Techno-Economic Analysis of Solar Grid Based Virtual Power Plant in Indian Power Sector: A Case Study of PSPCL

A Thesis

Submitted in partial fulfillment of the requirements for the

award of the degree of

DOCTOR OF PHILOSOPHY

in

ELECTRICAL ENGINEERING

By

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LOVELY PROFESSIONAL UNIVERSITY
PUNJAB
2020

This thesis dedicated to my parents and my close ones who created interest and curiosity in me for the understanding the different aspects of the life

DECLARATION

I declare that the thesis entitled “Techno-Economic Analysis of Solar Grid Based Virtual Power Plant in Indian Power Sector: A Case Study of PSPCL” has been prepared by me under the supervision of Dr. Sachin Mishra, Associate Professor, School of Electronics and Electrical Engineering, Lovely Professional University, India. No part of this thesis has formed the basis for the award of any degree or fellowship previously.

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THESIS CERTIFICATE

This is to certify that the thesis entitled **“TECHNO-ECONOMIC ANALYSIS OF SOLAR GRID BASED VIRTUAL POWER PLANT IN INDIAN POWER SECTOR: A CASE STUDY OF PSPCL”** submitted by **HARPREET SHARMA** to the Lovely Professional University, Punjab for the award of the degree of **Doctor of Philosophy** is a bonafide record of research work carried out by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

The environmental threat and rising fuel prices are the two major challenges faced by the utility to provide clean and affordable electricity to the consumers. The change in government policies assists with large scale deployment of Distributed Energy Resource (DER) such as rooftop solar Photo Voltaic (PV). The increased popularity of small scale DER has replaced the well-established concept of a central generating plant around the world. In the present energy scenario, a significant share of energy production comes from the grid integrated DERs installed at consumer premises. Another major driving factor in shifting of present grid paradigm to an active grid network is the reliability and resiliency of the utility network. With hefty investment in the distribution network, the reliability of the feeders is considerably enhanced, however, a large number of outages are still occurring every year, which cause major production loss to the industries. The concept of Virtual Power Plant (VPP) can be a possible way to address these challenges through its coordinated operation of aggregated generation, energy storage, and flexible demand with the active participation of the consumers.

This thesis evaluates the state power utility for implementation of the VPP, where the DERs are integrating into the grid at a very high pace. The existing distribution network is incapable of higher penetration of DERs and instead of providing benefits; it would adversely affect the power quality and reduces the utility revenue. The energy generations from DERs during low demand period causes reverse power flow in the distribution network, which needs to be a tackle for the safe operation of the protective devices. The generation also does not aid in reducing the peak load as the generation is not scheduled according to the demand pattern. The DERs energy generation reduces the utility imports significantly; hence the revenue of the utility to meet the distribution network expenses could be insufficient. The effective utilization of this high share of DERs is only possible through the VPP concept implementation. The pilot study on various benefits of establishing VPP in the part of the distribution network is analyzed. The implementation of VPP in a selected area is found to be beneficial for both utility and consumers.

The study also deeply analyzes the influence of VPP on the reliability of the grid. The Monte Carlo Simulation (MCS) method is utilized to compute the reliability indices with various scenarios such as DER and recloser. The computed indices from the probabilistic method are fed to the designed multi-objective model for finding optimal scheduling configuration. The Mixed Integer Linear Programming (MILP) optimization is utilized for finding an optimal solution after considering various technical and economical constraints. A case study of an 11 kV Industrial feeder is selected for reliability assessment with the inclusion of DERs and reclosers at different locations of the feeder. The various reliability indices are improved with the VPP implementation, which further declined the cost related to the loss of load. The flexibility of the grid is also enhanced with the VPP as the considerable demand is dispatched by the VPP during the outage or scheduled shut down of the feeder. The results are validated by the use of the IEEE 34 bus test system and the proposed model found to be effective in enhancing the system reliability.

Another major application of the VPP is to flatten the demand profile of the utility. Already, the present maximum demand on the feeder is surpassed the current carrying capacity of the system, which results in conductor breakdown and grid outages. The case study of Industrial and residential feeder is discussed to determine the influence of the VPP on the distribution network load profile. The DER-CAM model has been used to design the optimal VPP configuration. The optimal dispatch of DER and DR results in a significant reduction in peak demand of the feeder especially the Industrial feeder as the large share of the demand coincides with the solar generation during the daytime. However, the excess generation during weekends, when the load on the feeder is negligible results in the reverse power flow in the industrial feeder, which could be transferred to the residential feeder for the effective utilization of generation. The reduced peak demand defers the utility investment in the distribution network for augmentation in components capacities. The VPP is also beneficial for congestion management as the DER dispatch the load locally, which defers the need of installing the equipment of higher rating.

A multi-objective optimal model based on modified PSO (Particle Swarm Optimization) is proposed for the objective of cost minimization, peak shaving, and reliability improvement within the VPP framework from both utility and consumer point of view. For feasibility analysis, the case study of state power utility is evaluated, a 90 bus industrial feeder with grid integrated PVs as DER is selected. The model of feeder including all its parameters is designed on ETAP software for checking the load flow constraints. The individual components of the VPP such as PV, battery, load, and grid is modeled as multi-objective functions. In grid-connected mode, the VPP supplies the load through DER, and the remaining demand is met by the grid. On the other hand, when there is a utility outage, the VPP autonomous mode supplies the emergency demand by completely through the DERs and batteries, the remaining low priority demand is either shifted or curtailed to balance the system. The optimum results in both VPP modes show a considerable reduction in operational energy cost with the inclusion of DER generation dispatch. The peak load of the utility is also declined by the combined dispatch of the DERs, battery, and DR within the concept of the VPP. The load dispatch in an autonomous mode of the VPP increases the reliability of the system by supplying the demand in the absence of the grid and hence the EENS (Expected Energy Not Supplied) is reduced. Apart from providing multiple benefits to the utility, the VPP also reduces the energy and demand charges of the consumer. The results of the designed VPP model are also validated through comparing the results using other optimization techniques.

ACKNOWLEDGMENTS

This thesis would not have been possible without the support of glorious people who motivated me during my doctoral study. I am thankful from my bottom of my heart toward the numerous persons who assisted me while conducting this study.

First of all, I would like to thank my supervisor, **Dr. Sachin Mishra**, for his worthy guidance, support, and suggestions, in every step of this research project during my Ph.D. journey. Dr. Mishra has an optimistic personality with helpful nature, he has always made himself ready to clarify my doubts and it was a great opportunity to work under his supervision. He always shed light whenever I was feeling stuck in my path of research ambitions.

