods

As established, passive IDM watches its derivative rather than monitoring the observed electrical amount. In this case, achieving the passive stage of hybrid approaches can also be done by measuring the rate at which an electrical variable changes. A hybrid IDM using the ROCOV as the passive stage is proposed in this context by [22]. To diverge the voltage magnitude beyond the permitted range of operation, an RPS is started when the detected ROCOV value rises above a particular threshold. The technique was evaluated in various scenarios, including the energization of transformers, the starting of induction motors, and the functioning of several DGs. The findings show that the approach can identify IS for loads falling inside the quality factor range of $0 < Q_f \leq 5$ and is specific for non-IS events. Nonetheless, further research and development are required to validate the approach.

2.2.5 Intelligent Passive Techniques

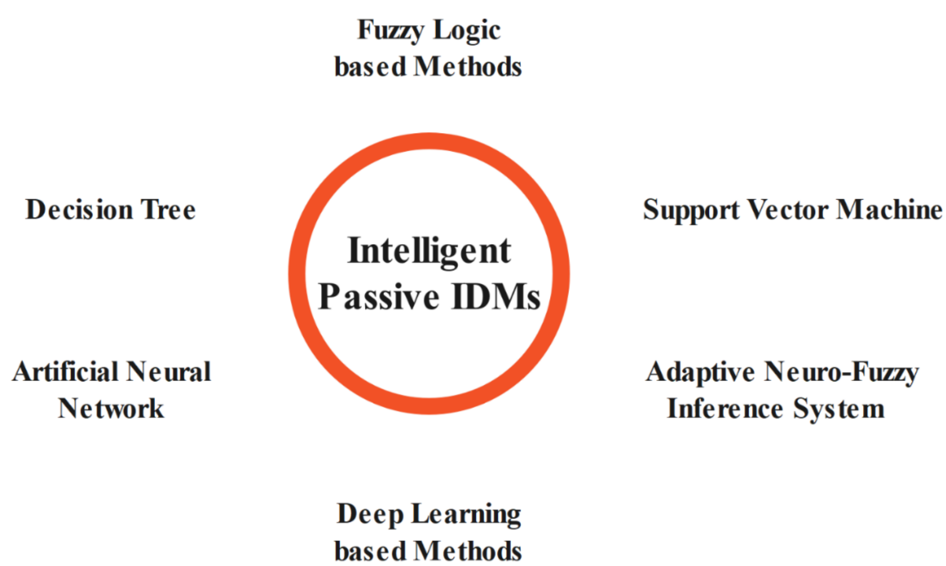


Fig. 2.4 Intelligent Passive IDMs

Selecting the suitable threshold for detection is challenging for many techniques used to identify power system events. While standards specify recommended thresholds for frequency- and voltage-based schemes, the application of other approaches, is characterized by the challenge of choosing the appropriate threshold for detection. Under this situation, [36] predicts that IDM research will move toward using intelligent classifiers, as shown in Fig. 2.4, including SVM, ANN, FL, DT, and ANFIS. Because they extract features from the signal and use them as input for judgment, these classifiers do away with the difficulty of setting detection thresholds. Specific active approaches, such as those covered in [133] and [169], use ML and its algorithms. Though they don't directly affect the IS decision, they are left out of this part because the primary goal of using ML is to parameterize the techniques dynamically.

2.2.5.1 Decision Trees

DTs are a subset of ML algorithms that use feature-based binary classification to evaluate data inputs and provide conclusions. DT can be taught to identify the electrical signals connected to IS by giving instances of regular grid functioning and IS occurrences. The DT can be trained to identify fresh data and isolate DG if an IS event is recognized, enhancing grid safety and dependability [174]. A DT-based method in [175] avoids falsely tripping the DGs by processing the signals using WT and extracting characteristics from transient variations in PCC voltage and inverter output current. The acquired findings outperformed passive options regarding IS detection. In contrast, the ROCOF method and OUV/OUF attained a 100% selectivity rate, while the DT solution only managed a 93.75% selectivity rate, with an average T_D of about two conduction cycles. The DT+WT combination is also used in the technique suggested in [176] to carry out loss of mains detection. An approach based on the Random Forest Classification (RFC) concept is put forth in [25]. Alternatively, the computational overhead can be decreased by employing just four conditions. However, the overall efficiency drops to 98%. A DT-based IDM is presented in [177], where the chosen features are placed in several measurement windows based on their specificities. This is a significant benefit regarding T_D, as it enables the quick classification of incidental IS scenarios when an imbalance between energy generation and consumption is not confirmed. The findings show an accuracy rate of >99%, and 79% of the evaluated cases had less than 20 ms T_D.

2.2.5.2 Artificial-Neural-Network

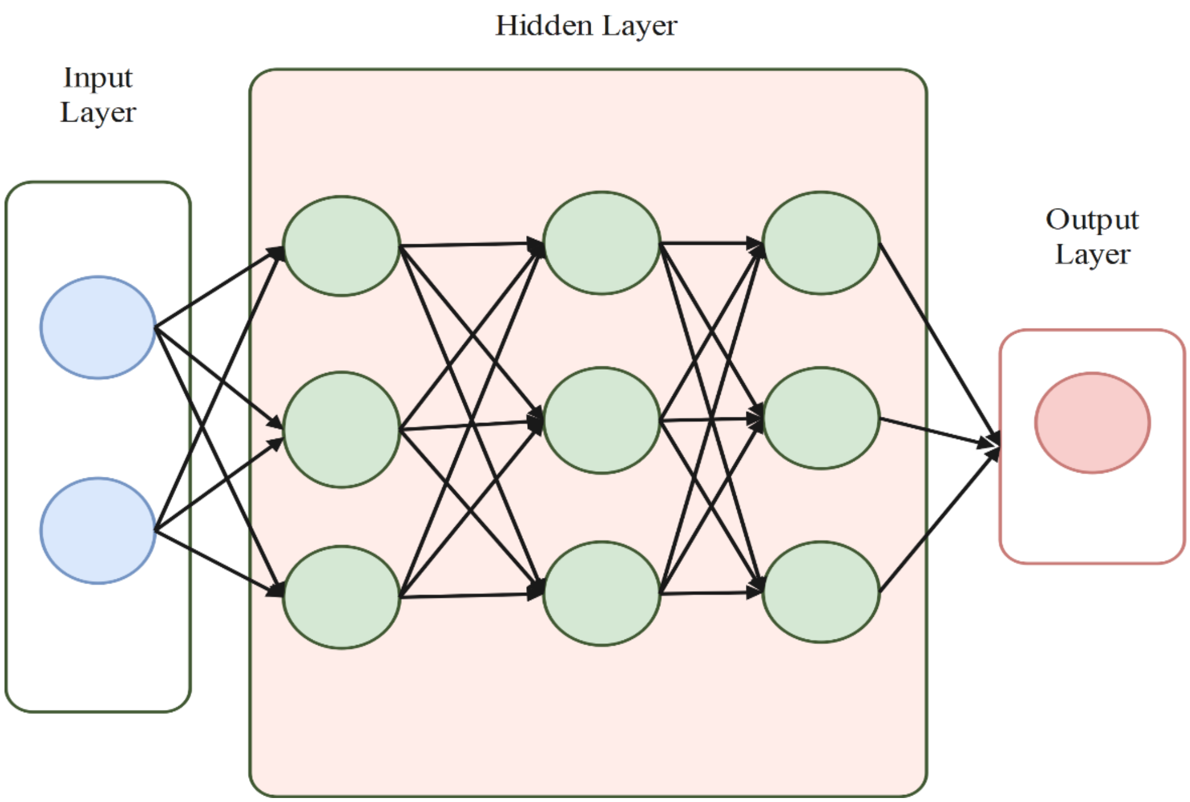


Fig.2.5 Generic ANN representation

An ML technique known as an ANN comprises many interconnected processing units, or neurons, arranged in layers. As shown in Fig. 2.5, each neuron receives input signals from other neurons and produces an output signal that can be used to input signals to neurons in layers below [178]. Feature extraction is a crucial phase in the training of ANNs. The primary techniques used to extract features are phase space, DWT, HT, TQWT, and DFT [38]. It is suggested in [179] to use an ANN-based IDM that uses the GreyWolf Optimized ANN as the intelligent IS classifier and the VDM and HT to facilitate feature extraction. The system was tested in a multi-DG scenario with two synchronous machines and two PV systems. According to the results, the calculation time, robustness against noise conditions, and IS classification accuracy are all adequate. A two-stage mechanism for detecting IS is proposed in [29]. Extracting features from recorded voltage and current waveforms using the DFT is the initial step. The second stage consists of classifying the existence of IS using a KNN-based classifier that receives nine features as input.

The classic method for a single-hidden layer, FNN, is recommended to replace a new ANN-based IDM in [180]. Analytically, it determines the output weights by randomly selecting the input weights and hidden layer biases. To achieve a total accuracy of 99.09%, the ELM approach is also used in [181]. Specific methods employ the WT to ensure accurate feature extraction. An IDM that employs both WT and MM in the extraction stage is presented in [182]. An ELM is in charge of the classification. Depending on the size of the training data set, the produced result, which has an accuracy of 100%, demonstrates the usefulness of the proposed IDM even in boisterous environments. The paper [183] presents an IDM based on ANN. TQWT is used to extract features. The WT method, TQWT, allows for adjusting a control signal's oscillatory behaviors through configurable control parameters. The algorithm's parameterization process is also presented in the publication. Computational studies show 98% efficiency for both IS and non-IS occurrences.

2.2.5.3 Support Vector Machine

Regression analysis and classification are two applications for supervised learning techniques called SVM. SVM seeks to identify the hyperplane that divides the data into classes as much as possible, leaving a margin between the nearest data points in each class. Because SVMs can process linear and non-linear data, they are frequently used in electrical power system protection, particularly for event categorization and IS detection [184]. Compared to the previous ANN performance, this method offers a significant advantage. It works based on structural risk elimination, beyond eliminating training data errors to minimizing an upper bound on the projected risk. As a result, using a smaller training sample can lead to improved accuracy [27]. Within the framework of IDM, several SVM-based methods might be emphasized. The following features are extracted using the IDM presented in [185]: voltage, frequency, phase angle, ROCOF, and ROOV. When the active power imbalance is 5% or more, the method effectively identifies IS events; however, when the imbalance is less than 8.8%, the VS relay malfunctions. An SVM-based event classification approach that can be applied to identify IS is proposed in [186]. Under

UL741 testing conditions, the IDM demonstrated efficacy, selectivity, accuracy, and precision. The solution outperformed results obtained by ANN-based algorithms, with an average T_D of 40 ms.

2.2.5.4 Fuzzy Logic

FL can be used for IS identification in electrical power networks [187]. A FL-based IDM that performs IS detection in two stages is proposed in [188]. To diagnose loss of sources, the first one comprises a DT algorithm that takes features and selects the three most important ones. The FL classifier divides IS and non-IS electrical events into two classes, making up the second stage.

2.2.5.5 Adaptive Neuro-Fuzzy Inference System (ANFIS)

Combining the best features of ANN and FL classifiers, ANFIS algorithms are a hybrid technique. ANFIS is a versatile tool that may be utilized for various tasks, such as electrical fault classification and IS detection. These jobs include regression, control, and classification [189]. An ANFIS IDM specifically for wind turbines is presented in [190]. Conversely, [191] presents a novel technique for passive IS detection through data clustering, wherein subtractive clustering is used to build a robust and simplified fuzzy classifier. The ROCOF relay was outperformed, according to the results. A method for ANFIS extraction of seven PCC inputs is presented in [28]. Testing of the procedure was conducted with UL741 standards. Findings show a 78.4% success rate for accurate IS detection. Furthermore, it exhibits a quicker detection than the other tactics in this section. In comparison, the data indicate selectivity and efficiency.

2.2.5.6 Deep Learning Based Methods

DL is an ML method that learns representations of data with various degrees of abstraction by utilizing numerous processing layers. A proposal for using DL for islanding detection is found in [193]. The suggested classifies whether or not an IS event is present using a regression method and a deep neural network built on stacked auto-encoders. The findings show a 98.3% accuracy rate and a 0.18-second T_D. This method performs better than alternative classification techniques but requires a very high sample size. A two-stage DL technique is proposed in Reference [95]. First, a DFT is applied to voltage data detected from the PCC to ensure selectivity and extract features specifically linked to IS events. The ability to identify IS in 6 ms with an average accuracy rate of 99.61% was shown via computational testing. The outcomes also show that this strategy is better than others, including DT, SVM, and ANN, in terms of accuracy and T_D. This paper [24] proposes a new DL-based IDM that consists of four stages: obtaining voltage data in three phases, concatenating the data, and feeding the phase and magnitude data into a DNN to classify IS and non-IS events. The outcomes show a 98.76% efficiency rate. Furthermore, it could accurately diagnose IS in a multi-DG context without compromising PQ. Selectivity tests were conducted to demonstrate its ability to differentiate between non-IS contingencies.

2.2.6 Signal Processing Based Methods

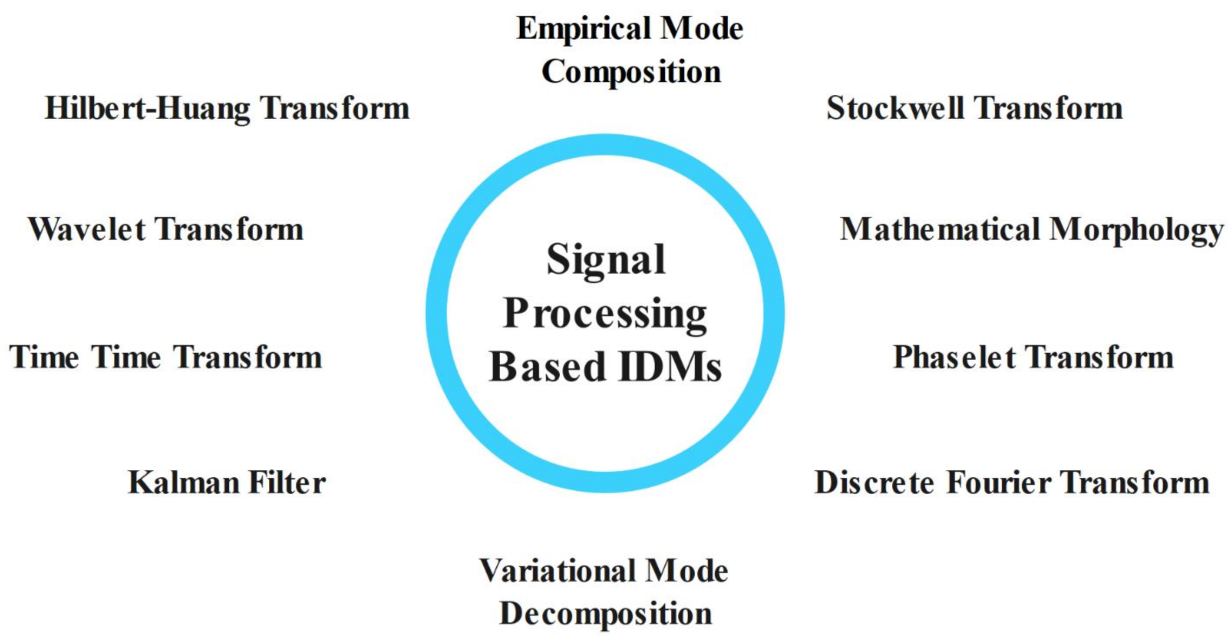


Fig. 2.6 Signal Processing-based IDMs

As shown in Fig. 2.6, SP methods can be applied to improve passive methods of IS detection. These techniques offer cost, stability, adaptability, and flexibility, which help researchers identify hidden characteristics in recorded signals for IS detection. Based on these detected qualities, decisions can be made on the likelihood of islanding. Several SP tools are used to detect islanding, including the FT, ST, HHT, WT, and TT-transform; they are explained in more detail in the following sections [39]. It is important to note that, as was previously said, some intelligent algorithms use SP technologies to extract features. This subsection will not address these techniques.

2.2.6.1 Wavelet Transform (WT)

Due to this decomposition, the signal is represented in both the temporal and frequency domains, making it possible to identify localized features. The WT is an adaptable tool that may be used to analyze signals of any size and detect changes over short and extended periods. Its uses go beyond SP, including data extraction, audio analysis, and image processing. WT has been used in electrical power systems for fault categorization and IS identification. The first use of WT for IS detection has been reported in [195]. This technique uses WT to separate high-frequency harmonic components. Results from computation and experimentation show that the approach can detect source loss in less than 400 ms, especially when the grid's active and reactive power contributions are zero. A new approach to Active IDM based on WT is presented in [196]. Detailed coefficients are obtained by applying WT to three-phase voltage signals. These coefficients are then utilized to build a singular value matrix and calculate the WSE for every phase. The WSE index is then calculated, the total of the WSE values from every phase. The proposed method has been found to provide increased selectivity and faster detection of IS occurrences when compared to traditional ROCOF and ROCOV relays.

WPT is used in [197] to extract features from the apparent power of the three-phase system to implement an Active IDM. A combination of wavelets called WPT helps capture high-frequency harmonic component transient oscillations. The results of the experiments show an average T_D of 10 ms, as well as acceptable low-voltage ride-through performance and minimal effect on PCC PQ. Furthermore, Paper uses an analogous IDM in a cogeneration plant [199], and a similar technique is applied in farm collector systems [200]. Based on WT, the Active IDM is presented in [201]. It changes the traditional continuous WT. IS pattern detection entails examining a dataset containing multiple PQ variables. The results show it can differentiate between electrical occurrences, including two-phase failures, phase-to-line short circuits, and IS events. Another novel approach to Active IDM is presented in [30], which involves modifying the discrete WT. This technique uses a Maximum Overlap Discrete Wavelet Transform (MODWT) and a Second-

Generation Wavelet Transform (SGWT) instead of the conventional discrete WT. Reduced memory usage, less computational load, and fewer pointless calculations are the goals of the SGWT. In the meantime, the length of the signal is maintained because the MODWT stops the sample size from decreasing at every stage of decomposition.

2.2.6.2 Mathematical Morphology

The time-domain analytical technique known as MM focuses on signal form, integral geometry, and set theory. Compared to other SP techniques like WT, ST, HST, and TTT, morphological filters based on MM have lower computational needs since they use simple signal transformation operations like addition and subtraction. Because of its straightforward implementation can also be used for fault categorization and source loss detection in DG [32]. The MM operator dilation and erosion are used in [202] to produce a DED filter. This is a proposed MM technique of IS detection. A comparable method that develops an IDM based on MM specifically for MGs is suggested in [203]. It detects IS solely by measuring the PCC voltage, although employing the same DED filter idea. The results of the computation show that IS detection is possible in less than 10 ms on average.