I would like to express my gratitude toward the entire **Lovely Professional University** family for providing suitable infrastructure and environment for completing my research work in a time-bound manner. Also, I like to thank the Division of Research & Development and School of Electrical and Electronics Engineering for their help and encouragement in my entire Ph.D. journey.

Last, but not the least, I am very grateful to the staff of **Punjab State Power Corporation Limited** for their tremendous technical support and valuable guidance, which makes the research a real-time practical study instead of a theoretical one.

Finally, I like to thank almighty God who helped me to achieve such a big milestone.

Harpreet

Date: 26-11-2020 **Harpreet Sharma**

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CHAPTER 1

INTRODUCTION

1.1. Background

From the last two decades, the energy sector has been witnessed a dramatic change in the generation and distribution sector, which is prominently due to higher fuel prices and global warming. Every nation of the world puts its rigorous efforts into searching and developing clean and affordable resources of energy. The investment in larger central generating plants such as thermal power plants is significantly declined and the paradigm is shifted toward the more efficient and small energy generators in the form of Distributed Energy Resources (DER). The role of DER in the present global and Indian scenario is discussed in this chapter:

1.1.1 Global Energy Scenarios

In a recent trend, the share of renewable energy resources is increasing sharply, to have a sustainable energy future [1]. The present renewable share in the global energy scenario shown in Fig.1.1 below:

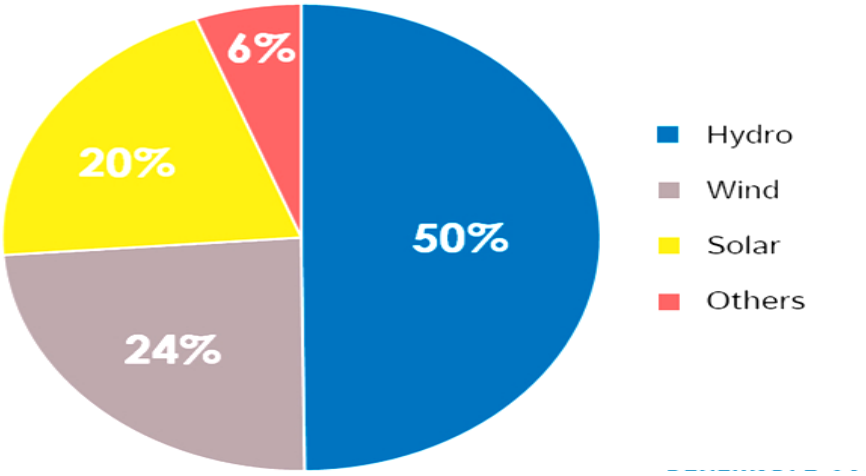


Figure 1.1 Global energy scenario

Considering the present power generation sector, the solar generation capacity has not prominently shared the total electricity production in comparison to other renewable resources such as hydro and wind. However, the growth rate of solar capacity is highest among the other renewable, and its installed capacity is expected to further increase in the upcoming years with technological advancement, which is illustrated in Fig.1.2.

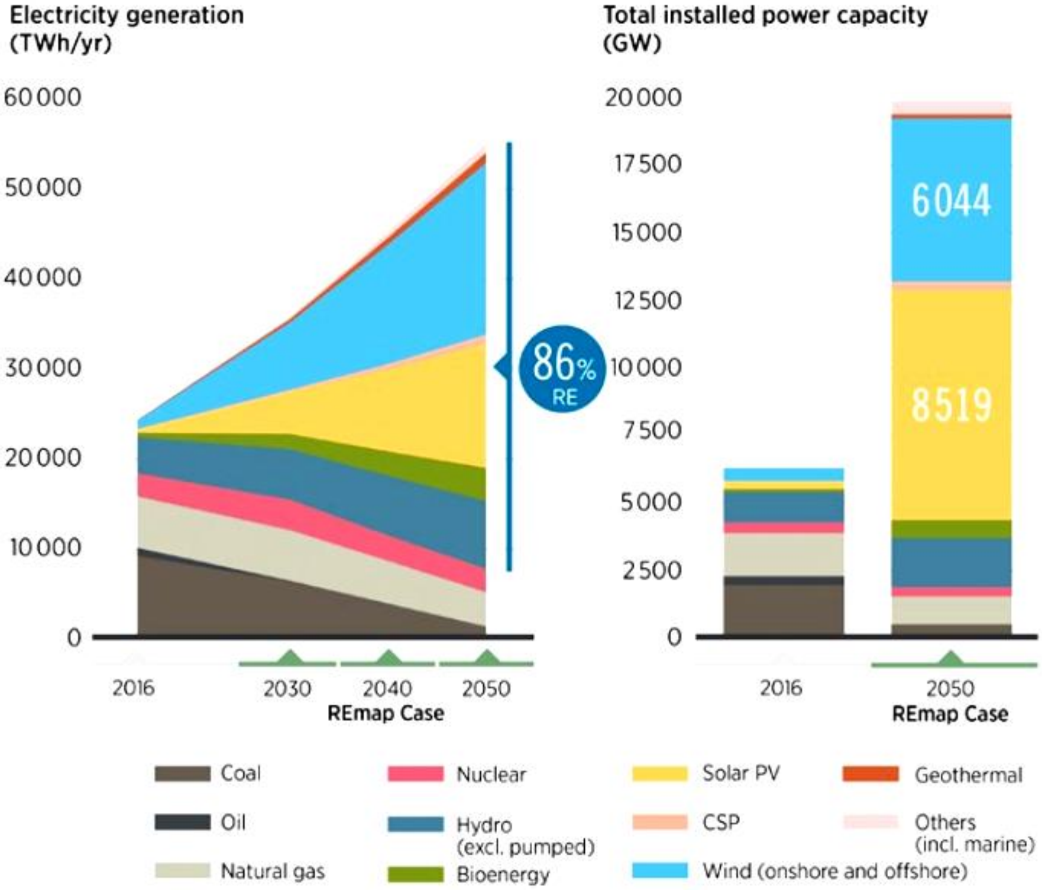


Figure.1.2 Solar energy forecast

In India, the energy scenario is even more favorable for solar PV due to the abundant solar radiation that it received throughout the year. The PV is well popularized both among energy players and ordinary consumers [2]. The Ministry of New and Renewable Energy published data regarding future solar capacity in India [3], [4]. The projected growth of PV installation capacity in upcoming years is illustrated in Fig.1.3. With the advancement in solar technology, it is highly expected that PV integrated capacity will be significantly increased as the forward step in the path of a sustainable energy future.

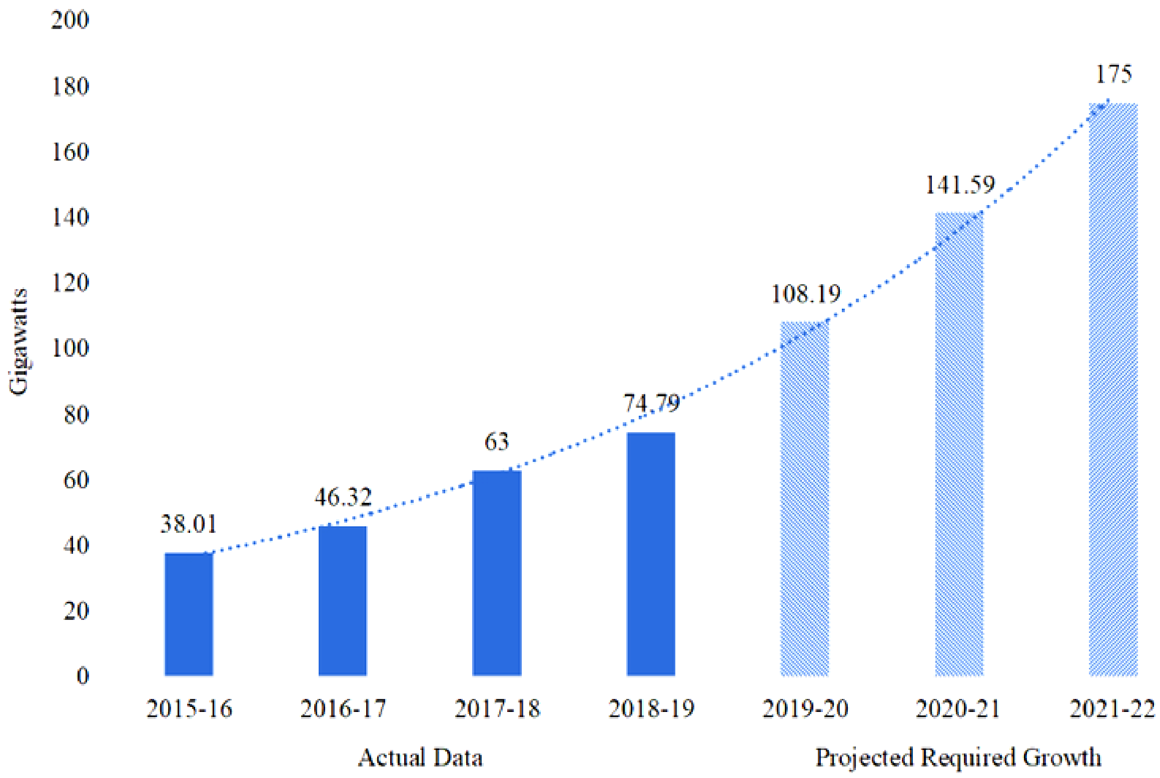


Figure.1.3 Projected PV capacity growth

1.2. Virtual Power Plant Concept and its Components

The concept of Virtual Power Plant (VPP) is driven from a microgrid, but unlike the microgrid, the working of VPP is also autonomous. The VPP aggregate different type of DGs located at different points in the distribution grid and hence creates the single operating profile. The impact of this DG on the distribution network can be easily analyzed by aggregation and this aids in decision making while making contracts in the energy market and generation capacity augmentation. Fig.4 shows a detailed VPP structure below [5]. The VPP not only provides generation flexibility but can also change the consumer load profile by direct load control or by cost incentives. The VPP integrates the DER technologies with Demand Response (DR) programs and storage devices for the efficient operation of energy systems[6]. The VPP needs four major components for its operation, which are visualized in Fig.1.4.

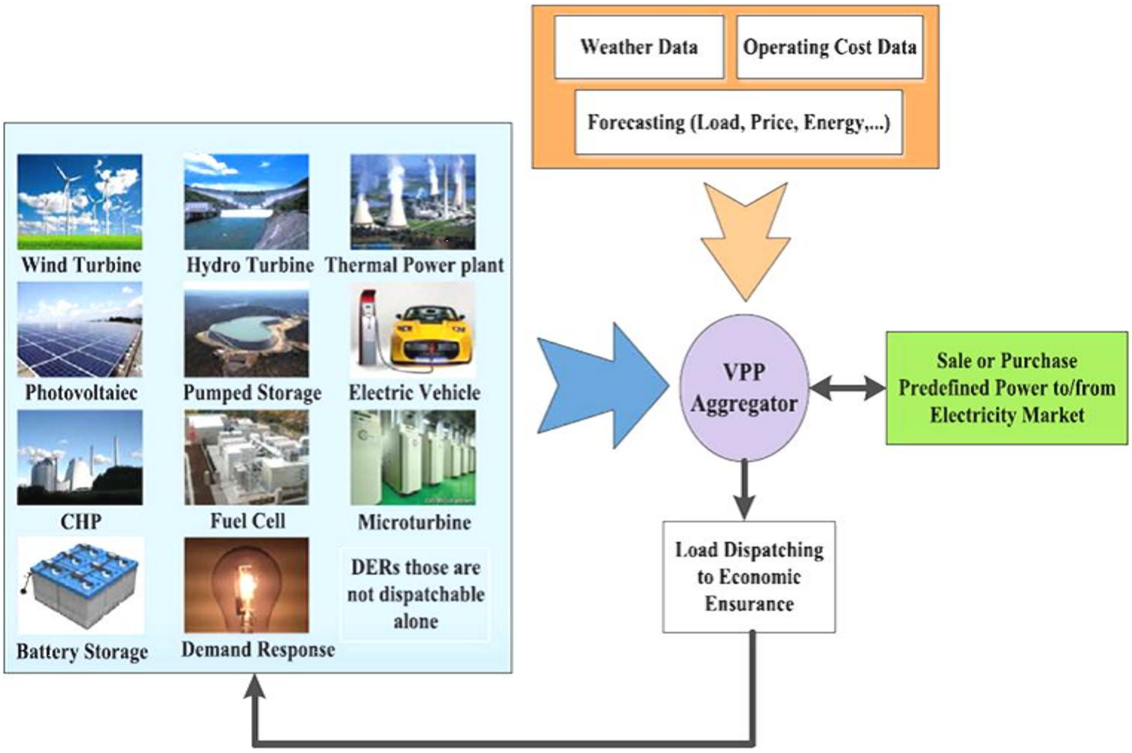


Figure.1.4 VPP structure

1.2.1 Distributed Generation Technologies

The small scale DGs having renewable resources are the key generation technologies of VPP. The technology advancement changes the traditional consumer to "Prosumer", which can consume or produce electricity at the same time. The DER provides cost-effective and clean energy, which is the main need for a sustainable future. These generation technologies can be dispersed in different geographic locations and linked to the distribution grid at different points. Solar PV, wind, and biomass are few generation technologies are utilized in VPP.