2.2.6.3 Stockwell Transform (ST)

The WT shortcomings, such as batch data processing and noise sensitivity, are suggested to be remedied by the ST. Short-time FT and WT are combined using a scalable Gaussian variable window. With the help of this technique, a time series signal can be converted into a time-frequency representation with frequency differentiation. Multi-resolution is possible with this method without changing the phase of the different frequency components. ST uses the amplitude or phase time-frequency spectrum to help identify disturbances like electrical faults or islanding and observe local spectral patterns [204]. The ST is used in [31] to assess the inverter output current and produce a MIRF, the first step in the Active IDM. To determine the CIRFC, the RMS current is differentiated over time to assess the rate of change of MIRF. For IS contingencies, two thresholds are set: one for fault detection. Assuming a signal-to-noise ratio of 10dB, the results show selectivity for non-IS events and precise identification of IS. [23] uses a technique to extract harmful sequence data from voltage and current signals and construct an indicator for current IS detection by combining the ST and HT. This method, tested with an IEEE-13 nodes model, achieves an efficiency of more than 98% and can successfully identify IS events even in noisy surroundings with a signal-to-noise ratio of 20dB. A comparative analysis was also carried out, which shows that the suggested approach outperforms WT-based algorithms, traditional passive solutions, and ANN-based IDMs. A technique for identifying events as IS or non-IS is introduced in [205]. The system performs well in noisy situations and can distinguish between non-IS events and grid interruptions. Software from MATLAB/Simulink was used to conduct the investigation, and a real-time digital simulator was used to validate the results in real-time. The findings show that IS occurrences and temporary, normal changes in electrical amounts can be accurately distinguished.

2.2.6.4 Empirical Mode Composition (EMC)

An adaptive multi-resolution SP method, EMC, can separate non-stationary or non-linear signals into distinct groups of IMFs at different resolutions. In [35], IS detection was achieved by the use of EMC. A novel approach to Active IDM is presented in this work. It is based on a Time-Varying Filter (TVFEMC), which uses an adjustable cutoff frequency filter to create two IMFs. A Teager energy operator calculates the IMF's energy density.

2.2.6.5 Hilbert-Huang Transform (HHT)

Hilbert Spectral Analysis (HSA) and EMD are the two processes that make it up. An EMD breaks down a signal into a collection of IMFs, or intrinsic mode functions, that describe different frequency components in the signal. In contrast, the HT is employed by HSA to investigate the instantaneous frequencies and amplitudes of these IMFs. Because HHT can analyze non-stationary signals, it can capture changes in frequency content and amplitude over time, which makes it useful for IS identification [204]. In [206], an HHT-based Active IDM is unveiled. It entails monitoring the inverter output current and PCC voltage and then analyzing these signals using EMD to obtain IMFs. After computing the HT for both voltage and current signals, a ratio index is obtained from these transforms. The ratio index functions as a cutoff point to detect IS events and differentiate them from switching events that are not islanding. Even with a 5% discrepancy in reactive power, the suggested method could identify islanding.

2.2.6.6 Variational Mode Decomposition (VMD)

A method for SP called VMD breaks down the input signal *u(t)* into discrete signals $u_k(t)$, also known as band-limited IMFs or sub-signals. It provides a more accurate and stable signal breakdown compared to other methods. VMD has proven effective in various sectors and can provide novel perspectives on problems in science and engineering. VMD algorithms can be used in DG and MGs for fault classification and IS detection. Five IMFs are extracted from the PCC voltage by the novel Active IDM described in [207]. This algorithm makes use of the VMD idea. A control system then calculates statistical parameters like standard deviation and Kurtosis index. Comparing these characteristics to predetermined thresholds is how islanding is determined. Computational results in both IS and non-IS scenarios demonstrate the method's usefulness. It can even detect mains failure when there is a zero-power mismatch. In [208], a VMD-based method is put forth that computes the energy index using an empirically determined equation after breaking down the PCC voltage into four IMFs. Findings show that IS may be identified for loads with Q_f = 3.5, even at a signal-to-noise ratio of 20dB. A unique technique for identifying IS occurrences is provided in [34], whereby the SSKNN method and VMD are integrated. This method works by extracting three-phase voltage signals, determining the significant modes by VMD, and creating four feature indices based on the first three modes. Empirical findings validate the efficacy of this methodology, which conforms to the standards specified in IEEE 1547.

2.2.6.7 Kalman Filter

An algorithmic mathematical tool called the KF estimates variables over time intervals by considering noise and observed measures. It provides precise estimates of the state of a system by computing joint probability distributions across variables for every timeframe. It is appropriate for several applications, such as frequency measurements, harmonic decomposition, PQ monitoring, control of power conditioners and synchronization, and IS detection, due to its strong signal estimating capabilities, even in the face of distorted data.

The KF has been used for loss of sources classification in the field of IS detection, as [33] shows. An expanded version of the KF is used in this innovative IDM to estimate frequency in an MG context. The frequency variance is compared to a predetermined threshold to determine islanding. Based on computational results, the extended KF performs better in frequency estimation than traditional KF and Fourier filtering. Additionally, even with balanced power settings, the method's accuracy in diagnosing IS seems promising; nevertheless, selectivity outcomes were not given.

2.2.6.8 Other Signal Processing Based IDMs

TTT and PT are two more SP techniques used for IS identification. With PT, features are extracted from the input signal more effectively by using an adaptive measurement window and applying sinusoidal or co-sinusoidal functions to the sum of squared data samples. It is evident from [211] and [212] that PT successfully detects islanding. As opposed to this, TTT creates a two-dimensional representation of a one-dimensional signal using the ST. IS detection has made use of it in [213].

Following a detailed review of various IDMs, it is essential to synthesize these techniques' key characteristics and performance metrics.

Table 2.1 Overview of prior research contributions

IDM	Overview of prior research contributions along with our insights and evaluations
Remote IDMs	Remote IDMs offer accurate islanding detection and eliminate NDZs, but are costly and complex for small DGs [5][6][8][11][72]. Impedance Insertion is low-cost but slow and less reliable [6], while PLCC and DTT need strong communication infrastructure [5][8]. PMU/MPMU methods enhance speed and precision but face cyber vulnerability and high implementation demands [74][75][81][82].
Local Passive IDMs	Local passive IDMs are simple and non-intrusive but suffer from large NDZs and slow response [37]. Common methods like OUV/OUF [16], PJD [12], and HD [84][91] face reliability issues and threshold challenges. ROCOF, ROCOV, ROCPAD, and hybrid variants improve detection but still risk false trips and complexity [96][102][119].
Local Active IDMs	Local active IDMs introduce controlled disturbances to reduce NDZ, trading off power quality (PQ) for reliability [18]. Methods like AFD, SFS, SMS, RPV, and harmonic injection offer enhanced detection but face issues like PQ degradation, complexity, and slower detection in multi-DG systems

	[124][106][142][151]. Advanced techniques improve accuracy but increase computational cost and sensitivity to grid/load dynamics [129][160][166].
Local hybrid IDMs	Local hybrid IDMs combine passive monitoring and active perturbation to reduce both NDZ and PQ degradation, though they increase complexity and detection delay [19][170]. SFS and SMS-based hybrids improve performance in multi-DG and weak grid scenarios, while methods using voltage imbalance, ROCOF, and ROCOV enhance selectivity and adaptability [90][146][172]. These schemes show promise in simulations, but many require further experimental validation to confirm reliability in real-world applications [173].
Intelligent Passive IDMs	Intelligent passive IDMs use machine learning methods to eliminate fixed threshold issues and enhance accuracy and selectivity [36][174][178][184][189]. These methods extract features from voltage/current signals and classify IS events with high accuracy, reduced detection time, and robustness in multi-DG and noisy conditions [29][179][183][193]. DL-based IDMs outperform others in speed and precision but require larger datasets and higher computational cost [24][95].
Signal Processing based IDMs	Signal Processing (SP)-based IDMs enhance traditional passive methods by extracting time-frequency features from electrical signals using WT, ST, HHT, EMC, VMD, and Kalman Filter [39][195][204]. These methods offer high adaptability, accuracy, and faster detection, especially under non-stationary and noisy conditions, though they may require computational resources and fine-tuning [196][207][33]. SP techniques like WT, MODWT, MM, and VMD show detection times as low as 10 ms and outperform conventional passive and intelligent methods in various test cases [197][202][34].

A comprehensive comparison in Table 2.2 has been compiled to understand each method's strengths and limitations better. This table evaluates the discussed IDMs based on critical criteria.

Table 2.2 IDM Comparison

IDMs		**PQ impact**	**Detection Time**	**Dependency of parameters on the MG and DG**	**Suitable Type of DG**
Local Methods	Passive	No effect	Low	Moderate to High	Inverter-based DGs / Synchronous DGs
	Active	degrade	Fast	High	Mostly Inverter-based DGs
	Hybrid	Slightly degrade	Moderate to Fast	Low	Inverter-based DGs / Synchronous DGs
Remote Methods		No impact	Low	Low	Universal, suitable for all DG types
Computational Intelligence - based Methods		No Impact	Low to Moderate	Low	Inverter-based DGs / Synchronous DGs
Proposed		**Negligible Impact**	**Low**	**Low**	**Hybrid DGs**

2.3 Research Gaps

The above section highlights several vital gaps in the literature that need to be filled to advance the topic of ID in HMGs.

- Most IDMs are primarily designed for traditional power systems or MGs solely inverter-based. This limits their applicability in the more complex environment of HMG, which combines synchronous and inverter-based DG, posing particular operational challenges not sufficiently addressed by existing detection methods.
- Passive IDMs are insufficient for scenarios involving balanced active and reactive power, necessitating the development of NDZ-free IDMs for HMG.
- Despite their increased robustness, active IDMs have the potential to cause system disruptions like frequency deviations, especially in multi-inverter systems that lack synchronous control. This restriction emphasizes the need for a more dependable IDM suited to the complexity of HMGs.

- As HMGs are increasingly digitized, Signal interference and cybersecurity vulnerabilities are major practical issues for communication-based IDMs for HMGs.
- Hybrid IDMs, which aim to leverage the strengths of both passive and active techniques, continue to encounter significant NDZs and challenges in selecting thresholds. These concerns indicate that hybrid detection approaches require additional refinements to improve their accuracy, speed, and overall efficacy in hybrid MG applications.

2.4 Objectives

1. Islanding detection in AC-DC microgrid by using a hybrid method.
2. Performance analysis of proposed islanding detection technique by performance Indices.
3. Comparison analysis of the proposed hybrid method and existing islanding Detection methods for AC-DC microgrid based on performance indices.

2.5 Methodology

1. Islanding Detection in AC-DC Microgrid Using a Hybrid Method.

(Including Design and Development of the HMG and Implementation of Hybrid Islanding Detection Method)

1.1 Design and Development of Hybrid Microgrid

The design and development of an HMG, which integrates both AC and DC components, is crucial to creating a system that efficiently supports various DERs, batteries, and conventional power sources. HMG combines the benefits of both AC and DC systems, providing enhanced flexibility in integrating RES and improving overall energy efficiency.

1.2 Implementation of Hybrid Islanding Detection Method

The methodology for detecting islanding in an AC-DC MG uses a hybrid approach, combining passive and active islanding detection techniques to leverage their advantages while minimizing their limitations. The AC-DC MG presents unique challenges, such as the presence of both AC and DC power systems, which introduces complexity in synchronization and protection. Hybrid IDMs seek to address these challenges by integrating passive monitoring of grid parameters with active techniques that inject disturbances into the system to provoke measurable changes during islanding events.

1.3 Performance Analysis of Proposed Islanding Detection Technique by Performance Indices

A set of key performance indices quantify detection accuracy, speed, and system reliability to evaluate the effectiveness of the proposed islanding detection technique. These performance indices are critical in determining how well the hybrid IDM performs under various operational conditions and help benchmark the technique against existing standards.

Key Performance Indices:

- **Non-Detection Zone (NDZ)**: One of the primary performance metrics is the NDZ, which represents the region where the islanding detection technique fails to identify islanding events. The methodology seeks to minimize or eliminate the NDZ by integrating active and passive methods, ensuring the system detects islanding across various operating conditions.
- **Detection Time (TD)**: The detection time refers to the interval between an islanding event's occurrence and the system's identification. A critical objective of the hybrid method is to reduce this detection time to ensure rapid system response, which is vital in maintaining grid stability and preventing hazards associated with delayed detection.
- **Power Quality Impact**: The impact on power quality, particularly during active detection stages, is evaluated to ensure that the injected disturbances do not

negatively affect the MG's stability and reliability. The methodology aims to limit power quality degradation by minimizing the size and duration of disturbances during the detection process.

This methodology measures performance indices under various test conditions, including scenarios with balanced and unbalanced loads, different penetration levels of DERs, and varying levels of grid strength. Simulations and real-time experiments are conducted to assess how well the hybrid detection method performs, providing data compared against performance benchmarks from IEEE 1547.

3. Comparison analysis of the proposed hybrid method and existing islanding Detection methods for AC-DC microgrid based on performance indices.

The third objective compares the proposed hybrid IDM with existing techniques for AC-DC MGs. This comparison is based on the performance indices described earlier to understand the strengths and weaknesses of different approaches in practical settings.

CHAPTER-III

METHODOLOGY

3.1 Introduction

The review of existing IDMs has highlighted significant limitations in their application to HMGs, which integrate synchronous and inverter-based DG. Passive IDMs suffer from extensive NDZs, particularly in balanced active and reactive power scenarios. In contrast, active IDMs often introduce system disturbances, such as frequency deviations, in multi-inverter systems. Although effective in centralized grids, communication-based methods face growing challenges related to signal interference and cybersecurity vulnerabilities as HMGs become increasingly digitized. Hybrid IDMs, which attempt to combine passive and active approaches, struggle with accurately selecting thresholds and the persistence of NDZs. This methodology proposes developing an advanced IDM framework tailored explicitly to HMGs to address these challenges. The approach focuses on eliminating NDZs through enhanced detection algorithms, minimizing system disturbances with adaptive control strategies, and mitigating communication vulnerabilities by incorporating secure and interference-resilient protocols. Furthermore, the hybrid IDM will be refined using dynamic threshold optimization and real-time learning techniques to improve detection speed and accuracy. The subsequent sections will detail the specific models, algorithms, and methods used to develop and implement this solution, ensuring its applicability in complex HMG environments.

3.2 Hybrid Method Design Principle

The qualities, benefits, and drawbacks of active and passive methods must be appropriately understood to develop a hybrid method that performs effectively. In the hybrid method, the passive technique detects the possibility of an islanding state, and only then does the active method become active, and the active method ultimately carries out the tripping operation. It is important to emphasize that arbitrarily combining passive and active methods will not yield the intended outcome. Therefore, to achieve the desired performance in HMG, the proposed hybrid ID approach uses the ROCPAD method, a passive detection technique noted for being extremely sensitive. The active method is the IB-BRPV technique, which removes NDZ without adding harmonic components. The following sections explore the ROCPAD, IB-BRPV, and potential hybrid operational methods.

3.2.1 Rate of Change of Phase Angle Difference Method

The ROCPAD method relies on precisely detecting the phase difference between voltage and current signals to compute the ROCPAD value accurately. This is accomplished by transforming time-domain instantaneous voltage and current signals into their phasor, which processes the instantaneous voltage and current data gathered from the system. The system's signal x(t) is represented as shown in equation (3.1):

$$x(t) = \sum_{k=1}^{\infty} B_k \sin(2\pi k f_t + \delta_k) \qquad \text{……… (3.1)}$$

where δ_k and B_k represent the angle and amplitude of the kth order waveform, and f denotes the system frequency.

Conversion of $x(t)$ into d and q quantities as per (3.2):

$$\begin{bmatrix} X_d \\ X_q \end{bmatrix} = \begin{bmatrix} \sin(\omega_0 t) & -\cos(\omega_0 t) \\ -\cos(\omega_0 t) & -\sin(\omega_0 t) \end{bmatrix} \times \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \qquad \text{……….…... (3.2)}$$

d and q quantities in the mth order sample time, as per (3.3)

$$\begin{bmatrix} x_d(m) \\ x_q(m) \end{bmatrix} = \frac{3}{2} \begin{bmatrix} \sum_{k=1}^{\infty} B_k \cos[2\pi(kf - f_0)mT_s + \delta_k) \\ -\sum_{k=1}^{\infty} B_k \sin[2\pi(kf - f_0)mT_s + \delta_k) \end{bmatrix}$$

.... (3.3)

For k=1,

$$x_{d1}(m) = 1.5B_1 \cos[2\pi(f - f_0)mT_s + \delta_1]$$

$$x_{q1}(m) = -1.5B_1 \sin[2\pi(f - f_0)mT_s + \delta_1]$$

…………………….………………..… (3.4)

from (3.4), δ_1 is calculated as:

$$\delta_1 = \arctan\left[-\frac{x_{q1}(0)}{x_{d1}(0)}\right]$$

……..… (3.5)

$$ROCPAD = \frac{\Delta(\delta_v - \delta_i)}{\Delta t}$$

…………………….. (3.6)

The quicker response time and superior performance with an active power imbalance of 0% are the significant benefits of ROCPAD. The disadvantage of this approach is that, even though the DG is linked to the UG, it may still result in an annoyance trip during significant load changes or nonlinear load integration [36]. Through the collaborative effect, these weaknesses are addressed by combining ROCPAD with an active approach. By adding an extra layer of analysis to ROCPAD, the active technique makes it possible to evaluate ID reliably. By taking advantage of the responsiveness and reliability of ROCPAD and the discriminating power of the active method, this combination plays to the benefits of both strategies.

3.2.2 Bilateral Reactive Power Variation Method

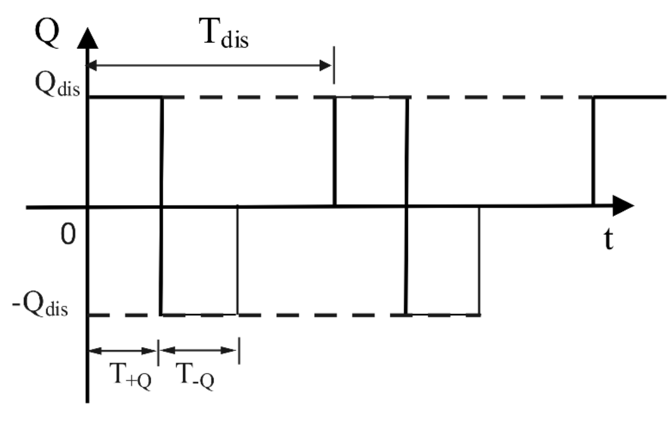


Fig. 3.1 Schematic Diagram IB-RPV

Due to its ease of implementation and lack of harmonic introduction, the IB-RPV method is often regarded as one of the most alluring active methods. The PCC frequency subsequently drifted beyond the permissible range by controlling the inverter to provide enough RP. Numerous approaches have been suggested in the literature on RPV, but the IB-RPV technique effectively removes the NDZ with no impact on PQ [37]. RP perturbation time is decreased, and PQ is improved by the IB-RPV method, which alternates the output RP's amplitude between positive Q_{dis} and negative -Q_{dis}, and 0 intermittently, as shown in Fig. 3.1

The active and RP used by the local load can be described as follows when the DG is linked to the utility:

$$P_L = P + P_G = 3\frac{V_{PCC}^2}{R}$$

…………. …. (3.7)

$$Q_L = Q + Q_G = 3V_{PCC}^2\left(\frac{1}{2\pi f L} - 2\pi f C\right)$$

…………………. (3.8)

VPCC and f, as well as voltage and frequency of the PCC, respectively. P and Q, the inverter's output is active and RP.

Q_f and resonance frequency f_0 can be defined as

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

……..……….... (3.9)

$$Qf = R\sqrt{\frac{L}{C}}$$

…………………………. (3.10)

Inferring from (3.7) and (3.8), the system frequency.

$$f = \frac{f_0}{2}\left[\sqrt{\left(\frac{Q_L}{Q_f P_L}\right)^2 + 4} - \frac{Q}{Q_f P_L}\right]$$

………….………. (3.11)

Similarly, the frequency under islanding conditions is

$$f_{IS} = \frac{f_0}{2}\left[\sqrt{\left(\frac{Q}{Q_f P}\right)^2 \quad + 4} - \frac{Q}{Q_f P}\right]$$

……….…….….... (3.12)

The frequency of a system during islanding is affected by the ratio of the reactive and active powers produced by the inverter, Q_f of RLC load, and the f_0. The RP generated by the inverter, about the active power, directly influences the frequency dynamics, as it affects the load-sharing mechanisms within the MG. Additionally, the quality factor, representing the efficiency and energy losses within the system components, can significantly impact frequency deviations. Moreover, the resonance frequency of RLC loads, which characterizes the natural frequency at which these components oscillate, further contributes to frequency variations during islanding events.

As a result, by altering the RP's amplitude, the frequency after islanding can exceed the set threshold. When (3.11) and (3.12) are combined, the frequency under islanding condition is given by

$$= \frac{f_0}{2}\left[\sqrt{\left(\frac{Q}{Q_f P}\right)^2 + 4} - \frac{Q}{Q_f P}\right] f_{IS}$$

$$= \frac{f}{2}\left[\sqrt{\left(\frac{Q_L}{Q_f P_L}\right)^2 + 4} - \frac{Q}{Q_f P_L}\right] \times \left[\sqrt{\left(\frac{Q}{Q_f P}\right)^2 + 4} - \frac{Q}{Q_f P}\right]$$

….……………..... (3.13)

The NDZ can be obtained from (13) as follows, assuming that the frequency range is [f_{min}, f_{max}]

$$Q_f\left(\frac{f_{min}}{f} - \frac{f}{f_{min}\sigma}\right) \leq \frac{\frac{Q_L}{P}}{\frac{P_L}{P}} \leq Q_f\left(\frac{f_{max}}{f} - \frac{f}{f_{max}\sigma}\right)$$

………..………. (3.14)

Where,

$$\sigma = \frac{1}{2}\left[\sqrt{\left(\frac{Q}{Q_f P}\right)^2 + 4} - \frac{Q}{Q_f P}\right]$$

………………..…. (3.15)

The NDZ of BRPV is divided into two halves, according to (14). The NDZ can be characterized as Z+Q when the RP Q = Q_{dis}, and as Z-Q when Q = -Q_{dis}, therefore the system's ultimate NDZ would be the region that overlaps Z+Q and Z-Q. Z+Q and ZQ should not overlap to remove the BRPV's NDZ. Therefore, to complete (14), the RP's variation amplitude Q_{dis} should

$$Q_{dis} \geq \frac{f_{max} - f_{min}}{\sqrt{f_{max} f_{min}}}\ Q_f P$$

…………. …. (3.16)

Thus, it is especially appropriate for HMG applications because it can eliminate the NDZ of BRPV by carefully configuring the parameters, which guarantees minimal disruption to PQ and has a negligible effect on the PQ of grid-connected systems when compared to active IDMs that have been widely used [37]. Unfortunately, counteraction effects provide a challenge to the BRPV approach in HMG. Phenomena that cause the output RP to decrease and increase the possibility of detection failure is the source of this counteraction. However, when BRPV is included as the active approach in a hybrid framework, this problem can be successfully reduced by the Proposed Methodology of Hybrid Operation.

3.3 Hybrid Operation

Based on the abovementioned details, the ROCPAD and IB-RPV methods can be employed in a hybrid approach. In the suggested hybrid IDM, they are integrated to provide HMG with an acceptable performance.

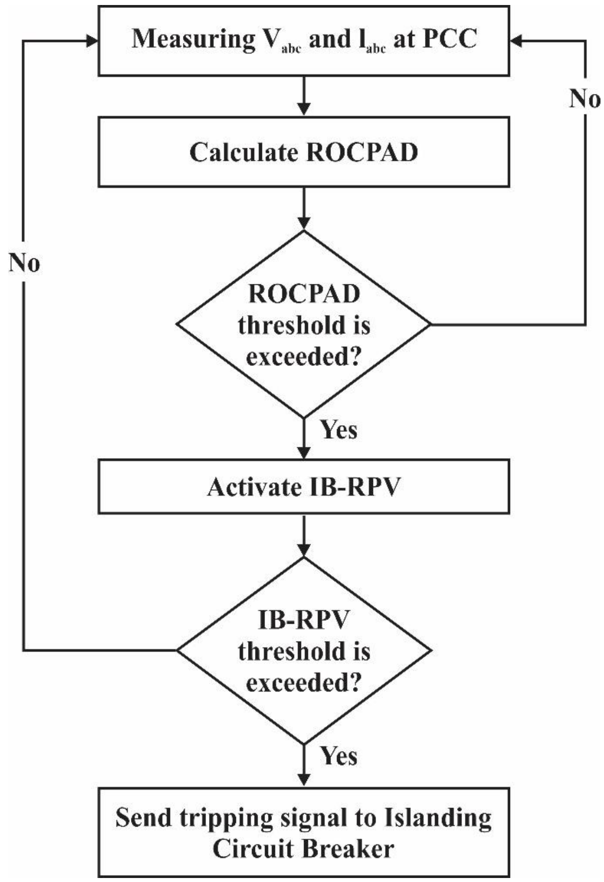


Fig. 3.2 Flowchart of Proposed Hybrid Method

Fig. 3.2 shows the flowchart for the suggested hybrid method. The phase angle difference deviation is calculated while the PCC voltage and current are continuously observed. The BRPV technique will be engaged when the ROCPAD threshold is surpassed. Unlike the typical approach of functioning periodically, the hybrid method suggested here requires the IB-RPV method to modify the amplitude of the output RP between Q_{dis} and -Q_{dis} only once upon receiving an activation signal.

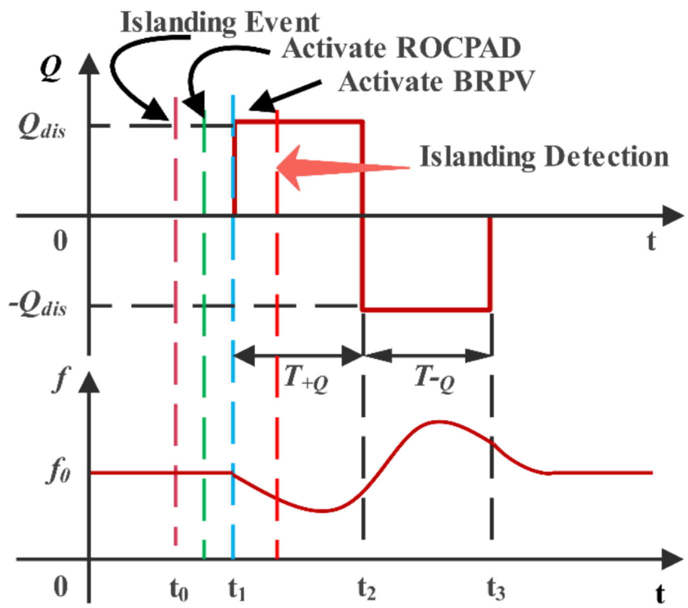


Fig. 3.3 Operational procedure for the proposed hybrid method

The suggested hybrid method's procedure illustration is provided in Fig. 3.3 to illustrate the operational principle effectively. When the ROCPAD threshold is surpassed, the ROCPAD method detects islanding. Consequently, the frequency will drift outside the permissible range due to the simultaneous activation of the BRPV, which adjusts the output RP. When the frequency crosses the cutoff, the islanding CB will open immediately upon the signal from the proposed IDM. Instead of operating regularly as with the traditional approach, the suggested hybrid BRPV technique requires that the output RP be changed once between Q_{dis} and $-Q_{dis}$ when it receives an activation signal. After that, the frequency will start to stray outside the allowed range with the appropriately specified parameters; if the DG is in islanding mode, the islanding breaker will trigger, isolating the UG from the HMG.

3.4 Parameter Design

During islanding events, significant fluctuations occur in the phase information of voltage and current signals. Consequently, the ROCPAD is chosen as the tracking signal for detecting islanding. The magnitude of ROCPAD experiences notable changes during islanding incidents, in contrast to the relatively stable conditions observed during non-islanding situations. This makes ROCPAD a reliable indicator for identifying islanding events in the system.

Consequently, a tripping signal can be triggered by setting a threshold value of 50 or 100 degrees per second. For relay operations, the reaction time can change by only 3 ms when the threshold is changed from 50 degrees/s to 100 degrees/s. When a threshold of 100 degrees/s is implemented from the start of islanding, the ROCPAD responds within 15 ms of the event. As a result, the suggested approach's threshold setting for the ROCPAD method is sufficient to predict the islanding state.

In the context of the IB-RPV method, it is imperative to ensure the elimination of the NDZ. This requirement is met when the local load Q_f is adjusted to 2.5, aligning with the specifications outlined in IEEE Std. 929 and IEEE Std. 1547, the maximum and minimum frequencies (f_{max} and f_{min}) are specified as 50.5 Hz and 49.5 Hz in a 50 Hz system. Equation (16) can thus be expressed as follows.

$$Q_{dis} \geq 5\ \%\ P \qquad \text{………………} (3.17)$$

Therefore, the magnitude of the RP disturbance in the IB-RPV can be chosen as

$$Q_{dis} = 5\ \%\ P \qquad \text{………………} (3.18)$$

In the context of the IB-RPV, the NDZ is effectively eliminated by setting the amplitude Q_{dis} to 5% of the active power P. This configuration ensures no overlap between the segments where the output RP corresponds to Q_{dis} and its negative counterpart, -Q_{dis}. Consequently, this elimination of overlap signifies the successful elimination of the NDZ. Although this approach might lead to nuisance pre-detections, it will not result in nuisance trips since the active method triggers the final tripping operation.

Therefore, this research aims to design and develop a hybrid IDM specifically for hybrid MGs. Following this, we propose a hybrid approach that combines the active approach of IB-RPV with the passive approach of the ROCPAD technique. It is essential to highlight that the suggested hybrid IDM is dynamic and adaptive, as it requires the ROCPAD method to identify islanding conditions to activate the IB-RPV method, which confirms the presence of an islanding event. Furthermore, by appropriately designing the parameters by the specifications outlined in IEEE Std. 929 and 1547, the NDZ of the IBRPV method can be eliminated. This ensures that the technique avoids any possible degradation of PQ and functions well in HMG systems consisting of several DGs. The efficacy of the proposed hybrid IDM is confirmed through a simulation assessment. The contributions of this article can be outlined as follows:

- A new hybrid technique is proposed and optimized for hybrid MGs with inverter-interfaced DGs. Based on derived design principles, it offers enhanced performance.
- The proposed two-stage verification approach eliminates the uncertainty between the annoying tripping phenomenon and islanding occurrence.
- The active technique is only used when the passive method suspects an islanding condition and is not used continually; the PQ impact is greatly minimized.
- Controlled RP by inverter under islanding ensures quicker ID.
- The counteraction issue between inverters in a system with several inverters is resolved as the passive technique can synchronize the active method's functioning.
- A comprehensive analysis and simulation evaluation is conducted to demonstrate the capability and confirm the effectiveness of the suggested approach.

In summary, the methodology outlined in this chapter presents a dynamic and adaptive hybrid IDM specifically designed to address the complex operational challenges of HMGs. By combining the strengths of the passive ROCPAD method and the active IB-RPV approach, this methodology effectively eliminates NDZs while maintaining system stability and power quality. The adaptive nature of the proposed IDM, where the active detection method is only engaged when the passive method signals a potential islanding event, minimizes the impact on power quality and ensures faster detection. Additionally, the careful parameter design following IEEE Std. 929 and 1547 further enhance the reliability of this method in systems with multiple DGs. The effectiveness of this approach has been rigorously validated through comprehensive simulations. With this foundation, the next chapter will focus on the design and development of the HMG itself, implementing the proposed IDM framework and evaluating its performance in different operational scenarios to confirm its robustness and practical viability.

CHAPTER IV

DESIGN AND DEVELOPMENT OF HYBRID MICROGRID

4.1 Introduction

The design and development of an HMG requires careful consideration of the electrical architecture and the operational dynamics to ensure seamless integration of various DG units and energy storage systems. In HMGs, the coexistence of inverter-based and synchronous generators presents unique challenges in maintaining grid stability, power quality, and efficient energy management, particularly during islanding events. This chapter focuses on an HMG's step-by-step design and development, incorporating AC and DC MGs, to create a flexible and resilient energy system. The design process includes the specification and configuration of each component, load balancing, and the control strategies needed for smooth operation under both grid-connected and islanding modes. The HMG is designed to maintain stability and efficiency under varying load and generation conditions by leveraging advanced control mechanisms and integrating the proposed IDM. The subsequent sections will detail the architecture, component integration, and control strategies necessary to develop a robust HMG that supports renewable and conventional energy sources.

HMGs are an innovative and advanced subset of MGs that integrate multiple types of energy generation sources, both renewable and conventional, along with energy storage systems to form a localized, self-sufficient power network. Unlike traditional centralized grids, HMG is designed to operate autonomously (islanded mode) or in coordination with the UG (grid-connected mode), offering enhanced flexibility, resilience, and efficiency in energy management. The strategic combination of diverse energy sources, and battery storage, enables HMG to optimize energy production, storage, and distribution, thereby addressing the intermittency and variability associated with RES.

4.2 Architecture of HMG

HMGs are composed of several key components, each serving a specific role in the system's overall functionality:

- **Renewable Energy Sources (RES):** RES forms the cornerstone of HMG, providing clean and sustainable energy. However, their inherent variability due to weather and time-of-day factors necessitates the integration of additional energy sources and storage systems.
- **Conventional Generators:** Diesel generators or fuel cells are included to provide dispatchable power, particularly during low renewable generation or high demand periods. They offer the necessary power backup to maintain system stability.
- **Energy Storage Systems (ESS):** Batteries, supercapacitors, and flywheels are crucial for balancing supply and demand. ESS absorbs excess energy generated during peak renewable production and discharges it during deficit periods, ensuring a continuous power supply.
- **Power Electronics:** Inverters, converters, and controllers facilitate the integration of diverse power sources by managing AC/DC conversions and regulating voltage and frequency.
- **Control Systems:** Advanced control algorithms coordinate the operation of all components, ensuring optimal power flow, stability, and efficiency.

4.3 Significance in Modern Power Systems

HMG plays a pivotal role in the evolution of modern power systems, offering multiple advantages that address critical challenges faced by conventional grids, as shown in Fig. 4.1:

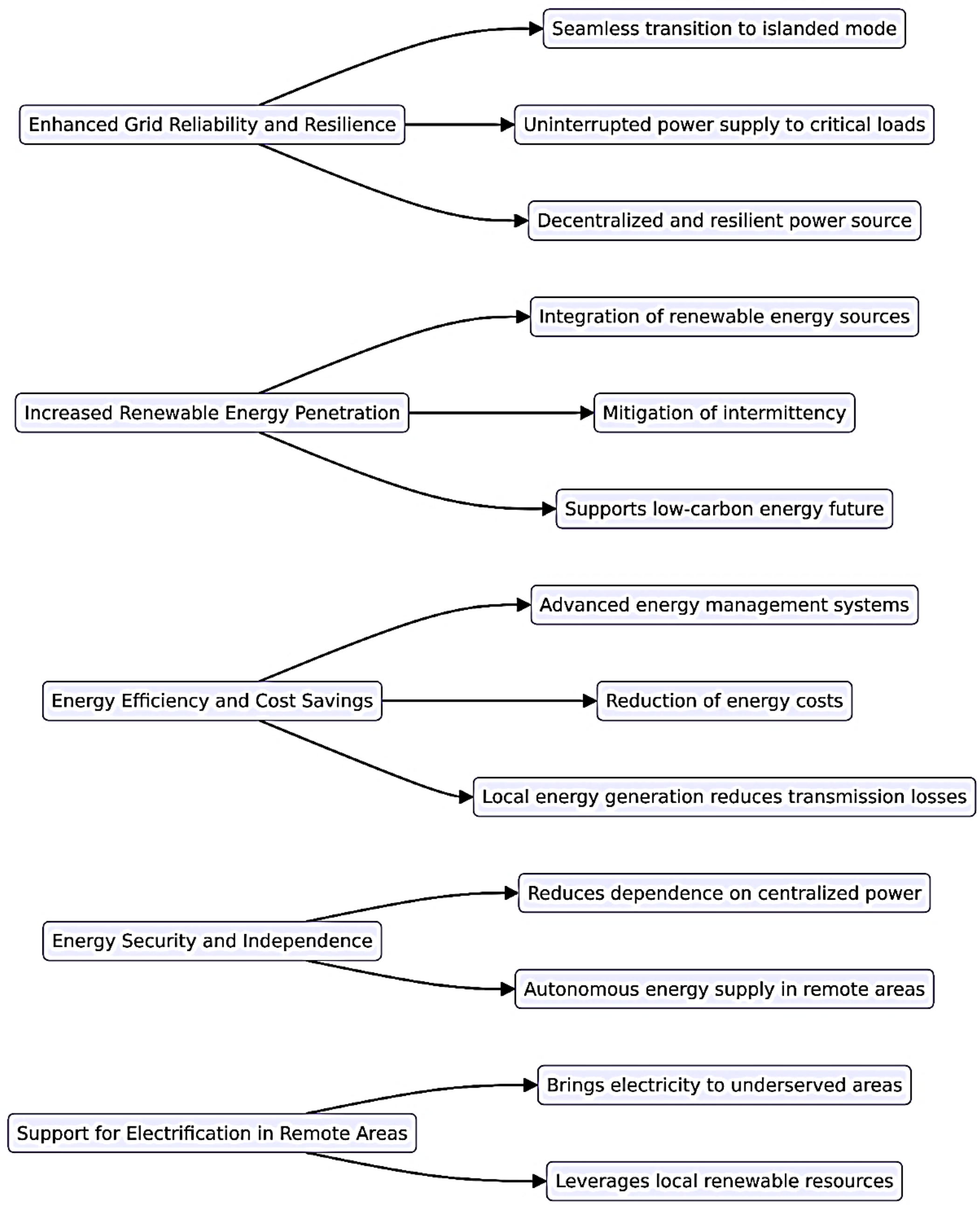


Fig. 4.1 HMG Merits

4.4 Challenges and Opportunities

While HMG offers significant benefits, they also pose technical and economic challenges as shown in Fig. 4.2. The complexity of integrating diverse energy sources and the need for sophisticated control systems increase the capital and operational costs. Furthermore, coordinating multiple power sources, especially in islanded mode, requires advanced control algorithms to maintain stability and power quality.