1.2.2. Energy Storage Technologies

The intermittency of DER based on renewable energy resources negatively affects power system stability. The short-period fluctuation due to cloud movement or wind speed can change the supply voltage profile significantly. To increase the flexibility in the utility grid with DG mix generation, various storage technologies can be used. The energy storage tackles the variable power issue by smoothing these fluctuations by charging and discharging cycles. The capacity, duration, and cost are some of the main parameters while selecting storage technologies. The various Energy storage technologies are as follows [7]:

- Battery energy storage
- Super conductor energy storage
- Ultra capacitor energy storage
- Flywheel energy storage

1.2.3. Controllable Loads

With the intermittency of renewable resources, the DGs are incapable to follow the energy demand. To tackle this issue, flexibility is required from the consumer in its energy pattern which is termed as Demand Response (DR). The electrical load is curtailed or shifted with the utility signal during an emergency or peak period. The load shifting and curtailment of load on peak time can be used for a significant reduction in energy and demand charges. The incentive-based and direct load curtailment approaches are utilized to control the demand.

1.2.4. Integrated Communication Technologies

The coordination between DER technologies and utility can make possible participation of small scale DER in the energy market [8]. For this coordination, the information technologies play a vital role by providing the bidirectional communication between consumer and utility and through which sharing critical information of energy generation and demand is possible. The control system like SCADA and EMS are fully dependent on communication technologies.

1.3 Types of VPP:

The VPP is broadly classified into two main categories:

a) **Technical Virtual Power Plant:** It consists of DER in the same geographic location. In this VPP the impact of aggregated profile on the distribution network is measured. The balancing, voltage profile, and reliability of the grid are considered. The optimal operation of DGs, controllable loads, and storage devices are to be done for providing reliable and economical supply to consumers.

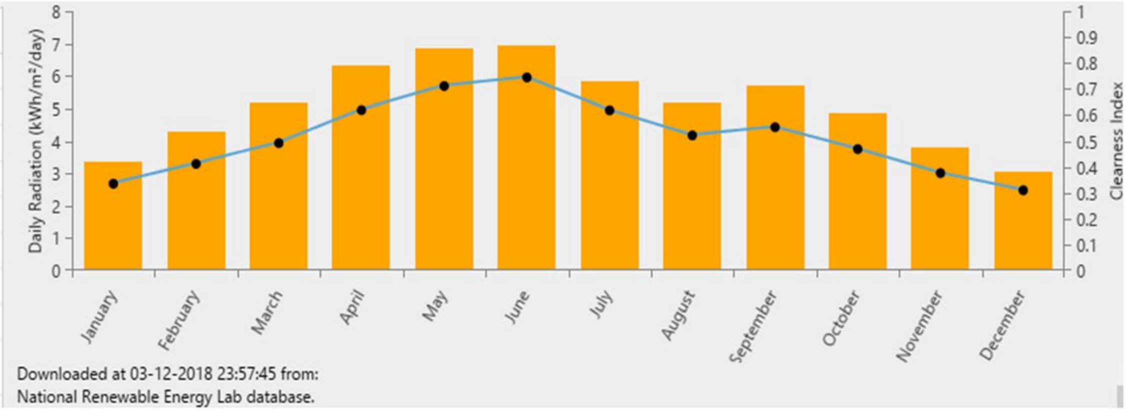
b) **Commercial Virtual Power Plant:** In this VPP the economical and operating parameters of the aggregated profile are analyzed without considering its impact on the utility distribution network. This VPP provides energy trading services to the system operator. The operator of this VPP can be a third party and trades the energy between small scale generators and utility.

1.4 Case Study

The Punjab State Power Corporation Limited (PSPCL) is the only power utility in the Punjab state of India, which assumes responsibility for both distribution and generation of energy. The PSPCL installed generation capacity by end of the year 2017 was 52204.9 MW. The generation is the mix of hydro, thermal, and co-generation [9] plants located at various parts of the state. Apart from this generation, the DER in the form of solar PV is now become an emerging resource of energy because of the clean generation and its weather suitability. The government gives subsidies and capital incentives for installing rooftop PV on residential and commercial buildings. These DERs are mostly grid-connected and from its present growth, it is visualized that this DERs grid penetration is expected to increase at a very high pace in upcoming years. The VPP concept could be a promising solution for efficiently and reliably integration of these DERs into the grid without any adverse effect. The present policy of PSPCL allows solar capacity ranging from 1kW to 1MW to install at consumer premises for grid-tied operation. In this case study, the potential of VPP is analyzed for PSPCL in a selected area.

1.4.1 Resource Data Assessment and Location Data of Study Area

In this area, the solar PV already showed great results in reducing energy bills for consumers. The annual average solar radiation and clearness index data is taken from the National Renewable Energy Lab Database is shown in Fig.1.5 below:



Downloaded at 03-12-2018 23:57:45 from:
National Renewable Energy Lab database.

Figure.1.5 Annual average solar radiation and clearness index data

The selected site is under the jurisdiction of East Division, PSPCL situated (31.3260° N, 75.5762° E) in the Jalandhar district of Punjab (India).

1.5 Scope of the research

The main purpose of this case study is to determine the role of VPP in the distribution network for the high penetration of solar PV in the state of Punjab, India. This result facilitates certain the capacity of solar PV which is technically and economically viable. The result also helps to defer the investment for augmentation in generation capacities. This study expected to address the following research questions:-

1. How the different types of VPP can be utilized for a different type of load profiles?
2. How much capacity of solar PV can be integrated into the distribution grid without affecting the grid reliability and its revenues?
3. To find the potential of the aggregated generating profile of solar PV helps to decide on augmentation of network capacity?
4. How the flexibility obtained from the load shifting can reduce the utility peak load and save for consumers on the energy bills?
5. To determine the role of VPP for enhancing grid reliability during the outage period.

1.6 Objective of Research Proposal

The key objectives of this research will be the following:-

1. To study the existing technical and economic parameters of the 11kV distribution network and study the impact of high penetration of DER without the VPP concept.
2. To determine the effect of VPP on the distribution grid:
    a) Reliability of grid during outages.
    b) The flexibility of the grid.
3. To investigate the effect of VPP scheduling on utility peak load.
4. To design a general VPP model after economical analysis which permits:
    a) High penetration of DER.
    b) Maximizing profits for both parties.