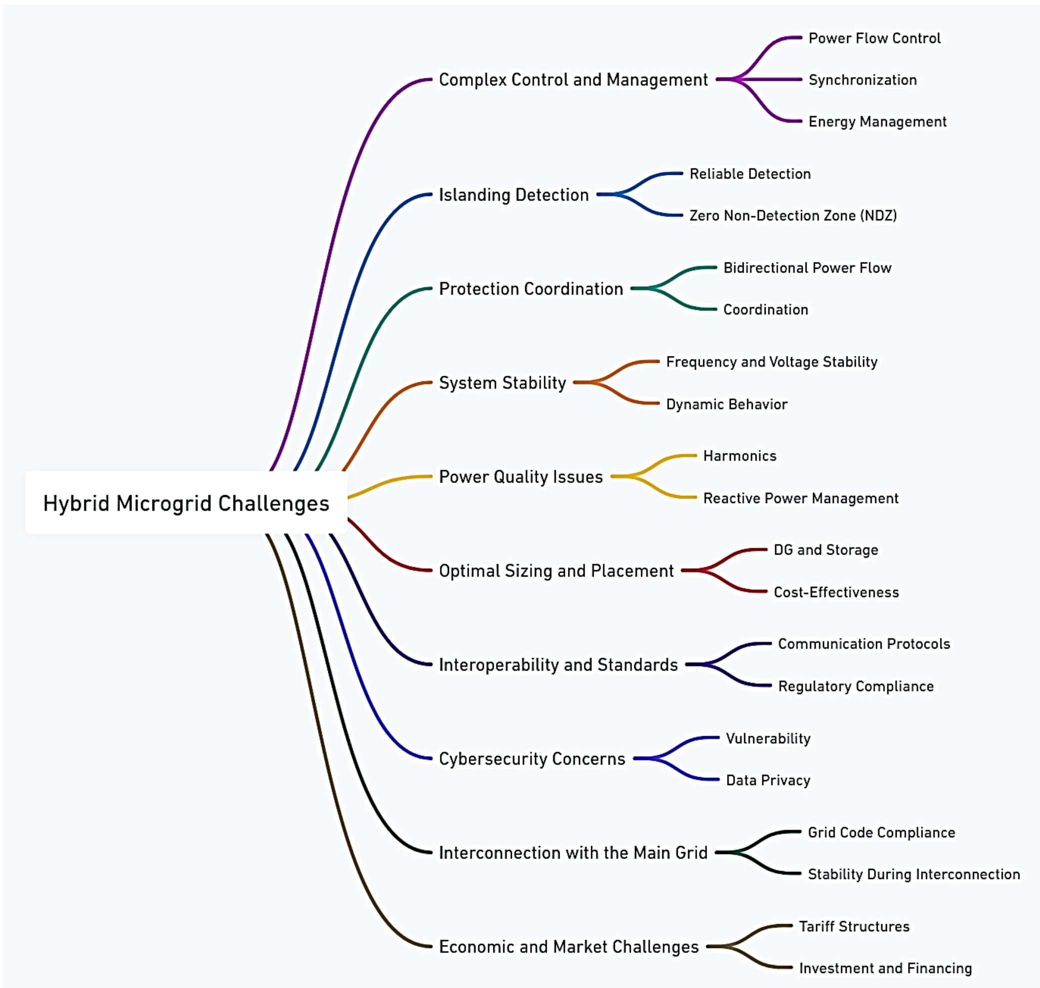


Fig. 4.2 HMGs Challenges and Opportunities

Despite these challenges, HMGs present a transformative opportunity for modern power systems. By enabling the integration of renewable energy, enhancing grid resilience, and providing a flexible and reliable power supply, HMGs are poised to become a cornerstone of future smart grid infrastructure. Their ability to operate autonomously and adapt to varying energy demands makes them a vital enabler of the transition towards a decentralized, sustainable, and resilient energy ecosystem.

4.5 System Architecture

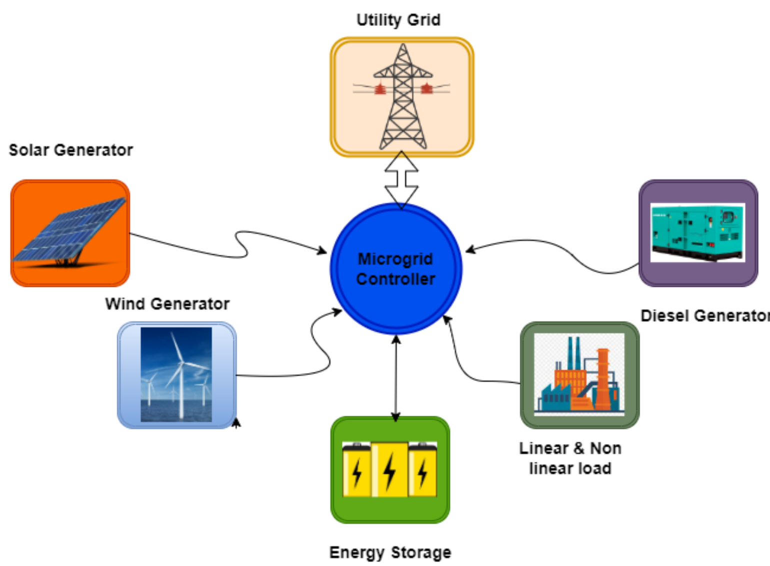
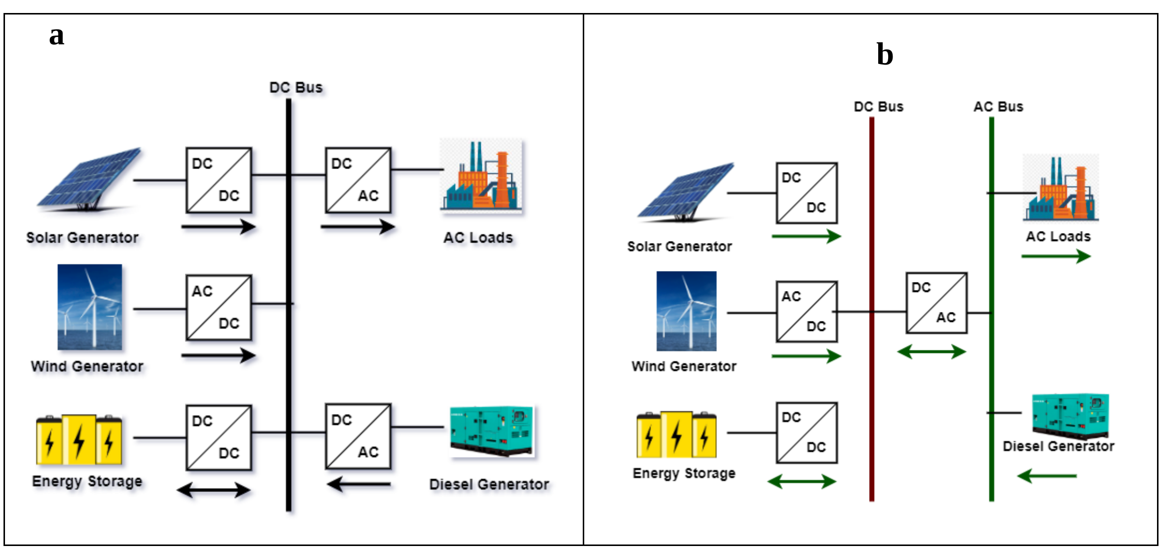


Fig 4.3 Electric MG

Electric MGs comprise numerous systems and subsystems, such as dispersed power generation, energy storage, and several types of loads, as shown in Fig. 4.3. The MGs can function in three different modes: isolated mode with independent power sources, connected mode with the UG set points; and parallel mode with the Main Grid without any power exchange.



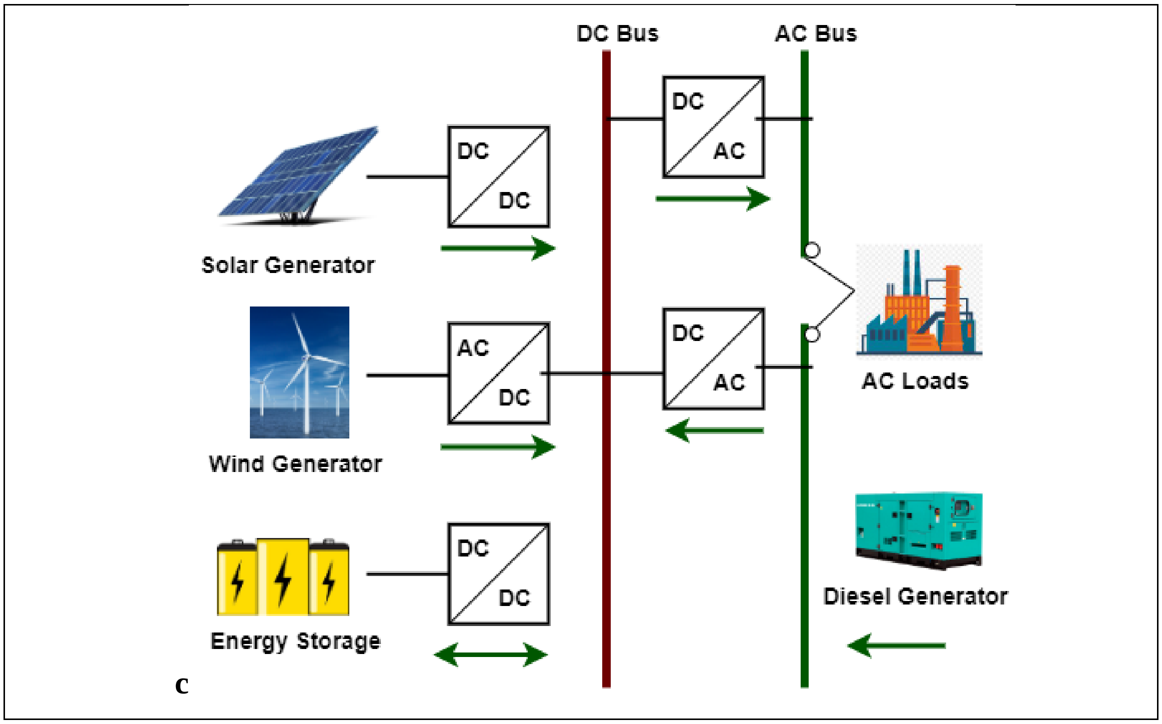


Fig. 4.4 MG Architecture

As presented in Fig. 4.4, AC/DC MGs are commonly deployed with different configurations such as series, parallel, switched, or a combination of these. In the series architecture of MG, all loads and generation units are linked to a DC bus (Fig. 4.4 a) via the appropriate converters.

The AC bus makes possible direct connection between the generating systems and loads, as seen in the parallel architecture (Fig. 4.4 b). In the switched layout, the DC devices are linked through their inverters. The load can receive power from a DG or the UG, but not simultaneously. As shown in Fig. 4.4 c, DC and AC MG are connected through two inverters.

AC MG configurations are commonly used, but DC MGs have become increasingly popular due to their benefits, such as the absence of RP and harmonics. Additionally, synchronization is unnecessary since the DC generation has little power loss, and the DC bus does not alter even after a blackout. Despite all of these advantages, there are some disadvantages as well. The two most significant ones are the lack of zero-crossing locations and the complexity of high-voltage protective systems.

The combination of both topologies, as shown in Fig. 2 c, leads to the development of AC/DC HMGs, which offer a superior approach by combining the advantages of both AC and DC MGs [4, 20]. In the future, there will be more demand and increased investment in research on adaptability, modeling and identification, layout, and control structures, which will enable the incorporation of HMGs into the UG. HMGs offer an intriguing option that merges the merits of DC and AC systems. AC MGs may be connected or dispersed (decoupled). Two methods for decoupling MGs have been identified: Completely and partially isolated topologies. In comparison, three topologies for decoupled AC are described. Three designs can be used to achieve isolation: a design with two fully isolated stages, a design with two moderately isolated stages, and a design with three partly isolated stages. The application and environment where it is implemented significantly impact the AC/DC HMG configuration to be created. The defining feature of the linked architecture is the direct linking of the AC MG to the UG through a transformer, effectively linking MG to UG. When TF is positioned at the grid connection point, electric MG is electrically isolated, and the voltage magnitude of the LV AC grid is decreased. Bi-directional AC/DC VSC may be used by the interconnecting HMGs in energy storage systems to control PF in both directions (production and consumption). It is crucial to remember that HMGs can be deployed at many levels and in different configurations and are easily scalable. HMGs can also be integrated with LV and medium-voltage UG to provide residential energy.

The emphasis on RES has resulted in increased integration of hybrid systems into smart grids, which can cause problems with power quality, reliability, and stability. One solution to this issue is the MG, which uses Electrical ESSs to provide more stable and reliable power. Electrical ESSs can help overcome uncertainties and intermittency of RE generation and provide a reliable source of electricity even when other means of generation are unavailable. Electrical ESSs are categorized by function and form. To ensure MG autonomy and stability, a Hybrid ESS is necessary. However, the lifespan of these systems can be affected by the battery's charge and discharge cycles. SCs and FCs are better alternatives to batteries in HMGs due to their higher power density, faster charging/discharging, longer lifespan, and lower maintenance requirements. They are more reliable for high-power applications and eco-friendly, making them ideal for HMGs focused on sustainability. SCs are used for power balance, while FCs improve power quality in the proposed HMG.

4.6 Development of Hybrid Microgrid

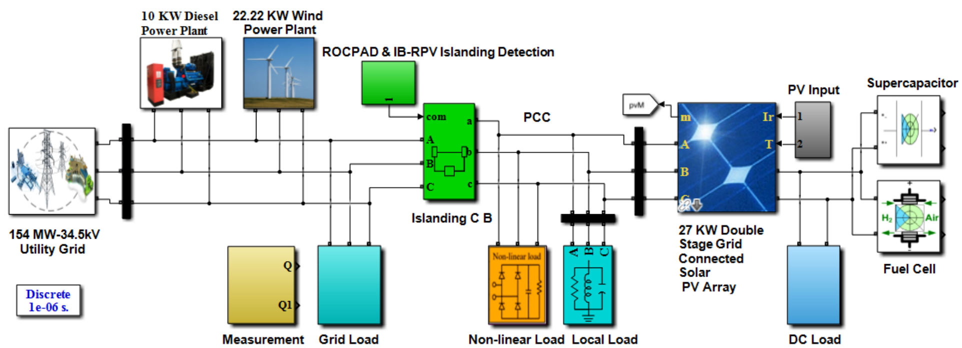


Fig. 4.5 HMG with Proposed Hybrid Islanding Technique

A detailed description of the HMG's MATLAB simulation model, consisting of the proposed hybrid IDM, is presented in this section. A one-line diagram describing the setup is shown in Fig. 4.5. In this schematic representation, the HMG is interfaced with the UG at the electrical sub-transmission system. The AC MG operates with a diesel generator and wind power plant and supplies energy to the connected AC load within the system. The DC MG consists of a supercapacitor and a fuel cell. Solar PV system with a double-stage bidirectional converter facilitates the interaction between the AC and DC MGs. Table 4.1 provides details on the specifications of this study system.

Table 4.1 System Details

Component	**Specification**
Utility Grid	154 MW, 34.5 KV, 50Hz
AC Microgrid	400 V, 50 Hz
DC Microgrid	300 V
Diesel Generator	11 kW, 50Hz, Xd=1.305 pu , Xd'=0.296 pu, Xd"= 0.252 pu, Xq= 0.474 pu, Xq"= 0.243 pu Xl= 0.18 pu
Wind Power Plant	22.22 kW, 50Hz, Rs = 0.004843 pu, Lls = 0.1248 pu, Rr' = 0.004377, Llr' = 0.1791

Supercapacitor	EDLCs 99.5 F
Fuel Cell	PEMFC, 6 kW, V_{dc} = 45V
Solar PV System	27 kW, V_{OC} = 37.1 V, I_{SC} = 8.18 A, V_{MPP} = 29.9 V, I_{MPP} = 7.65 A

4.6.1 Reactive Power Control

The suggested technique's primary reliance on the functioning of a double-stage bidirectional converter is for managing intermittent bilateral RP. An essential function of this converter is to control the power flow between the linked loads or the UG and the AC and DC MG. To enable the system to supply power to the AC loads within the MG, the first stage of the converter usually entails an AC/DC conversion process. This involves converting the AC from the grid or RES into a DC and recovering the DC power.

The second stage uses DC/DC conversion to power a DC load, which enables adequate energy storage and control. This bidirectional capability is crucial for maintaining the balance between supply and demand, mainly when islanding occurs. To adequately compensate for any disparities and maintain a stable system frequency, the converter can modify the phase difference between the voltage and current to modify the RP output.

A PI controller and feedforward decoupling control technique are implemented for the double-stage bidirectional converter. The perturbation intervals T_{+Q} and T_{-Q}, corresponding to the RP with positive Q_{dis} and negative $-Q_{dis}$ amplitudes, respectively, are selected to be equal. Considering the system's transient response, the t_s can be approximated as 70.4 ms, based on the filter design. The perturbation time in the suggested method can, therefore, be set to

$$T_{+Q} = T_{-Q} = 150 \text{ ms} \qquad \text{……………………… (4.1)}$$

With this perturbation time setting, the suggested method's ID is adequate. This option also improves synchronous operation in multiple inverter systems as long as the active ways can be effectively triggered.

4.6.2 Double-Stage Bidirectional Converter

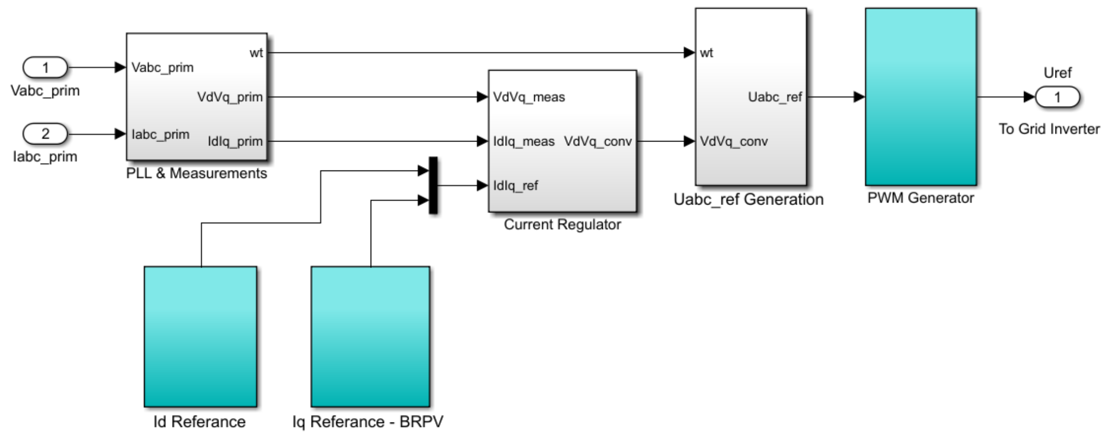


Fig. 4.6 Converter Control

The three-level double-stage bidirectional converter regulates the DC bus voltage at 400 V and keeps the unity power factor. The converter controller illustrated in Figure 4.6 incorporates a sophisticated dual-loop control system designed to enhance the stability and efficiency of power conversion. This control system comprises an outer and an inner control loop. The outer loop regulates the DC-link voltage, maintaining a precise reference value of 400 V. Concurrently, the inner control loop focuses on managing the grid currents, I_d, and I_q. The reference for the I_d current is continuously modified according to the output from the DC voltage regulator. In contrast, the I_q current reference is kept at zero to ensure a unity power factor, enhancing PQ. Additionally, the voltage outputs from the current controller are transformed into three modulation signals. These signals are subsequently utilized by the PWM generator, which operates on a three-level pulse modulation scheme to ensure efficient and accurate power control.