1.7 Chapter Wise Summary

- **Chapter 2** deals with all the relevant studies reported so far, starting with the effect of high penetration of DERs on the distribution network without the VPP concept. The literature review regarding the cost minimization with DER, DR, and storage both in the individual and combined configuration are reviewed. The reliability enhancement of the utility distribution network with the inclusion of DGs and DER is also analyzed. The chapter also reviews various VPP models that are based on different optimization techniques. At last, the potential research gaps after an in-depth analysis of the present studies are discussed.
- **Chapter 3** deals with the investigation of the current paradigm of the PSPCL distribution network, which includes the loading, generation, and economical parameters. The 11 kV distribution feeders are selected for studying the load and grid-connected PV profiles. The influence of PV on the load profile of consumer and utility is also the focus of this chapter. Finally, the penetration of grid-connected DER is analyzed for determining the influence of utility security and economic viability. The adverse effect such as reverse power flow

also considered at different days of the week at different PV penetration levels.

- **Chapter 4** deals with the effect of VPP on the reliability of the Industrial feeder. The Monte Carlo Simulation (MCS) is utilized to determine the reliability indices by generating the artificial failure history of components. The multi-objective optimal model of VPP is introduced which optimizes the electrical dispatch to minimize the energy cost and Expected Energy Not Supplied (EENS). Both modes of the VPP such as grid-connected and autonomous mode have been discussed. Lastly, the results of the developed model with Mixed Integer Linear Programming (MILP) are also validated by the proprietary derivative algorithm. The flexibility of the utility with the VPP implementation is also verified in this chapter during an outage. The section-wise length of the feeder is analyzed for VPP dispatch in the event of fault and reclosers at suitable points. The techno-economic analysis of reliability improvement with VPP is analyzed. The MCS probabilistic model is also validated through IEEE 34 node system.
- **Chapter 5** deals with the design of the VPP model for the PSPCL 11 kV distribution network, which assists the utility in flattening its demand profile and permits high integration of grid-connected DER in a secure and economical manner. The residential and Industrial feeder demand profiles are studied to determine the influence of VPP on the maximum demand of the feeder. The optimal solution, which ensures benefits for both consumers and utility is found. The annualized and operational cost is calculated to sort out the different optimized configurations. The role of DR to tackle the reverse power flow and effective utilization of PV generation is also the main focus of the chapter. The utility investment deferral is also computed with the VPP.
- **Chapter 6** Designing the general VPP model based on modified Particle Swarm Optimization (PSO). The objective of the optimized function is cost minimization, peak load reduction, reliability enhancement subjects to various technical and economic constraints. The modeling of various components of the VPP has been done such as PV, loads, battery, and utility. The VPP grid-connected and autonomous operations are studied for normal and outage

periods respectively. The techno-economic analysis has been to find the optimum dispatch solution. The optimal operational cost and contribution of the battery in the electrical dispatch are calculated. The results of the designed model are then compared with MILP and other optimizations to find the effectiveness of the proposed optimal model.

- **Chapter 7** Summarizes the results and contributions of this thesis work. The future research potential of this research is also stated in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

The increasing share of renewable energy is a viable way for the fast track progression of any nation to meet their energy needs, especially for developing countries [10], [11]. The import of expensive fossil fuels hampers the nation's financial growth and this leads to utility in search of alternative energy resources [12], [13]. However, there are numerous barriers, which need to be addressed before moving towards a complete paradigm of renewable energy [14],[15]–[18]. The interconnection of grid-connected DER such as solar PV needs to meet grid codes, design, and standards to effectively participate in the distribution network [19], [20].

2.2. Energy Dispatch with High DER Penetration

Previous studies were limited to the small share of DGs for standalone operation, however, with the need for clean resources of energy emerges, the large scale integration of DER now becomes the main objective of the nations [21]–[23]. The various architectures are now available for the combined operation of DERs to simplify the computation of power flows [24]–[27]. The intermittent generation of solar PV due to dependence on weather conditions causes various technical difficulties for grid penetration such as harmonics, islanding, and voltage fluctuation [28]–[32]. In [33] a novel method is proposed for scheduling non-dispatchable renewable resources using fuzzy control and static machines as an electrical hub. In [34] Regrouping Particle Swarm Optimization is utilized to dispatch the microgrid with high penetration of DER in both grid-connected and standalone mode. The modeling of VPP with different energy market trends has been done [35] to assess the influence of forecasting errors due to variation in the weather conditions without considering the utility aspects. Another study introduces energy management techniques [36] using a nonlinear optimization problem to dispatch the various resources to meet residential load in standalone operation. The single large capacity DER such as solar PV is used in [37]–[44] for meeting the demand of a specific load profile without assessing the impact on the distribution network. Another study [45] access the performance of PV on various parameters by using different types and ratings of solar panels to meet the load demand. The utilities having a radial distribution network introduces different measures to mitigate the adverse effects of DER integration [46]. The energy policy of different countries around the globe has been changed according to make the balance the revenue generation by the PV and its implications towards the distribution network [47]. The Net Present Value (NPV) is computed for the feasibility analysis of VPP by ensuring the benefits of both consumers and supply sides [48]. A study [49] introduces flexibility measures to integrate the intermittent generations and describes the already established projects of large scale integration of DER.

2.3. Scheduling of DER for Cost Minimization

The different studies have focused on cost minimization by optimal scheduling of DG [26], [50]–[57] but utility advantages like peak shaving and investment deferral in distribution infrastructure are not considered in these studies. The different algorithms [58]–[60] are introduced for profit maximization in the VPP framework and validated on the IEEE bus system despite these studies lack the real-time constraints and benefits for the utility grid. A case study [48] of the specific island shows the feasibility of VPP for self-power support by its DER standalone operation, whereas operation with the grid is out of the scope in this research. The fuzzy-based dispatch method is introduced in [33] for non-dispatchable resources like solar PV and wind energy without implementing DR. The studies [61], [62] discussed the influence of DERs without the inclusion of DR on the competitiveness of the energy market. The related review regarding this research [23] is introduced different algorithms for calculating investment deferral with the integration of DG into the utility grid without considering DR. The DER CAM also utilized in research [63] for optimal sizing of DER while considering the variation of solar irradiation due to cloud movement. Techniques such as smart transformers and battery storage systems are introduced in [64], [65] to mitigate the unfavorable consequence of reverse power flow, however, the DR based technique is not utilized in any reported study. The optimal price taker model is purposed in [66] with an aggregated load profile in different approaches. The three different case studies are studied to determine the benefits without focusing on the technical constraints of the utility. In [67] a techno-economic analysis of a hybrid energy system for electrification has been done using HOMER software without implementing the DR concept. Another tool AIMMS, modelling software is utilized in [68] for optimizing various DERs and storage devices for dispatching microgrid energy.