The active and reactive power of the converter in a dq frame can be expressed as follows

$$P = \frac{3}{2}\left(V_d i_d + V_q i_q\right)$$

…..…………..… (4.2)

$$Q = \frac{3}{2}\left(V_d i_d - V_q i_q\right)$$

………………..… (4.3)

Achieving unity power factor operation, characterized by grid current and voltage vectors in phase, necessitates maintaining zero desired reactive output power. I_{dref} is the desired active output power control. When the d-axis is in line with the grid voltage, the reactive and active powers can be written as

$$P = \frac{3}{2}(V_d i_d) \quad \text{……..…………… (4.4)}$$

$$Q = -\frac{3}{2}(V_d i_q) \quad \text{……………..………… (4.5)}$$

Equations (4.4) and (4.5) show that i_d can control P because it is proportional to it. Similarly, adjusting i_q controls the RP and Q. Therefore, by regulating an i_q, the suggested technique can regulate RP under islanding.

In light of the study above, the ROCPAD and the BRPV techniques are applied as part of a hybrid approach. Due to various local load activities, the BRPV approach will be activated when the ROCPAD methodology surpasses its threshold. Gird faults that do not island but still produce significant voltage and RP changes can push the ROCPAD technique over the threshold, activating the BRPV method. However, it should be emphasized that the frequency determines the ID in the suggested hybrid technique. Overvoltage is due to excess RP in the system, raising the frequency. Conversely, low RP can cause lower frequency under voltage conditions. Hence, changes in RP levels affect the voltage and, in turn, the power system's frequency. Furthermore, since the frequency is a global variable independent of local events that alter voltage or RP, its behavior for these events is unimportant. Therefore, the suggested approach will succeed in these circumstances. Thus, the proposed method will avoid unnecessary trips, provided the HMG is connected to UG and the grid frequency stays within the specified operational limits. To sum up, the features of the suggested technique are as follows:

1. Instead of isolating the MG instantaneously, our suggested approach uses the IB-RPV approach and the ROCPAD approach to isolate when the ROCPAD and system frequency exceed the set threshold. It ensures that only actual islanding

events result in a disconnection, avoiding unforeseen interruptions during momentary grid disturbances or situations.

2. The ROCPAD method is recognized for identifying islanding conditions when the UG is disconnected quickly and the IB-RPV is activated. This quick reaction time ensures critical loads are easily switched to the HMG's power source, reducing downtime and keeping vital services running despite grid interruptions.
3. Since the IB-RPV technique is only activated when the ROCPAD method suspects an islanding condition, the trigger signal from the ROCPAD method can synchronize the IB-RPV method. This allows the hybrid method to function as designed in an HMG and has a minimal impact on PQ.

4.7 Components of the Hybrid Microgrid

4.8.1 Solar PV System with Double-Stage Bidirectional Converter

Fig. 4.7 displays the configuration settings for a double-stage grid-connected solar PV array system rated for 27 kW. The system is configured to connect to a grid with a V_L of 400 V_{rms} and operates at a standard grid frequency of 50 Hz. Additionally, the controller's time step is set at 1×10^{-4} seconds, indicating the frequency at which the control algorithms are executed to manage the solar PV system's integration with the UG.

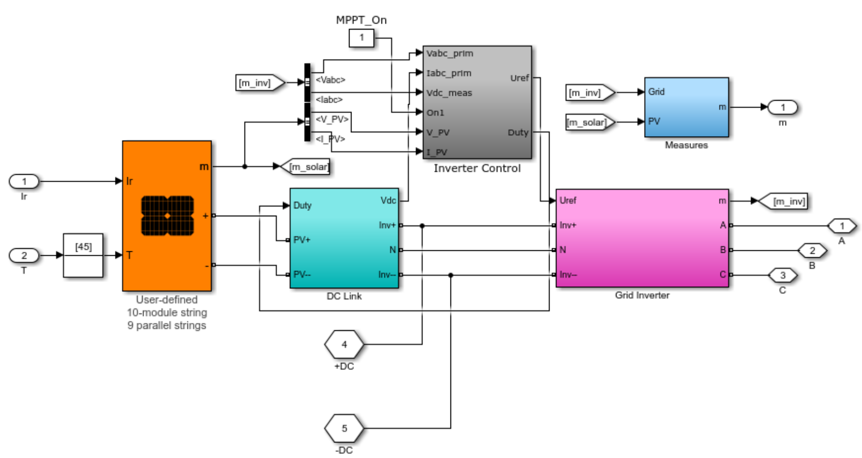


Fig. 4.7 Solar PV System with Double-Stage Bidirectional Converter

4.8.1.1 Double-Stage Feed-forward Bidirectional Converter with Decoupling Control

The system employs a double-stage feed-forward bidirectional converter integrated with a solar array to efficiently convert solar energy and manage power flow within a HMG. This design maximizes energy harvest, maintains grid stability, and supports dynamic power exchange. The detailed components of the system include the PV array, DC-DC converter with MPPT, DC link stabilization, and the inverter with advanced control strategies, as explained below:

4.8.1.2 DC-DC Converter (First Stage):

The solar PV array, represented by the orange block, is connected to a DC-DC converter using **MPPT** control. MPPT adjusts the operating point of the PV array to maximize power extraction under varying environmental conditions such as irradiance and temperature. In addition, a feed-forward bidirectional converter enables power flow between the solar array and the DC link, allowing energy transfer in both directions. Feedforward control enhances the converter's dynamic response, helping to stabilize the DC link voltage during sudden load or generation changes in HMGs.

4.8.1.3 DC Link (Intermediate Stage):

The DC link functions as an energy buffer between the DC-DC converter and the DC-AC inverter, stabilizing voltage and smoothing power fluctuations for efficient AC inversion in HMGs. Additionally, voltage decoupling control allows independent management of active and reactive power by separating voltage control from power control, critical for handling multiple power sources and dynamic load variations in HMG applications.

4.8.1.4 DC-AC Inverter (Second Stage):

The grid inverter converts DC power from the DC link into synchronized AC power, ensuring phase alignment and matching frequency and voltage. It supports bidirectional power flow, allowing both injection into and withdrawal from the grid. The decoupling control strategy enables independent active and reactive power management, contributing to grid stability and power quality.

4.8.1.5 Decoupling Control:

The inverter control employs decoupling control for independent management of active (P) and reactive (Q) power, which is crucial for grid-tied systems in HMGs. This enables the inverter to effectively handle varying demands from grid and local loads while maintaining a balanced power flow. Additionally, decoupling control enhances the system's response to fluctuations in generation and load, improving overall stability by ensuring that rapid changes in power demand or generation do not negatively impact grid performance.

4.8.2 Wind Power Plant

Wind power control in a Doubly-Fed Induction Generator (DFIG) wind turbine system involves multiple control layers to efficiently manage power generation, grid interaction, and turbine operation. These control layers include Grid-Side Control (GSC), Rotor-Side Control (RSC), and Speed and Pitch Control. Each plays a crucial role in ensuring optimal performance, power quality, and compliance with grid requirements. overview of these control components as shown in Fig. 4.8:

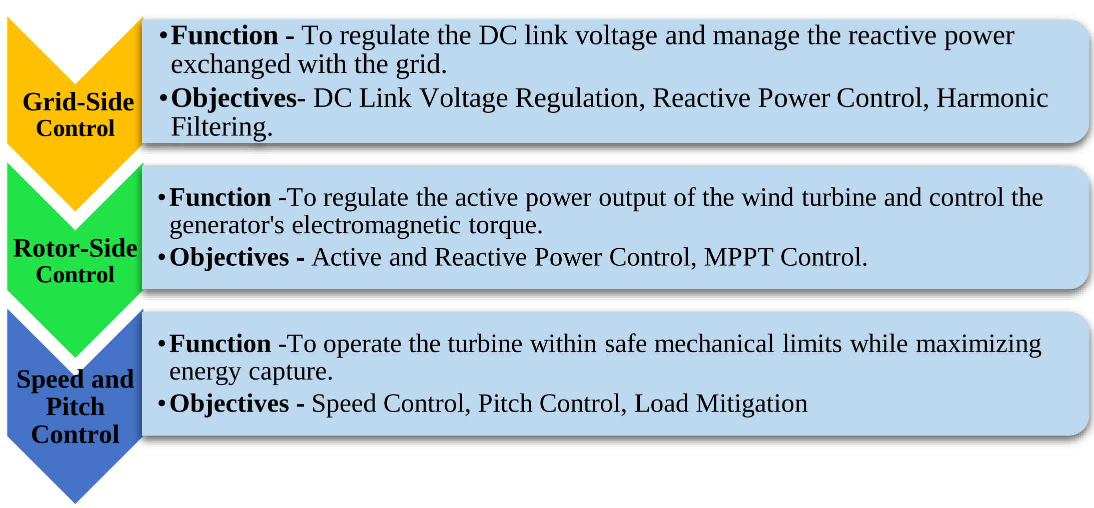


Fig. 4.8 Wind Power control components

The coordinated operation of Grid-Side Control, Rotor-Side Control, and Speed and Pitch Control in a DFIG wind turbine ensures that the system extracts and converts wind energy efficiently and integrates seamlessly with the UG. This comprehensive control approach allows DFIG wind turbines to operate flexibly, support grid stability, adapt to changing wind conditions, and provide high-quality power, making them a critical component in modern RES.

The mathematical modeling of a wind power plant in an HMG involves capturing the dynamics of wind energy conversion, which converts the wind's kinetic energy into electrical energy. The main components of a wind power plant are the wind turbine, the drive train, and the electrical generator. This section outlines the mathematical models for each of these components, leading to the overall model of the wind power generation system.

4.8.2.1 Wind Turbine Model

The following equation governs the power extracted from the wind by the wind turbine:

$$P_w = \frac{1}{2}\rho\, A v_w^3 C_p(\lambda, \beta) \qquad \text{……………. (4.6)}$$

Where:

- P_w is the power captured by the turbine (W),
- ρ is the air density (kg/m³),
- A is the swept area of the turbine blades (m²),
- V_w is the wind speed (m/s),
- C_p (λ, β) is the power coefficient, which depends on the tip-speed ratio λ and the blade pitch angle β.

The tip-speed ratio λ is defined as:

$$\lambda = \frac{W_t R}{V_w}$$

……………. (4.7)

The power coefficient C_p represents the turbine's efficiency in capturing the kinetic energy from the wind, and it is typically a nonlinear function of λ and β. The maximum value of C_p is limited by Betz's law, which states that a wind turbine can capture no more than 59.3% of the kinetic energy in the wind.

4.8.2.2 Drive Train Model

The drive train connects the turbine to the generator, typically through a gearbox. The mechanical power transmitted through the drive train is expressed as**:**

$$P_m = T_w \, \omega_t$$

……….………. (4.8)

Where:

- P_m is the mechanical power transmitted to the generator (W),
- T_m is the mechanical torque (N·m),
- ω_t is the angular velocity of the turbine (rad/s).

For a system with a gearbox, the relationship between the turbine side and generator side of the drive train can be modeled using the gear ratio G

$$\omega_g = G . \omega_t$$

……………. (4.9)

$$T_g = \frac{T_m}{G}$$

………. (4.10)

Where:

- ω_g is the angular velocity of the generator (rad/s),
- T_g is the torque on the generator side (N·m),
- G is the gearbox ratio.

4.8.2.3 Electrical Generator Model

The generator converts the turbine's mechanical energy into electrical energy. Typically, a doubly-fed induction generator (DFIG) or a permanent magnet synchronous generator (PMSG) is used in wind turbines. The generator model involves the relationship between mechanical input power and electrical output power.

For an induction generator, the electrical power output P_e is given by:

$$P_e = \eta_g . P_m$$

…………………. (4.11)

Where:

- Pe is the electrical power output (W),
- η_g is the generator efficiency,
- P_m is the mechanical power delivered to the generator (W).

The dynamic model of the generator includes the following electrical equations in the d-q reference frame for both stator and rotor quantities. For the stator, the voltage equations are:

$$v_{ds} = R_s i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_s \varphi_{qs}$$

………………. (4.12)

$$v_{qs} = R_s i_{qs} + \frac{d\varphi_{qs}}{dt} - \omega_s \varphi_{ds}$$

………………. (4.13)

v_{ds} and v_{qs} are the d-axis and q-axis components of the stator voltage,

i_{qs} and i_{ds} are the q-axis and d-axis components of the stator current,

φ_{ds} and φ_{qs} are the stator flux linkages,

R_s is the stator resistance

ω_s is the stator angular frequency

4.8.3 Diesel Power Plant

Simulink model for diesel power plant is as shown in fig.4.9 consisting following components.

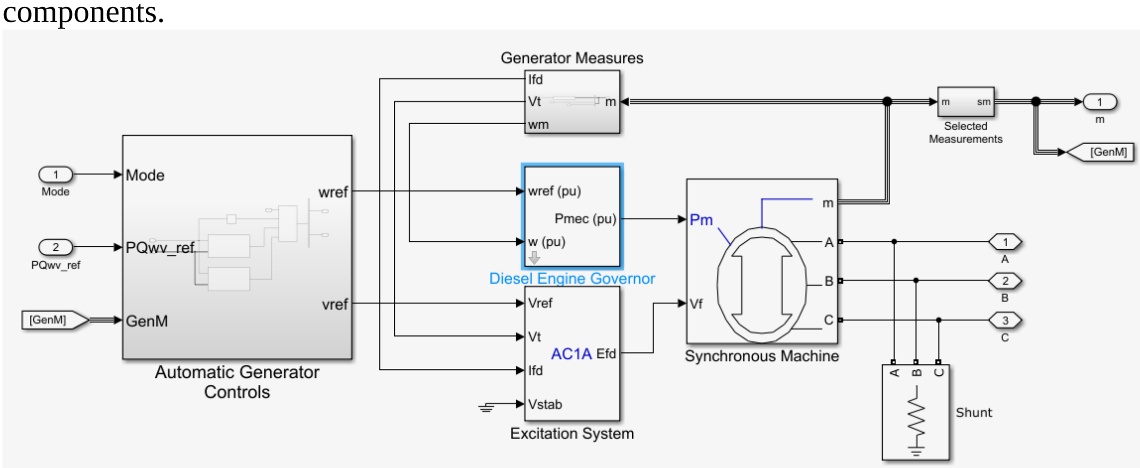


Fig. 4.9 Diesel Power Plant

Automatic Control: The AGC sets the desired operating conditions for the diesel generator, such as speed (frequency) and voltage. It continuously monitors the generator's output and adjusts the speed reference and voltage reference to maintain stability and power quality.

Governor Control: The Diesel Engine Governor adjusts the fuel input to the engine, regulating the mechanical power to match the load demand. It ensures the generator runs at the desired speed and maintains the frequency within specified limits.

Voltage Regulation: The Excitation System controls the synchronous generator's terminal voltage by modulating the rotor's field current. It ensures that the voltage and reactive power output meet the system requirements, stabilizing the power supply to the connected loads or grid.

4.8.4 Supercapacitor

The SC is utilized when the load is variable due to its high specific power. The battery's characteristics may prevent it from supplying the necessary power rapidly enough. However, the SC can bridge this power gap because it has an efficiency cycle of approximately 100%, making it appropriate for energy storage and numerous charge/discharge cycles. However, the battery primarily supplies most of the required power. It implies that the SC provides power more quickly and may be recharged more frequently than the battery [41]. Because of this, various electrical sources with varied dynamic behavior and varying amounts of energy storage are often utilized in conjunction with the SC as a complementary element [42].

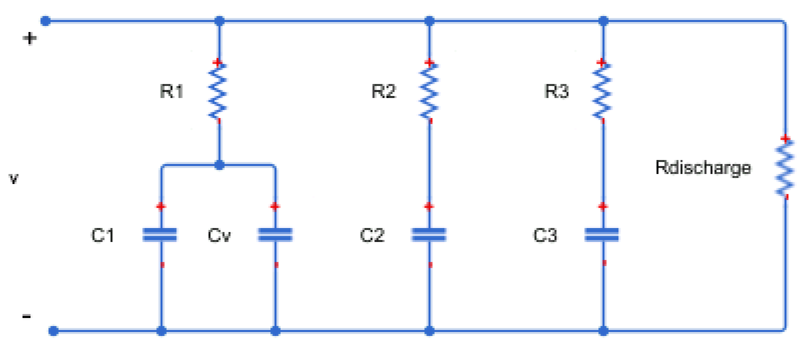


Fig. 4.10 Simulation Model for Supercapacitor

Fig. 4.10 shows simulation model for supercapacitor. The SC is interfaced to the DC voltage bus using a buck/boost converter. Energy from the SC's charge phase is transferred to the secondary source in the Buck mode of operation. When operating in boost mode, the SC produces enough power to meet load demands during islanding mode or other operating conditions.

SC's open circuit voltage

$$E_{sc} = E_{sc0} - \frac{1}{c_{sc}}\int_0^t i_{sc} dt$$

……………. (4.14)

Where $c_{sc}$and i_{sc} are respectively: the capacity of the SC (F) and the SC current (A).

SC energy is given by

$$X_{sc} = \frac{C_{Sc} E_{Sc}^2}{2}$$

…………………. (4.15)

$$X_{sc-max} = \frac{C_{sc} E_{sc0}^2}{2}$$

…………..……… (4.16)

The state of charge, or SOC, is expressed as

$$SOC = \frac{x_{sc}}{x_{sc-max}}$$

……………………...…. (4.17)

The output voltage of a SC is

$$V_{sc} = E_{sc} - R_{sc} i_{sc}$$

………………………. (4.18)

Where, x_{sc} , x_{sc-max}, and R_{sc} are respectively: the internal resistance of a SC (Ω), the energy contained in a SC (J) and the maximum energy contained in a SC (J).

4.8.5 Fuel Cell

The PEMFC boasts several benefits, such as an efficiency rate that can reach up to 45%, fast start-up, a high energy density in a compact size (up to 2 W/cm^2), noiseless operation, ability to function in lower temperature environments, and overall system durability [60,61]. The primary benefit of using a PEMFC over an FC is its minimal pollution level. This is because the hydrogen fuel utilized by FCs can have adverse environmental consequences. [62, 63]. Although the FC has several advantages, it also has significant drawbacks. These factors consist of a delayed response time to variations in load, an unsteady output voltage, a restricted lifespan caused by heightened current ripple, and a relatively higher cost

4.8.5.1 FC Mathematical Model Equations

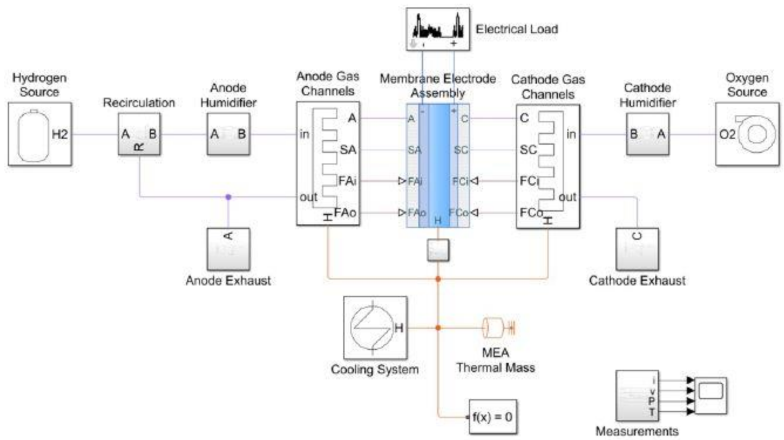


Fig 4. 11 Proton Exchange Membrane FC (PEMFC)

The Proton Exchange Membrane FC (PEMFC) comprises multiple elements. Fig 4.10 shows simulation of PEMFCs. Charge, mass, thermal energy, momentum, and living things comprise the model proposed by FC's theory. Five equations serve as the theoretical basis for this FC model. These equations are used together to model an electrochemical process that represents the kinetics of reactions and the movement of charged particles within the polymer electrolyte system.

4.8.5.2 Continuity Equation

The FC's electrodes are constructed from carbon fabric or fiber. The reactant gases are distributed over the catalyst layer, and porous material holds the electrodes throughout. The equation represents the porosity using a continuity equation for the electrodes (ε).

$$\left(\frac{\partial \varepsilon \rho}{\partial t}\right) + \nabla \times \left(\varepsilon \rho U\right) = 0$$

…..…. (4.19)

Where ε = porosity, ρ = liquid density, U = floating speed vector, and t = time.

4.8.5.3 FC Momentum Conversion

Equation (2) contains the Navier-Stokes equation created for a Newtonian fluid.

$$\left(\frac{\partial\left(\varepsilon\rho U\right)}{\partial t}\right)+\nabla.\left(\varepsilon\rho U^{2}\right)=-\varepsilon\nabla p+\varepsilon F+\nabla.(\varepsilon\tau)-\left(\frac{\varepsilon^{2}\mu U}{k}\right)$$

………. (4.20)

where; τ = stress tensor; F = floating mass vector; ρ = pressure, μ = liquid viscidity degree; k = permeate ratio of the liquid by porous medium.

4.8.5.4 Charge Equation Conversion

CL carries out electrochemical processes using PEMFC. The charge equations, a crucial component of the FC, are composed of two equations: proton transference above the membrane and electron removal above the conductive solid phase. To determine the current density flowing through the catalyst layer, it is necessary to decide on the oxygen diffusion flux on the catalyst's surface. This can be done by solving the two-dimensional Poisson's equation for the CL:

$$\nabla\cdot i=0$$

….. (4.21)

The total current I, provided in the following equation, is equal to the sum of the phase currents of the solid (is) and membrane (im) during CL.

$$i=i_{m}+i_{s}$$

..……. (4.22)

The transfer current density (Jt) with solid surface tension is calculated using Ohm's law as follows:

$$J_{t}=-\nabla\cdot-(\sigma_{s}\nabla\varphi_{s})=\nabla\cdot(-\sigma_{m}\nabla\varphi_{m})$$

………..…. (4.23)

Where Jt = transfer current density at time t, σ_s = solid phase surface tension, σ_m = membrane phase surface tension, ϕ_s = solid phase flux, ϕ_m = membrane phase flux

4.8.5.5 Electrochemical Reaction Dynamics equation

The current density at a particular time is the term used to describe the classification of the rate of electrochemical reactions, the concentration of species, and potential difference across the solid phases and membrane. (Jt). The following is how Butler-Volmer (B-V) is stated.

$$J_t = J_0 \left\{ \exp\left[\frac{\alpha_a F}{RT} (\phi_s - \phi_m) \right] - \exp\left[\frac{\alpha_c F}{RT} (\phi_s - \phi_m) \right] \right\} \prod_{j=1}^{N} [\Lambda]^{\alpha j}$$

………. (4.24)

Where R = electrical resistance, F = Faraday's constant, J_0= exchange current density, α_j = charge transfer coefficient, α_a and α_c = transfer coefficients of cathode and anode, Λ = mol concentration of the reactant.

4.8.5.6 PEMFC output voltage

$$V = E_{nerst} - V_{act} - V_{ohm} - V_{conc}$$

……… (4.25)

Where,

$$E_{nerst} = E^0 - RT \ln \frac{PH_2 \sqrt{Po_2}}{PH_2O}$$

……………………. (4.26)

Where V, E_{nerst} , V_{act} , V_{ohm} , V_{conc} , PH_2 , Po_2 , PH_2O are, respectively, the fuel cell voltage (V), the activation Voltage losses, the ohmic Voltage losses (V), the concentration Voltage losses (V), the voltage Nernst (V) and the partial pressure of hydrogen, oxygen, and water (atm).

The Tafel equation can express the activation losses:

$$V_{act} = \frac{RT}{2\alpha F} \ln \left(\frac{I_{FC}}{I_0} \right)$$

………………. (4.27)

The following equation gives the ohmic losses

$$V_{ohmic} = I_{FC}R$$

……………………. (4.28)

The concentration losses can be expressed as

$$V_{conc} = -\frac{RT}{2F}\ln\left(1-\frac{j}{j_{max}}\right)$$

……….. (4.29)

Where I_{FC}, α , I_0 and j_{max} are respectively: the current of PEMFC(A), the tafel slope for the activation losses, the exchange current density for the activation(mA/cm^2) and the maximal current density for the concentration(A/cm^2).

4.9 Power Management in HMG

The AC MG, DC MG, and AC/DC power flow coordinator enable smooth energy transfer between the AC and DC buses. The AC/DC HMG design supports two unique operating modes: isolated and grid-tied modes. In grid-tied mode, the MG works with the primary UG; in isolated mode, it operates independently without assistance from the UG. The overall grid's stability and dependability largely depend on the functioning of critical components, specifically the bidirectional converter that converts DC to AC power and vice versa, the energy storage system essential for reducing oscillations, and the various conversion technologies integrated into the hybrid system. The constituents above are of utmost significance in guaranteeing the AC/DC HMG's stability, as they impact the MG's capacity to sustain consistent operations, augment overall dependability, and effectively shift between distinct operating modes.

4.9.1 Grid-Tied Mode

When the HMG is linked to the utility grid, the UG plays a crucial role in controlling power balance and satisfying various load demands. The HMG's power-generating surpluses are effectively directed into the utility grid, serving as a vast energy storage facility. On the other hand, when there are power outages in the hybrid system, the utility grid automatically provides the necessary energy, establishing a mutually beneficial connection. Because the utility grid ensures power balance, the network functions in this way like an almost infinite energy storage system, making the battery storage systems function less crucial for the system's immediate operations. Following accepted practices and physical principles, the system's power equilibrium is represented by formulas that capture the energy exchange between the MG's AC and DC components. The conceptual framework provides a fundamental basis for understanding the complexities of power management and optimization tactics in AC/DC HMG. It also offers insightful information about how the system operates efficiently when connected to the grid.

$$\text{AC MG: } P_G = PL_{AC} + P^* - P_{WAC} - PL_{DG} - PL_{PV} \quad \text{……………... (4.30)}$$

$$\text{DC MG: } P^* = PL_{SC} + PL_{DC} - PL_{FC} - PL_{PV} + PL_{SC} \quad \text{………...…. (4.31)}$$

$$PL = PL_{AC} + PL_{DC} \quad \text{................ (4.32)}$$

4.9.2 Islanded Mode

The AC/DC HMG operates in several modes, especially in its islanded mode as per Table 4.2, where an advanced power management algorithm controls each mode. The MG's algorithm uses complex decision-making procedures to maximize power flow, guarantee load balancing, and preserve voltage stability throughout its AC and DC components. Energy storage systems, converters, and dispersed energy resources must all be precisely coordinated for this islanded operation. To run the system properly, it considers the primary criteria listed below.

- The combined AC/DC load power and PV power difference (PD)
- SC operation at both the maximum and lowest SoC limits
- The SC operates at high and low voltage limits.
- The fuel cell operates at maximum/rated current and minimum/zero current limits.
- The PV operates in MPPT mode or Off MPPT/de-rate.

Table 4.2 Power Management under the islanded mode of operation

Operation Modes	Conditions		Description
	SoC	V_{SC}	
Mode I: Generation dominant mode (PD>0)	$SoC_{SCL}<SoC_{SC}<SoC_{SCH}$	$V_{SCL} < V_{SC} < V_{SCH}$	When PV power exceeds the required load, the SC will charge itself based on the current references generated, and the fuel cell will supply the minimum or zero reference current to meet the load demand.
	$SoC_{SC} > SoC_{SCH}$	$V_{SCL} < V_{SC} < V_{SCH}$	SC's reference current is set to zero when it reaches a high SoC limit and can no longer charge itself. PV derating reduces PV power and brings the reference SC current to zero.
	$SoC_{SCL}<SoC_{SC}<SoC_{SCH}$	$V_{SC} > V_{SCH}$	The SC's current reference drops to zero when the voltage exceeds its upper threshold V_{SCH} since it can no longer absorb power.
	$SoC_{SC} > SoC_{SCH}$	$V_{SC} > V_{SCH}$	When SC voltages are higher than VSCH, HES cannot absorb any power. As a result, the system will become unstable when the DC link voltage increases. PV MPPT mode is off, and the current duty ratio is constant to counter these effects.
	$SoC_{SC} < SoC_{SCL}$	$V_{SC} < V_{SCL}$	The SC is charged to the reference value using the extra power. V_{DC} drops if there is insufficient surplus power to charge the SC to the reference value. FC thereby provides the necessary energy.

Mode II: Load dominant mode (PD<0)	$SoC_{SCL}<SoC_{SC}< SoC_{SCH}$	$V_{SCL} < V_{SC} < V_{SCH}$	Since the power required for the load exceeds the energy from the PV, steady-state power assistance from SC is needed for secondary source FC, which supplies power.
	$SoC_{SC} < SoC_{SCL}$	$V_{SCL}<V_{SC}< V_{SCH}$	Since SC is unable to assist FC, its reference current is 0, and SC provides power to load demand.
	$SoC_{SCL}<SoC_{SC}< SoC_{SCH}$	$V_{SC} < V_{SCL}$	While SC provides its reference power, it cannot deliver transient power. In contrast, FC provides constant-state power.
	$SoC_{SC} < SoC_{SCL}$	$V_{SC} < V_{SCL}$	FC will provide the average power needed to meet the load demand. However, without any storage component, it cannot provide power instantly; as a result, load shedding is activated when the DC link voltage drops and approaches the allowable limit.
Mode III: Normal mode (PD≅0)	Since the power from the PV and the load are nearly equal in this mode, the PV operates at MPPT, and the SC regulates the DC link voltage to supply or absorb the little oscillatory power.		

The HMG was developed to validate the performance of the proposed hybrid IDM. By integrating both inverter-based and synchronous generator-based DG units, the system can capture diverse operating conditions, such as varying load demands, renewable generation fluctuations, and fault scenarios typical in HMG. The AC and DC MG, advanced energy management systems (EMS), and coordinated control strategies facilitate smooth transitions between grid-connected and islanding modes, ensuring the MG operates efficiently under various conditions. This architecture provides a robust testing platform to assess the IDM's effectiveness rigorously. In the following chapter, a detailed performance analysis emphasizes the IDM's behavior across multiple operating scenarios, including grid strength variations, power fluctuations, and fault conditions.

CHAPTER V.

PERFORMANCE ANALYSIS

The HMG performance analysis is a critical step in validating the efficacy of the proposed hybrid IDM under different operating conditions. This section aims to rigorously evaluate the system's behavior across various scenarios to detect islanding events and eliminate NDZs accurately. Key performance indices such as detection time, accuracy, and impact on power quality are examined in detail. The analysis will also consider the effects of renewable energy inputs, varying load conditions, and fault scenarios to ensure that the proposed IDM can handle the complexities of modern HMG. By simulating different operational environments and fault conditions, this section will provide a comprehensive assessment of the proposed methodology's overall effectiveness, reliability, and efficiency in enhancing the stability and performance of HMG.

5.1 Simulation Results

This section thoroughly analyzes the proposed hybrid IDM, rating its performance across realistic conditions. Complying with established standards, IEEE Std. 929 and 1547, is an essential benchmark for evaluating the effectiveness of the proposed hybrid IDM. IEEE Std. 929 offers testing and validation guidelines for grid-tied inverters, emphasizing the inverters' ability to sustain grid stability in the event of disruptions.

In contrast, the IEEE Std. 1547 standard addresses DER connection to the UG. It lays forth the technical specifications and performance benchmarks for DERs to ensure their safe and efficient operation with the grid. This comprehensive assessment establishes the viability of the suggested hybrid IDM as a feasible option for improving the functionality of HMG systems. It promotes the grid integration of RES by validating its efficacy and dependability.

5.1.1 Islanding Detection Test

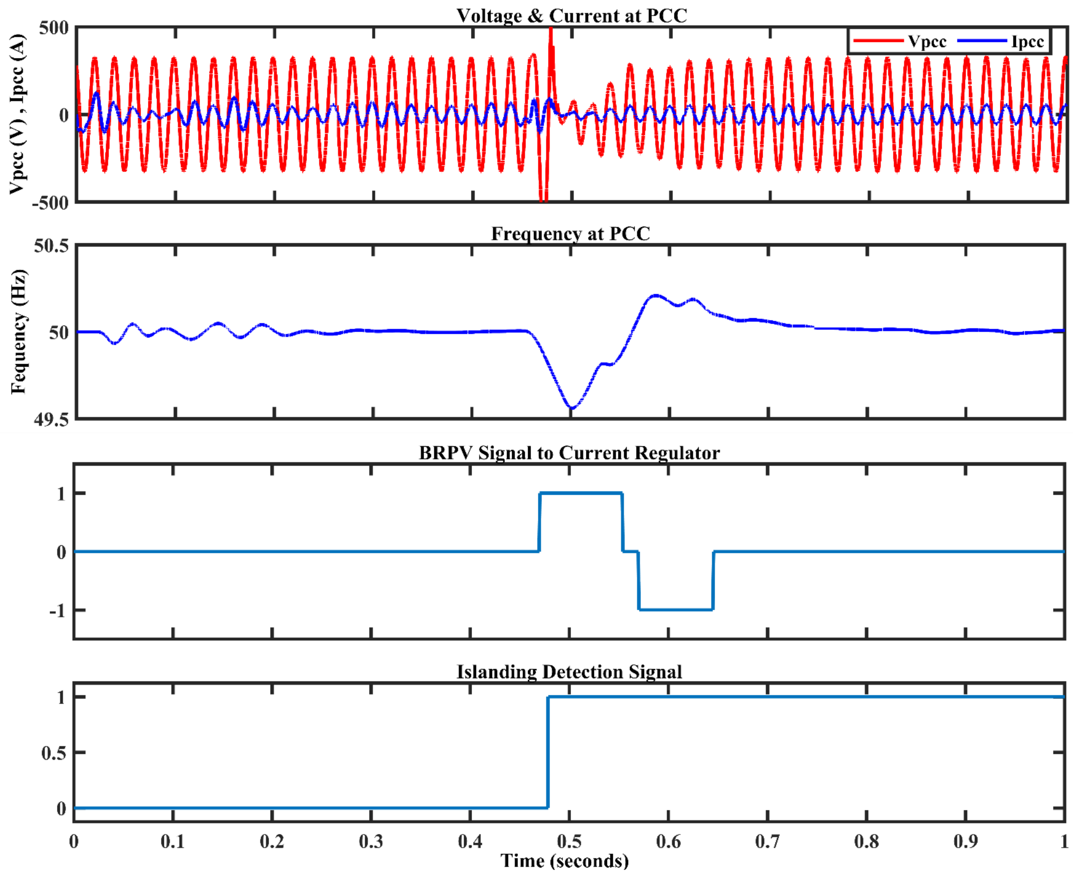


Fig. 5.1 Simulation results of the proposed method

The simulation results in Fig. 5.1 clearly show the islanding event, which takes place at t = 0.45 sec. PCC voltage and current are examined at this crucial time, and the ROCPAD is instantly detected to deviate noticeably from the preset range. When ROCPAD detects islanding, an IB-RPV trigger signal will be sent to the current regulator. The ROCPAD trigger and IB-RPV trigger signal will be the same on the positive rising edge of the IB-RPV signal. The IB-RPV approach is instantly employed to handle this islanding incident effectively. The system's frequency changes quickly upon activation of the IB-RPV system, reaching a set threshold value. In this situation, the rate at which the detection process proceeds are highly remarkable. The total detection time is just 36 ms, starting with the initial detection of the islanding event and ending with the tripping signal to the islanding CB. One of the main benefits of the suggested hybrid approach's effectiveness in identifying islanding states is its quick reaction time.