2.4. Scheduling of Grid Integrated DR for Cost Minimization

DR programs are introduced for effective implementation of the VPP under which the consumer is charged at a lower tariff for a particular time of a day than the remaining period, which helps the load to follow DER generation [69]. The consumer participation demand response program for maximizing the profit of the VPP in [70]. The different case studies are done to determine the role of DR in maximizing grid efficiency [53], [54] and a reduction in network investment, without considering the DER effect, furthermore, the investment deferral in the distribution network is also not part of these researches[70], [71]. The DR programs are utilized by various case studies to increase distribution network efficiency [73], [74], and defer the network investment but they don't consider DER during electrical dispatch. The flexible scheduling and DR aggregation using a quadratic function are utilized to optimize the DR response in the energy market [75]. In [76] DR is utilized to encourages the consumers to change their demand patterns to coincide with PV output The analytical approach of computing DR benefits in the distribution network is studied in [77].

2.5. Combined Scheduling of Grid Integrated DER & DR

The studies purposed simultaneous dispatching of DER and DR [78]–[81] for profit maximization of the VPP. The novel methodology is introduced in [82] for the combined dispatch of DER and DR for energy and reserve needs. The demand-side management techniques in conjunction with DGs are scheduled through HOMER software in [83], [84] to find economical dispatch configuration. The DER-CAM and MATLAB are used in [85] for techno-economic assessment of DER installed mid-rise apartment without taking the utility influence. The study [86] pointed out the application of DER CAM for multi-objective analyses of a case study of the island for cost minimization and reliability maximization for only standalone operation. The risk-based stochastic framework consisting of wind-based dispatchable resources, DER, DR, and storage devices for short term and reserve scheduling in [87]. The bi-level mathematical model with equilibrium constraints is introduced in [88] for determining the behavior of each producer. This research utilized various optimization techniques for the optimal bidding of VPP. However, the focus of this study is limited to the commercial aspect of VPP only and technical constraints are not sufficiently taken. Another study relevant to the commercial VPP [89] purposed a bi-level multi-time scale scheduling method based on bidding to increase the competitiveness of VPP in the energy market, while there is no emphasis is given on technical constraints. The industrial technical VPP is proposed in [90] to manage the aggregated load of the industry, which includes the stochastic nature of demand response, however, the utility benefits such as peak shaving and network augmentation deferral are out of scope. The study [91] proposed an agent-based model for combined scheduling of DER & DR within the prosumer framework, however, the complete day profile is not taken into account, and in addition to that, the power exchange between agents also not part of this research. In [92] a combined dispatch solution is proposed for minimizing consumer energy cost utilizing demand-side management techniques and optimal dispatch of PV generation. The MILP and Genetic Algorithm is used in [56] for scheduling different DERs and storage in the day-ahead energy market.

2.6. Reliability Evaluation with DER or DR

In [93] the utility case study is taken into account to determine the effect of multiple DGs on the grid reliability and power loss using Matlab and DIgSILENT without calculating the financial implications of DG on the distribution network. In the study [94] for reliability improvement and loss reduction, an optimal solution of DER placement based on the performance index such as total energy consumed and energy not supplied is introduced, the research does not consider the multiple DG influences on the reliability, and the economical constraints are also not sufficiently taken. The multi-objective function is introduced in [95] for the reduction in power loss and reliability enhancement with the application of dynamic programming considering

DGs. However, the reliability indexes such as SAIFI and SAIDI are not focused while enhancing reliability, furthermore, the probabilistic way such as MCS is also not utilized for system failure calculation. The transformer's reliability improvement is analyzed in [96] with high penetration of DERs such as diesel generators, PV, and wind, however, overall system reliability indices are not evaluated and economic analysis has not been done. In [97] the genetic algorithm embedded MCS is applied on 15 bus and 33 bus radial feeders to meet the growing load demand and enhance the reliability of the network. However, there is no attention is given to system overall reliability enhancement and the effect of multiple located DGs as VPP is not evaluated. The study [98] calculates the various reliability indices of the IEEE RBTS integrating DERs using the Markov model, which is not efficient for a large network and there is a provision of multiple DGs. In [99] the ETAP software is used to evaluate the reliability of the IEEE RBTS integrating DERs at one or multiple locations, but the financial aspects of these improvements are not taken into account. The flexibility of the grid within different DER framework is analyzed in [100] for providing flexibility to the utility grid while there is no concern is given on technical and economic analysis of the system. The risk aversion model is introduced in [101] with aggregated DGs from the VPP point of view and simulated in IEEE 30 bus system. The objective of the model is profit maximization with a limiting focus on technical aspects of VPP. Apart from DER, the DR individually play a significant role in reliability enhancement by controlling the demand as per utility requirement [102].

2.7. VPP Models

In [103] the VPP model is proposed, which offers the coordinated operation of electrical and gas networks. The role of two DR models such as coupon-based and interruptible load based model is evaluated on 118 bus IEEE feeder with bi-level optimization for the cost minimization, however, the DER and energy storage are not part of this study. The Industrial VPP model is introduced in [104] for the management of industrial loads and generation using stochastic Mixed-Integer Non-Linear Programming (MINLP), which includes wind energy resources and demand response programs, however, the impact on utility is not taken into account, moreover, the storage devices are not used during dispatch. The aggregate generation and demand response of the prosumers is scheduled optimally for the day-ahead energy market and real-time transactions using a two-stage Stackelberg model in [105] without giving stress on the technical aspects of the utility and storage devices. In [106] the combined optimization, which is the combination of interval and deterministic approach for solving the VPP dispatch problem without taking the reliability constraint of the utility. The combined dispatch of energy and reserve is proposed in [55] with a probabilistic modified decision-making model with the inclusion of DER, storage, EV, and demand response, however, there is no consideration is given to the influence of VPP on the reliability of the utility network. In [107] the VPP based on a multi-objective model is introduced to maximize revenue, minimum risk, and carbon emission using robust optimization theory without taking the utility benefits such as peak load reduction and reliability enhancement. The techno-economic aspects of VPP for a case study of a university campus using a co-optimized model are introduced in [108] with different DERs, DR, and energy storage devices without studying the implications on the utility. The MILP optimization for techno-economic optimal dispatch VPP model is proposed in [109] for the integration of large and small scale DERs with the objective of energy cost minimization, however, the DR and energy storage are not the focus of this study. The study [110] introduces a multi-objective VPP model for maximizing day-ahead profits and minimize carbon emissions using the two-stage stochastic model without the inclusion of DR. The techno-economic assessment of VPP with DR for day-ahead scheduling is given in [70] using modified differential evolution algorithm, however, impact on utility is not studied in this research. The combined electrical and economical behavior of VPP is analyzed in [111] considering real-time case study without accounting for DR and utility technical constraints.