5.1.2 Large Load Switching Test

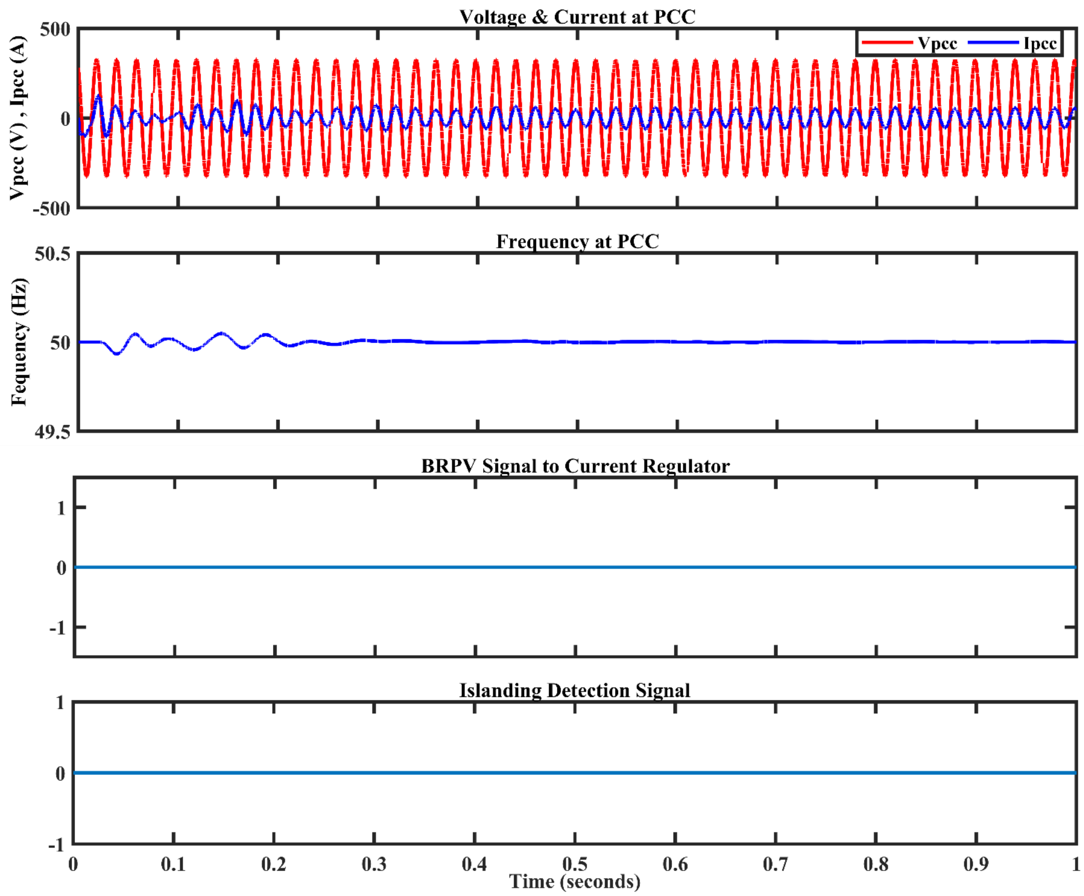


Fig. 5.2 Simulation results - significant load switching

The proposed hybrid approach is tested for a load-switching scenario in which a sizable load is removed from the HMG. This test is carried out to confirm the resilience of our proposed hybrid IDM and ensure it will not accidentally trip in grid-connected mode when faced with severe load switching. In this particular case, the 60kW load connected near to PCC is disconnected at t = 0.45 sec under grid-connected mode. As shown in Fig. 5.2, the ROCPAD system is inactive. As a result, the IB-RPV approach is likewise not triggered, demonstrating no effect of this significant load change event on the proposed hybrid IDM.

Despite the severe load change event, the HMG keeps connecting to the UG. The PCC frequency is precisely controlled to ensure synchronism with the UG.

5.1.3 Nonlinear Load Integration Test

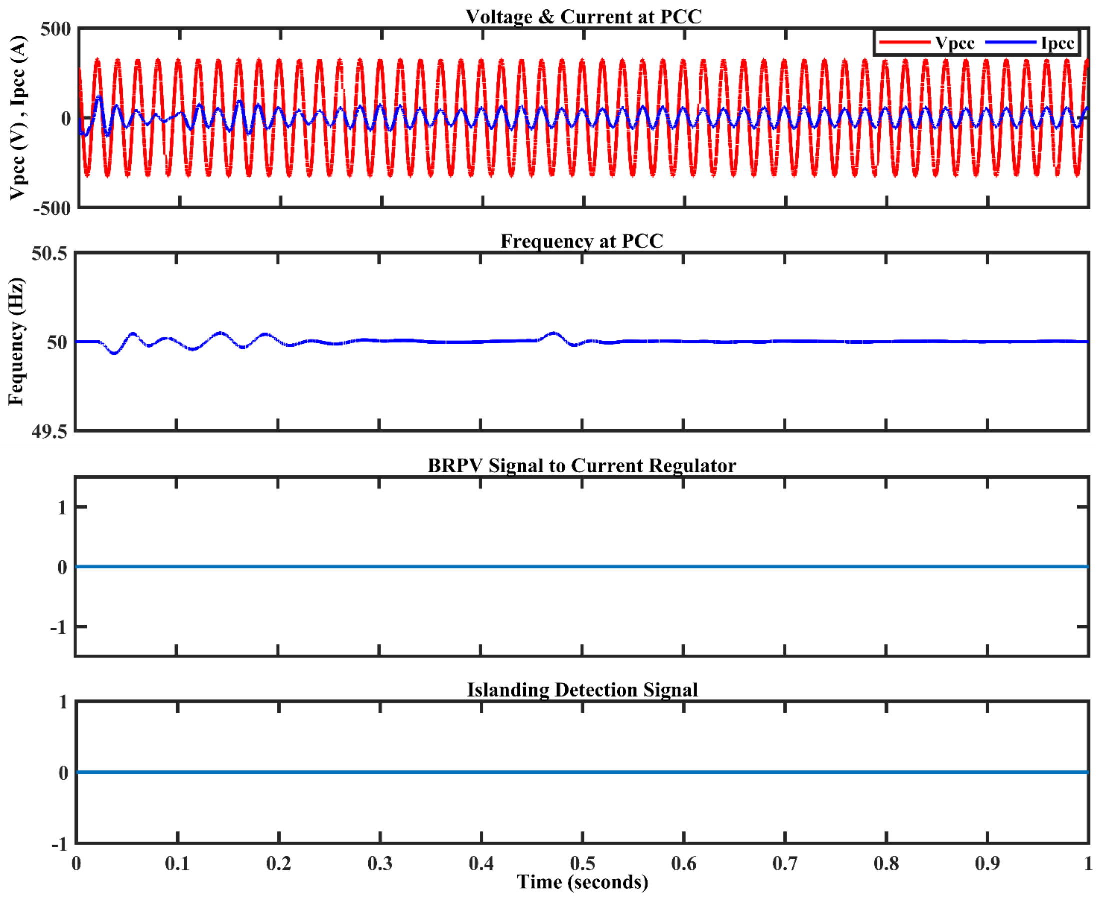


Fig. 5.3 Simulation results - nonlinear load integration

This test has the same goal as the prior one but with a sizable local nonlinear load. When nonlinear loads are incorporated into a grid-connected system, the main challenge is the possible rise in harmonic content. 10 kW nonlinear load is injected into the simulated system at 0.45 sec to test the resilience of the proposed hybrid IDM. Fig. 5.3 displays the simulation results. A difficulty for grid-connected systems might result from increased harmonics, characteristic phenomena linked to nonlinear loads. Due to the coordinated and regulated approach, the proposed hybrid IDM does not cause erroneous trips even while integrating a significant nonlinear load.

5.1.4 Grid Voltage Dip Test

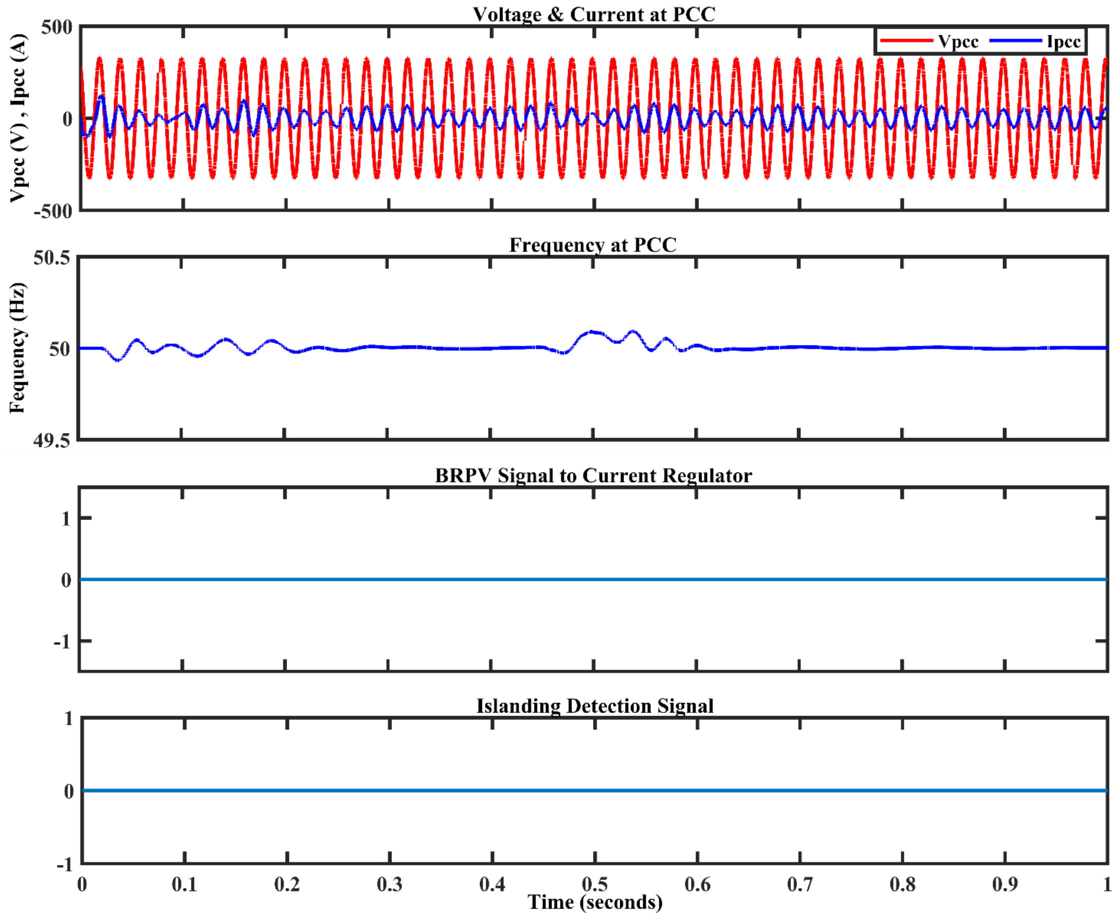


Fig. 5.4 Simulation results under voltage dip

In this test, the emphasis is shifted to evaluating the safety and dependability of the suggested method under conditions where the grid encounters voltage dips or disruptions that do not completely isolate the HMG. The simulation is run in grid-connected mode, and at time t = 0.45 sec, a nonlinear two-phase short circuit fault causes a voltage dip, as shown in Fig 5.4. It is significant to observe that the specified threshold of the ROCPAD approach is not satisfied during this voltage dip. This finding is important because it raises the possibility that the hybrid IDM under consideration could provide an extra layer of ID protection. Specifically, grid faults or disturbances do not result in the isolation of the DG units within the HMG.

5.1.5 Impact on Power Quality

A critical area of focus in the performance analysis of the proposed hybrid IDM is how it affects power quality. Power quality factor, harmonic distortion, greatly influence the grid's overall dependability and efficiency.

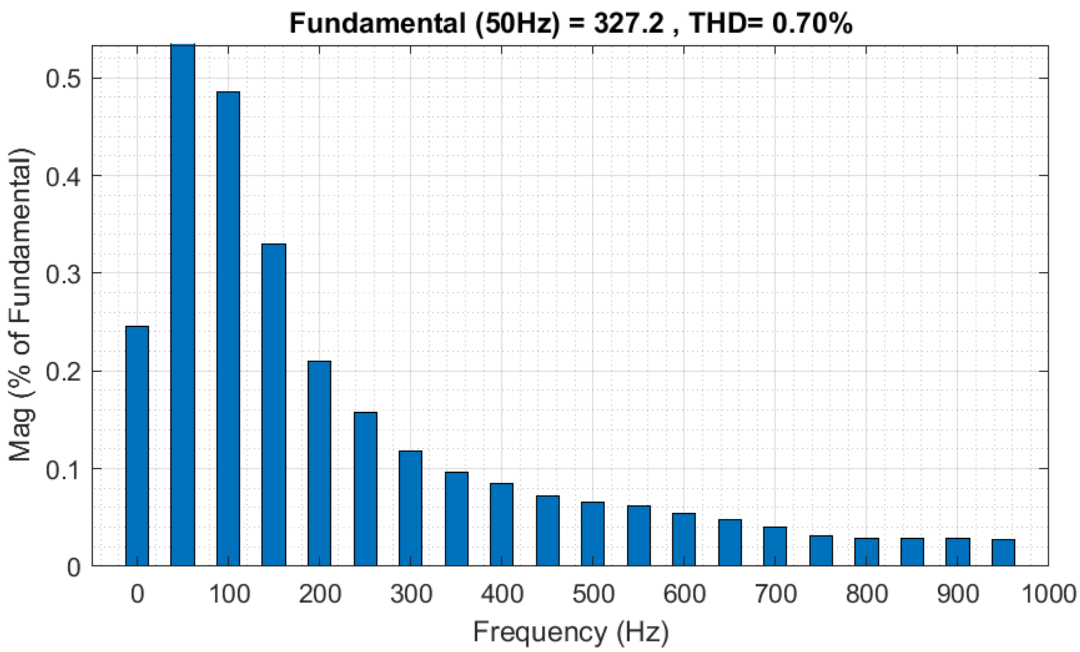


Fig. 5.5 Power Quality Impact

Fig. 5.5 shows the harmonic spectrum, and the computed THD of 0.70% shows that the system has minimal impact on power quality. With a low THD, the signal is less distorted by higher-order harmonics, indicating that harmonics contribute only slightly to the signal's power, primarily concentrated in the fundamental frequency (50 Hz). This implies that harmonic distortion is barely impacted by the proposed hybrid IDM, which improves the system's overall power quality.

5.2 Performance with IEEE-13 bus system

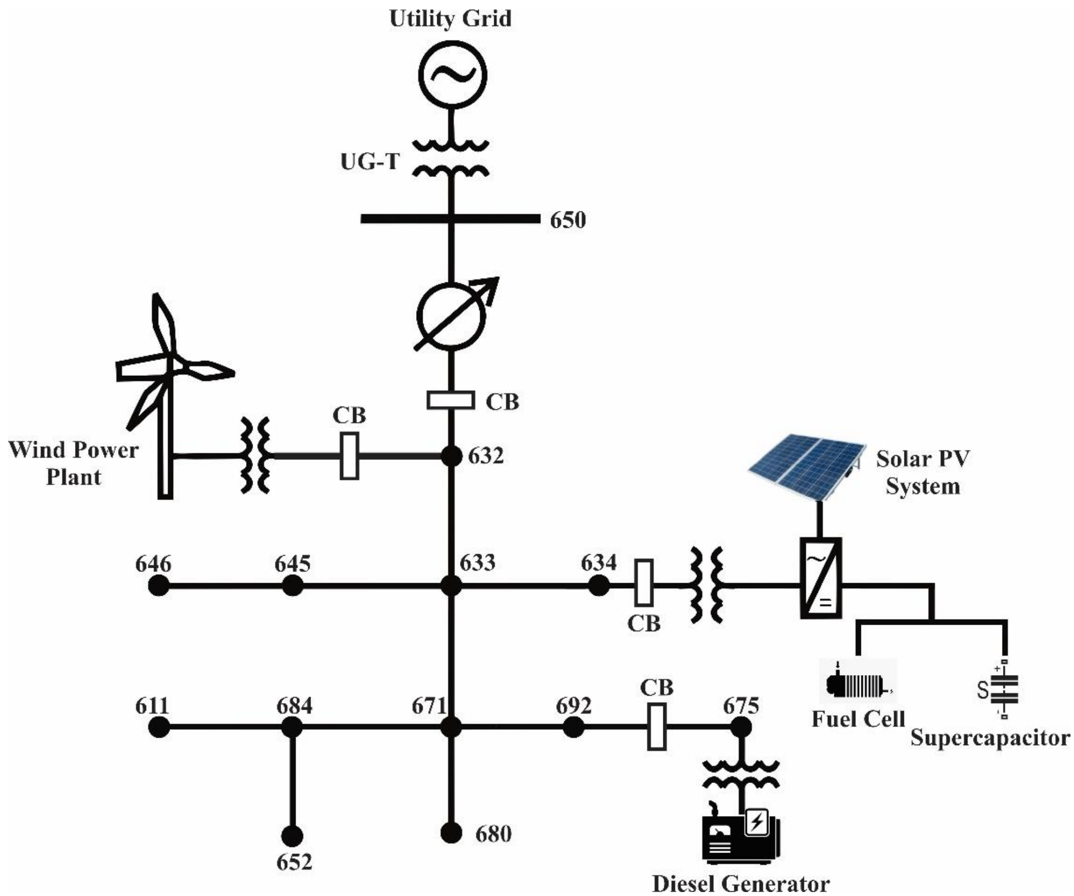


Fig. 5.6 IEEE-13 bus Test System

The proposed hybrid IDMs ' performance is evaluated using an IEEE-13 bus standard distribution system, as shown in Fig. 5.6. Extensive testing has been undertaken across various loading conditions to assess the effectiveness of the proposed Hybrid IDM. Specifically, the DG within the HMG, equipped with the capability to offer RP support, is systematically evaluated under diverse islanding scenarios as per Table 5.1 and non-islanding scenarios as per Table 5.2. The suggested approach shows reliable ID capability, demonstrating its dependability and robustness across various operating conditions.

Table 5.1 Proposed methods performance under islanding cases

Sr No	Description	$\frac{\Delta(\delta_v - \delta_i)}{\Delta t}$	$\frac{f_0}{2}\left[\sqrt{\left(\frac{Q}{Q_f P}\right)^2 + 4} - \frac{Q}{Q_f P}\right]$
Active Reactive Power Mismatch			
1	Δ P = -5 %, Δ Q = -5%	42	60.35
2	Δ P = -10 %, Δ Q = -10 %	72	60.60
3	Δ P = 5 %, Δ Q = 5 %	49	59.20
4	Δ P = 10 %, Δ Q = 10 %	86	59.00
5	Δ P = 5 %, Δ Q = -5 %	63	60.40
6	Δ P = 10 %, Δ Q = -10 %	102	60.50
7	Δ P = -5 %, Δ Q = 5 %	57	60.30
8	Δ P = -10 %, Δ Q = 10 %	87	60.45
Local Load Quality Factor			
9	Q_f = 1	45	60.33
10	Q_f = 1.5	66	60.42
11	Q_f = 2	83	60.53
12	Q_f = 2.5	109	60.66
Nonlinear Load Integration			
13	THD = 2 %	47	59.30
14	THD = 3 %	66	59.20
15	THD = 4 %	87	59.10
16	THD = 5 %	107	59.10
Multi-DG condition			
17	Δ P= -5 %, Δ Q = -5%	55	60.35
18	Δ P= -10 %, Δ Q = -10 %	79	60.55
19	Δ P= 10 %, Δ Q = 10 %	93	59.20

Table 5.2 Proposed methods performance under non-islanding cases

Sr No	Description	$\frac{\Delta(\delta_v - \delta_i)}{\Delta t}$	$\frac{f_0}{2}\left[\sqrt{\left(\frac{Q}{Q_f P}\right)^2 + 4} - \frac{Q}{Q_f P}\right]$
Induction Motor Switching			
20	7.5 KW	15	60.03

21	15 KW	25	60.1
Capacitor Switching			
22	10 KVAR ON	20	60.2
23	15 KVAR ON	30	60.15
24	10 KVAR OFF	18	60.05
25	15 KVAR OFF	28	60.10
Connection/disconnection of Load			
26	10 KW Connection	22	60.04
27	15 KW Connection	25	60.1
28	10 KW Disconnection	20	60.002
29	15 KW Disconnection	24	60.05

The higher detection time of 93 ms observed when testing the proposed hybrid IDM with the IEEE 13 bus system is theoretically justified by its complexity and the variety of operating situations it introduces. The minor increase in detection time reflects the IDM's adaptive reaction to increased complexity, which ensures reliable detection while being robust in a realistic, standard distribution network context.