2.8 Research Gap

After reviewing numerous researches regarding VPP, the following research gaps are identified:

1. The case study of a real-time utility distribution network is not considered in the present literature, which limits the VPP applicability in the real-time scenario.

2. The technical and economical constraints of utility are not considered sufficiently while implementation VPP. The proposed models mostly emphasize the financial aspect of the VPP.
3. The reliability of the distribution network with VPP during grid outage is also not studied in reported studies.
4. The application of VPP in peak shaving during utility peak load is still undiscovered.
5. The autonomous operation of VPP is not introduced in any reported study.

CHAPTER 3

EVALUATION OF EXISTING NETWORK & PILOT STUDY

3.1 Introduction

For the shifting of the power sector from the monopoly system of energy distribution to a competitive energy market, the DER has now become the main spotlight for energy policymakers. The small-scale DERs installation on consumer's premises make their participation possible in the energy market and influence the market prices. The consumers are no more limited to consuming electricity, but now they can also inject their surplus DER generation into the utility network and change their consumption pattern for monetary benefits. The government also takes rigorous steps for the facilitation of the large-scale penetration of renewable-based generators like solar PV through capital incentives and subsidies. In a country like India, the rooftop solar PV is very popular as most of its areas are receiving abundant solar radiation throughout the year. The small capacity rooftop PV panels are commonly installed on residential and commercial buildings throughout the country. The integration of DER in the distribution network provides various benefits such as peak load reduction, reduced network losses, improved voltage profile, and reduced grid dependency. On the contrary, with the dependency on the weather condition, the DER generation is intermittent in nature and creates various issues for the distribution network operator to maintain systems reliability and quality [29]. The high penetration of DER adversely affects the distribution grid by voltage fluctuations, reverse power flow, and reduction of utility revenue. These issues with the intermittent generation can be rectified by utilizing the concept of VPP which includes coordination of DER generations and consumers load profiles so that it acts as a single profile, which makes it easier to control its electrical dispatch [78], [112]. To implement the VPP concept, the smart grid technologies such as smart meter is installed at consumer premises, which provides the bidirectional communication between utility and consumers for sharing real-time data during electrical dispatch. The DR programs also introduce for effective implementation of the VPP under, which the consumer is charged at a lower tariff for a particular time of a day than the remaining period, which helps the load to follow intermittent DER generation [113]. The small-scale DERs and consumer loads located at the same or different geographical locations are aggregated to form a single operate-able profile, which schedules for cost minimization.

To study the detailed implication of VPP on power utility and its consumers, the PSPCL is selected for this case study. The PSPCL is a state government acquired utility and follows the regulation of the Punjab Energy Development Agency (PEDA) for installing and operating DER such as rooftop solar PV. The number of application for grid-integrated rooftop PV installation are escalating than ever and this high penetration of PV will negatively affect the grid in upcoming years if the operation of this DER is not controlled properly. The VPP can be a potential solution for this challenge by aggregating this small scale DER and creating a single generating profile. Another major issue utility faced is the peak load in the paddy season due to a sudden increase in agriculture load in July, when the peak demand is significantly higher than the average load. This forced the utility to buy power from private generating plants at a higher unit rate and fixed charges through long term contracts. Again the VPP can aggregate the loads into a single profile and provide flexibility by load shifting and load curtailments. This can reduce peak demand and which further deferred the utility investment in network augmentation.

3.2 Data Collection

Both commercial and technical data are collected to access the present scenario of the distribution network. The present grid integration of DER is studied to access its impact on the grid with an in-depth analysis of generation and demand data. The following data is collected from the utility database and the remaining data is collected from the field.

3.2.1 Resource Data Assessment

The resource data is shown in Fig.3.1 illustrates the average solar radiation received in the specific region where DERs are installed in the distribution network. The solar radiations are maximum in September, however, the clearness index is also the deciding factor for the generation of power from the solar panels. With the high temperatures in these months, the increase in the resistance of the solar cells reduces the overall output of the solar panels.

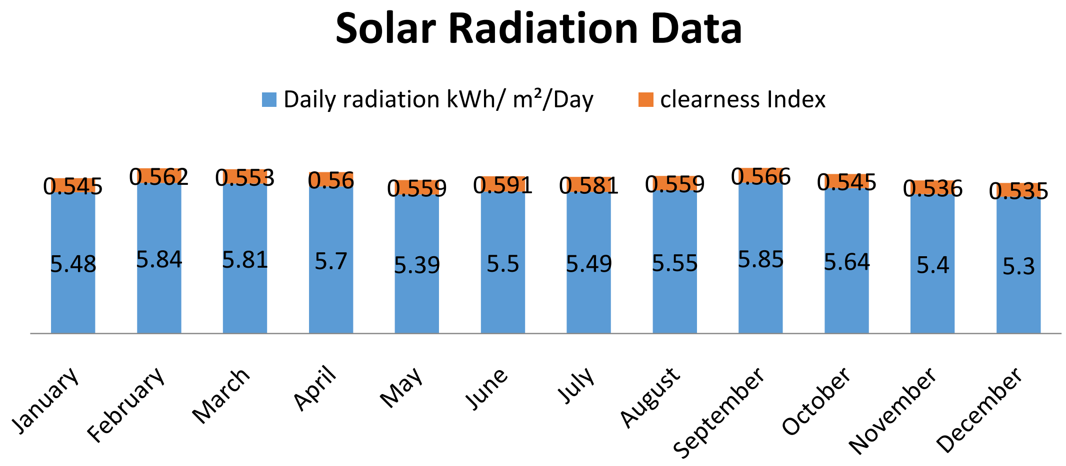


Figure.3.1 Average solar radiation

3.2.2 Load Data Assessment

The various load profiles have been studied to determine the scheduling of DER and other VPP components. The feeders based on two major load profiles as Industrial and residential are analyzed for VPP optimum dispatch. The data of these feeders have been obtained from 66 kV/11 kV step-down substation controlled through the SCADA system. The different characterizations of the feeders are tabulated in Table 3.1 below

Table 3.1 Load characteristic data

Load type	Industrial Feeder	Residential Feeder	Aggregated
Average demand	1033 kW	930 kW	1963 kW
Maximum demand	4288 kW	2050 kW	5105 kW
Annual energy demand	9718850 kWh	8338764 kWh	18057614 kWh

The further evaluation of feeder's demand is done by studying daily profiles like weekday, weekend, and peak-day load profiles. The various load profiles have been illustrated in the figures below. During the weekday, the demand ramps to the peak value and stays there for a particular duration. The demand also declined to a very low value in the night as most of the industries are shut down. The weekday profile of the industrial feeder is illustrated in Fig.3.2.