This chapter provides a detailed performance analysis of the proposed hybrid IDM under various operational conditions. Key performance indices are thoroughly examined, including NDZ, detection time, and power quality impact. Simulations demonstrate the method's effectiveness in islanding detection, large load switching, nonlinear load integration, and grid voltage dips. The IDM achieves zero NDZ, fast detection (93 ms), and minimal power quality disturbance, proving its reliability in HMGs with multiple DG sources. Testing with the IEEE-13 bus system further validates its robustness in complex grid environments. The next chapter presents a comparative analysis to benchmark the proposed IDM against existing methods, evaluating its advantages across multiple performance metrics.

CHAPTER VI

COMPARATIVE ANALYSIS WITH EXISTING METHODS BASED ON PERFORMANCE INDICES

6.1 Comparative Analysis based on performance indices

In the preceding chapter, a novel hybrid IDM was proposed. This approach leverages passive and active techniques to ensure zero NDZ, fast detection times, and negligible impact on power quality. These results highlight the robustness of the proposed approach, particularly in HMG with diverse and variable generation profiles.

While the proposed method's performance was rigorously analyzed, it is essential to evaluate its effectiveness compared to other state-of-the-art IDMs. Passive methods typically monitor system parameters, and Active methods inject perturbations into the system to provoke a detectable response during islanding, reducing NDZ but potentially degrading power quality. The proposed hybrid technique aims to strike a balance by combining passive monitoring with active measures to minimize NDZ while maintaining power quality.

This chapter presents a comprehensive comparative analysis of the proposed hybrid IDM against established hybrid IDMs and other IDMs. The comparison is made across critical performance indices, as shown in Table 6.1 including:

- **NDZ**: The range of power mismatches where islanding is undetected. A smaller NDZ indicates a more reliable detection method.
- **Detection Time**: The speed at which the IDM detects islanding is critical for ensuring grid stability and safety.
- **Power Quality Impact**: The extent to which the IDM affects voltage, frequency, and harmonic distortion during operation.

Table 6.1 Comparative analysis based on Performance Indices

Ref.	**DG Type**	**Power Quality Impact**	**NDZ**	**MG**	**Detection Time**
[215]	Inverter based DG	small negative impact, 5.62 %	Small	AC MG	small
[216]	Inverter based DG	negligible impact on power factor	Zero	AC MG	300 ms
[217]	Inverter based DG	negligible impact	Small	AC MG	300 ms
[218]	Inverter-based DGs and Synchronous based DGs	negligible impact	Small	AC MG	150 ms
[219]	Synchronous based DGs	negligible impact	Small	AC MG	200 ms
[220]	Inverter-based DGs and Synchronous based DGs	negligible impact	Small	AC MG	-
[221]	Inverter based DG	small negative impact	small	AC MG	-
[222]	Inverter based DG	low	-	AC MG	160 ms
[223]	Inverter based DG	small	small	AC MG	0.76 s
[224]	Inverter based DG	-	-	AC MG	160 ms
[225]	Inverter-based DGs and Synchronous based DGs	Not mentioned	-	AC MG	50 ms
[226]	Synchronous based DGs	No impact on Power Quality	Zero	AC MG	473 ms
Proposed	**Inverter-based DGs and Synchronous based DGs**	**No impact on Power Quality**	**Zero**	**AC-DC MG**	**93 ms**

6.2 Comparative Analysis with existing methods including performance indices

The comparative analysis also includes the following criteria with indices as mentioned above -

- **Compatibility with Multiple DGs**: The IDM can work with various DERs, each with distinct operating characteristics.
- **Suitability for Different Microgrid Configurations**: Evaluating the IDM's applicability in Small scale synchronous generator (SSSG), Synchronous generator based microgrid (SGBMG), and Inverter based microgrid (IBMG), representing different levels of grid complexity.
- **Dependence on X/R Ratio**: The method is sensitive to the reactance-to-resistance (X/R) ratio, which affects its performance, especially in fault detection and weak grids.
- **Effectiveness in Weak/Strong Grid Conditions**: The IDM's ability to perform effectively under weak grid conditions, where voltage stability is more challenging, and strong grid conditions, where the system's stiffness is higher.

The following Table 6.2 summarizes the comparative analysis of the proposed hybrid IDM and other state-of-the-art methods evaluated based on the above metrics.

Table 6.2 Comparative analysis of the proposed hybrid IDM and other state-of-the-art methods evaluated based on the above metrics.

	Method	**Reference**	**NDZ**	**Detection Time**	**Working with multiple DGs**	**Suitable for SSSG/SGBMG/IBMG**	**Dependence on X/R Ratio**	**Effective in weak grid /strong grid**	**Power Quality Impact**
Remote	Impedance insertion	[6]	High	60 ms	-	SGBMG & IBMG	Moderate	Weak grid	High
	DTT	[66]	Small	500 ms	Working satisfactory with 2 DGs	SGBMG & IBMG	Dependent	Effective in both	None
	PLCC	[68]	Small	200 ms	Working satisfacto	SGBMG & IBMG	Moderate	Effective in	None

					ry with 2 DGs			Strong Grid	
	SCADA	[71]	Small	-	-	SGBMG & IBMG	Moderate	Effective in Strong Grid	None
	PMU	[74]	Small	0.2 – 498 s	-	SGBMG & IBMG	Low to Moderate	Effective in Strong Grid	None
	MPMU	[81]	small	14 ms	Working satisfactory with 2 DGs	SGBMG & IBMG	Low to Moderate	Effective in Weak Grid	None
Passive	HD	[88]	High	53-129 ms	Working satisfactory with 3 DGs	SGBMG	Moderate to High	Effective in Strong Grid	None
	ROCOF	[97]	Medium	250 ms	Working satisfactory with 2 DGs	SGBMG	Low to Moderate	Effective in Strong Grid	None
	ROCOV	[114]	Small	510 ms	Working satisfactory with 2 DGs	SGBMG	Low to Moderate	Effective in Strong Grid	None
	ROCPAD	[119]	Small	100 ms	-	SGBMG	Moderate	Effective in Weak Grid	None
	ROCOP	[120]	Large	200 ms	Potentially affected	SGBMG	Low	Effective in Strong Grid	None
	ROCORP	[121]	Medium	-	-	SGBMG	Low	Effective in Weak Grid	None
	ROCOFOP	[122]	Large	300 ms	-	SGBMG	Low	Effective in Weak Grid	None
Active	AFD	[124]	Large	269 ms	unsatisfactory	IBMG	Moderate	Effective in strong grid	High
	IAFD	[125]	Large	200 ms	unsatisfactory	IBMG	Moderate	Effective in strong grid	Medium
	AFDPCF	[127]	Small	400 ms	unsatisfactory	IBMG	Moderate	Effective in weak grid	Low
	SFS	[124]	Small	167 ms	-	IBMG	Moderate	Effective in weak grid	Low

	SMS	[136]	Small	17-115 ms	-	IBMG	High	Effective in Strong Grid	Low
	APS	[135]	Small	200 ms	-	IBMG	High	Effective in Strong Grid	Low
	SVS	[139]	small	312ms	-	IBMG	Moderate to High	Effective in Weak Grid	low
	RPV	[142]	Medium	200 ms – 1s	unsatisfactory	IBMG	Moderate to High	Effective in Weak Grid	Significant
Hybrid	SFS and frequency estimation based method	[19]	Medium	-	Working satisfactory with 2 DGs	SGBMG & IBMG	Moderate to High	Effective in Both Grid Types	Medium
	SMS and frequency estimation Based Method	[171]	Medium	-	-	SGBMG & IBMG	Moderate to High		small
	Voltage Unbalance and frequency perturbation	[20]	-	150 ms	Working satisfactory with 2 DGs	SGBMG & IBMG	Moderate to High		Medium
	ROCOV and active power perturbation	[115]	Medium	14 ms	Working satisfactory with 2 DGs	SGBMG & IBMG	Moderate to High		small
Machine Learning	DT	[175]	Small	30 ms	Working satisfactory with 2 DGs	SGBMG & IBMG	Low	Effective in Both Grid Types	None
	ANN	[29]	small	15 ms	-	SGBMG & IBMG	Low		None
	SVM	[185]	Medium	200 ms	Working satisfactory with 3 DGs	SGBMG & IBMG	Low		None
	ANFIS	[190]	Medium	500 ms	-	SGBMG & IBMG G	Low		None
	DL	[193]	Small	180 ms	-	SGBMG & IBMG	Low		None
Signal Processing	WT	[30]	small	300 ms	-	SSSG	Low	Effective in Both Grid Types	None
	MM	[202]	Small	20 ms	Working satisfactory with 3 DGs	SGBMG & IBMG	Low		None
	ST	[205]	Small	40 ms	Working satisfacto	SGBMG & IBMG	Low		None

					ry with 2 DGs				
	HT	[206]	Medium	14 ms	-	SSSG	Low		None
	TTT	[213]	Medium	700 ms	Working satisfactory with 2 DGs	SBHMG	Low		None

Proposed Method	ROCPAD & IB-RPV	-	Zero	93ms	Working satisfactory with multiple DGs -	SGBMG & IBMG	Low	Effective in both grid types	Negligible

This chapter concludes by demonstrating the efficacy of the suggested hybrid IDM, stressing its benefits over current techniques and proving its suitability for use in contemporary MG settings. The proposed approach provides a reliable solution for the next-grid topologies, guaranteeing effective islanding detection with negligible effects on grid stability and power quality.

CHAPTER VII

CONCLUSION

This Ph.D. thesis introduces a novel and highly effective hybrid IDM designed to address one of the most critical challenges facing modern HMGs: reliable, fast, and accurate islanding detection. As HMG continues gaining traction due to the increasing integration of DERs, a robust islanding detection mechanism is paramount. Islanding, a condition where part of the grid operates independently after disconnecting from the UG, poses significant risks, including equipment damage, safety hazards, and disruption of power quality (PQ). The ability to detect islanding events accurately and rapidly ensures the safe and stable operation of HMGs and maintains grid integrity.

The main contribution of this research is the development of a hybrid IDM that combines the ROCPAD, a passive detection method, with IB-RPV, an active detection technique. This hybrid approach leverages the strengths of both methods: ROCPAD's high sensitivity to phase angle deviations and IB-RPV's ability to minimize NDZ while addressing their limitations. The hybrid method provides rapid detection, zero NDZ, and minimal impact on PQ, outperforming existing standalone passive and active IDMs.

7.1 Key Contributions and Findings

- **Zero Non-Detection Zone (NDZ)**: This hybrid IDM's key achievement is eliminating the NDZ, a persistent limitation in many conventional IDMs. This passive and active integration ensures that islanding is detected across various operating conditions, including scenarios that challenge traditional methods.
- **Significantly Reduced Detection Time**: Speed is critical in islanding detection, and the hybrid IDM substantially reduces detection time to under 36 ms and, when tested with the IEEE 13 bus system, 93 ms. This rapid response is essential for preventing operational instability and equipment damage, especially in MGs with high penetration of intermittent renewable energy.

- **Minimal Power Quality (PQ) Impact**: The hybrid IDM is designed to minimize PQ disruptions, a common drawback of many active islanding detection methods. The method's ability to effectively distinguish between non-islanding and islanding events, coupled with a THD value of less than 1%, underscores its minimal impact on PQ.
- **Optimized Design and Parameterization**: The hybrid IDM is carefully optimized to meet performance and operational standards, including IEEE 1547. Precise tuning ensures that the hybrid IDM operates effectively across various HMG configurations. Furthermore, the method is robust enough to handle different load profiles, varying DER penetration levels, and UG disturbances such as voltage sags and significant load changes.
- **Comprehensive Validation across Grid Conditions**: The hybrid IDM has been thoroughly validated through extensive simulation across various scenarios. The validation process using the IEEE-13 bus system further demonstrates the hybrid IDM's adaptability and scalability, making it suitable for HMG systems and combining renewable and conventional energy sources.

7.2 Broader Impact and Technological Advancement

The findings of this thesis offer transformative potential for the design, operation, and management of HMG, particularly as they adapt to accommodate increasing levels of DERs. The proposed hybrid IDM enhances MG safety, reliability, and efficiency by addressing the core technical challenges of islanding detection, positioning them for more resilient and sustainable energy futures.

While the method demonstrates effective performance in HMG and AC MG with inverter-dominated configurations, its control strategy is fundamentally reliant on the dynamic characteristics and controllability offered by inverter-based sources. As such, its applicability becomes significantly constrained in systems composed entirely of synchronous generators or passive components, where the underlying assumptions of inverter-based control no longer hold.

- **Enhanced Grid Resilience**: The hybrid IDM contributes to the grid's overall resilience by ensuring that islanding events are detected and isolated quickly and accurately, preventing potential damage to equipment and reducing operational risks. This is especially important in HMG, where RES introduces variability and complexity into grid operations.
- **Sustainable Energy Integration**: HMG is increasingly central to achieving energy security and reducing carbon emissions as the world transitions toward more sustainable energy systems. The hybrid IDM developed in this thesis provides a reliable tool for managing these MG, supporting the integration of clean energy while maintaining grid stability and operational efficiency.
- **Compliance with Industry Standards**: The hybrid IDM has been designed in compliance with essential industry standards, including IEEE 1547, ensuring that it can be seamlessly integrated into existing and future MG architectures. This compliance is critical for widespread adoption and implementation, ensuring that the method meets regulatory and safety requirements for grid-connected systems.

While the proposed HMG and the developed IDM have significantly improved stability, detection accuracy, and operational efficiency, several areas warrant further exploration. The successful implementation and performance validation through simulation highlight the system's robustness under controlled conditions. However, as HMG continues to evolve with higher integration of RES and more complex grid dynamics, additional refinements and scalability considerations will be essential. The next step involves addressing potential real-world challenges, such as the adaptability of the IDM under highly variable grid conditions and the impact of cyber-physical threats. This leads to exploring future directions where continued innovation is necessary to ensure the long-term success of HMG in modern power systems.

7.3 Recommendations for Future Research

- Integrating modern energy management systems will improve real-time optimization capabilities, allowing the IDM to respond dynamically to changing grid conditions.

Machine learning techniques can enhance adaptive threshold modification and decision-making processes, and addressing cybersecurity will take preference, increasing detection accuracy and efficiency.

- Cognitive Computing: Cognitive computing, motivated by human mental processes, provides a potential future direction. These systems can adapt to shifting grid circumstances and historical data learning. The task is designing cognitive ID systems that can reason, learn, and make judgments that resemble human cognition while boosting flexibility and resilience.
- Neuromorphic Computing: ID can use neuromorphic computing, which imitates the brain's capacities for processing information. The task is to create neuromorphic ID systems that recognize patterns, adapt to novel situations, and tolerate faults.
- Augmented Reality Interfaces: Augmented reality interfaces might improve the skills of islanding-detecting operators. These interfaces can give operators real-time grid status visualizations, enabling them to react more quickly to identified islanding occurrences and make wiser decisions.
- Global Grid Interconnectivity: Islanding identification becomes increasingly tricky as UG interconnection increases owing to long-distance transmission and the integration of RES across continents. Research should concentrate on creating ID technologies to solve such massive, linked grids' particular stability and dependability difficulties.
- Edge Computing: Utilizing the amazing potential edge computing offers is expected to become a significant trend. Edge computing is well-positioned to orchestrate a symphony of lowered latency and excellent responsiveness for ID strategies in scattered-producing landscapes. It handles data close to the source.
- Real-world variability: future work can incorporate factors such as component aging, communication latency, and environmental uncertainties.
- Account for hardware limitations: future research can account for hardware limitations. This includes inverter constraints, sensor inaccuracies, and real-world grid faults, which must be rigorously modeled and tested to bridge the gap between theoretical performance and practical deployment of islanding detection methods.

- Simplified Control Logic: future work can focus on validating control algorithms under real-world conditions, as their performance in simulations may diverge significantly from actual deployment due to system non-linearities, hardware delays, and unmodeled dynamics.
- Economic Analysis: Assessing factors such as implementation cost, operational efficiency, and return on investment is crucial to support widespread adoption, particularly in cost-sensitive or small-scale distributed generation systems.
- Cyber-security and communication aspect: Future work should also address cyber-physical threats and data transmission reliability, which are critical concerns in real-world microgrid control systems.
- Future research could thoughtfully explore the challenges of integrating multiple energy sources and storage systems, particularly as system complexity grows. Similarly, the development of more adaptive control and protection strategies may further support seamless operation across grid-connected and islanded modes.
- While simulation-based analysis offers valuable insights, future work could enhance realism by incorporating real-world operational complexities. Additionally, exploring more advanced or validated software tools may improve the precision and reliability of performance assessments.
- Recognizing that replicating exact conditions of existing studies or systems can be challenging, future research could focus on developing standardized benchmarking approaches or adaptable comparison frameworks to ensure more meaningful and equitable evaluations across diverse scenarios.

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Publication Details

Sr. No	Type of Paper (Journal Paper/ Conference proceeding/ Book Chapter)	Name of the Journal/Conference/ Book	Journal indexing (Scopus/UGC/ Web of Science)	Title of the Paper
1	Conference Proceeding	International Mobile and Embedded Technology Conference MECON 2022	Scopus	Performance Analysis of Islanding Detection Method for Grid-Tied Photovoltaic System.
2	Conference Proceeding	Recent Developments in Control, Automation and Power Engineering, RDCAPE-2023	Scopus	Implementation and Performance Evaluation of Intermittent Bilateral Reactive Power Variation islanding detection Technique in Hybrid Microgrid.
3	Journal Paper	Scientific Reports	Q1 Web of Science, SCIE	Enhancing grid resiliency in distributed energy systems through a comprehensive review and comparative analysis of islanding detection methods.
4	Journal Paper	Renewable Energy Focus	Q2 Web of Science, SCIE	Efficient islanding detection in hybrid Microgrids : The hybrid approach integrating ROCPAD and IB -RPV
5	Patent (Published)	Indian Patent	Application Number - 202411058914	Hybrid Islanding Detection Method Combining Rate of Change of Phase Angle Difference and Intermittent Bilateral Reactive Power Variation for Hybrid AC/DC Microgrid
6	Journal Paper (Communicated)	Scientific Reports	Q1 Web of Science, SCIE	An Intelligent Islanding Detection Strategy for Hybrid Microgrids Using K- means Clustering and Particle Swarm Optimized Neural Networks