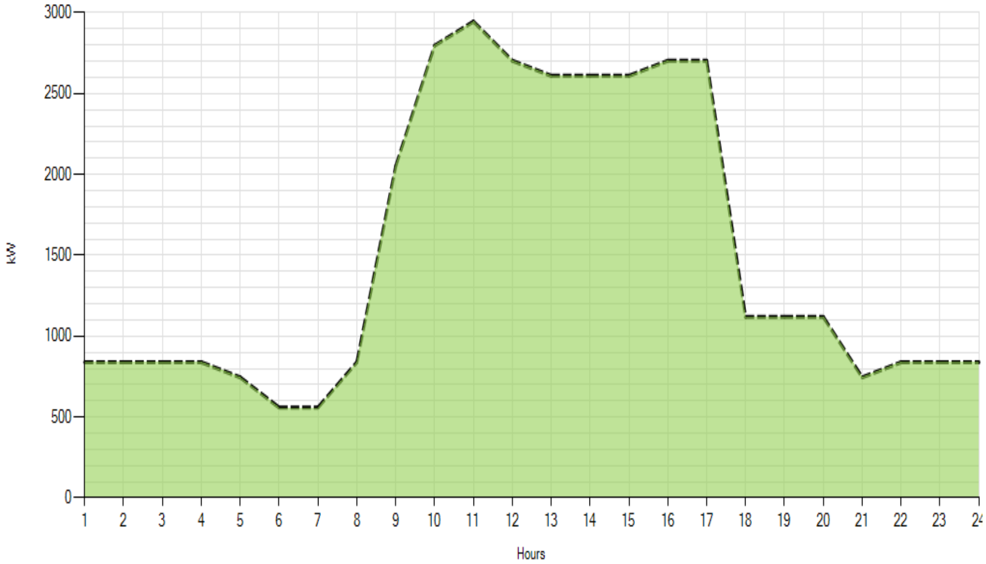


Figure.3.2 Industrial feeder week profile

On the contrary, during the weekend, the demand dips to a very low value as the demand is only of the standby or emergency unit of the industries. The load on the industrial feeder is declined by 70 to 75% of the weekday load. The load profile of the industrial feeder is shown in Fig.3.3

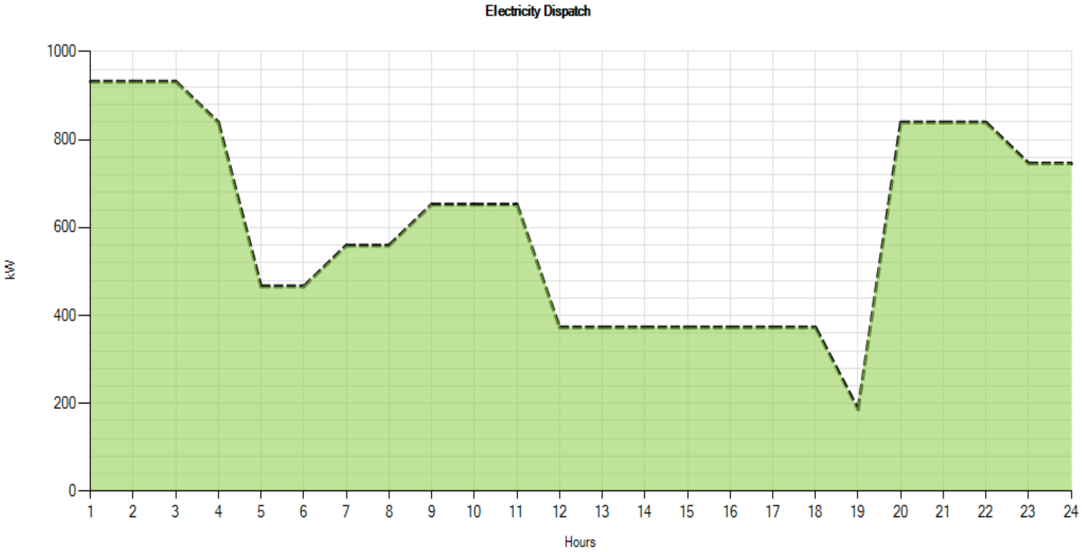


Figure.3.3 Industrial feeder weekend profile

The peak day demand on the industrial feeder is shown below in Fig.3.4.The peak load usually occurs from 11 to 12 hrs.

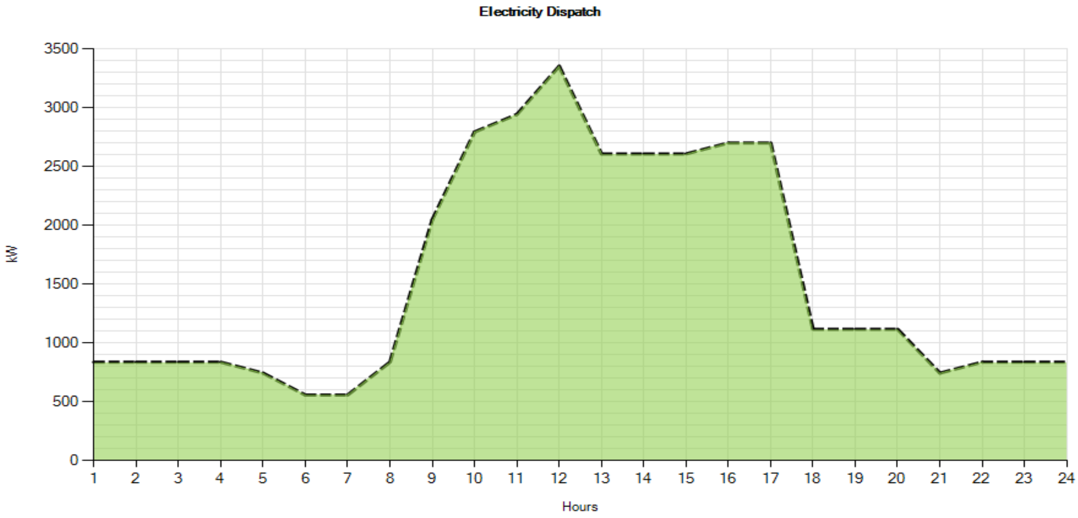


Figure.3.4 Industrial feeder peak load profile

The residential feeder has significant uniqueness in the demand profile as the demand on the feeder is change more often with the variation in the seasons and time duration of the day. The load on the demand is remaining higher during morning and evening time. The switching time of residential loads such as light and fan load varies from one region to another. The weekday profile of the residential feeder is illustrated in Fig.3.5 below.

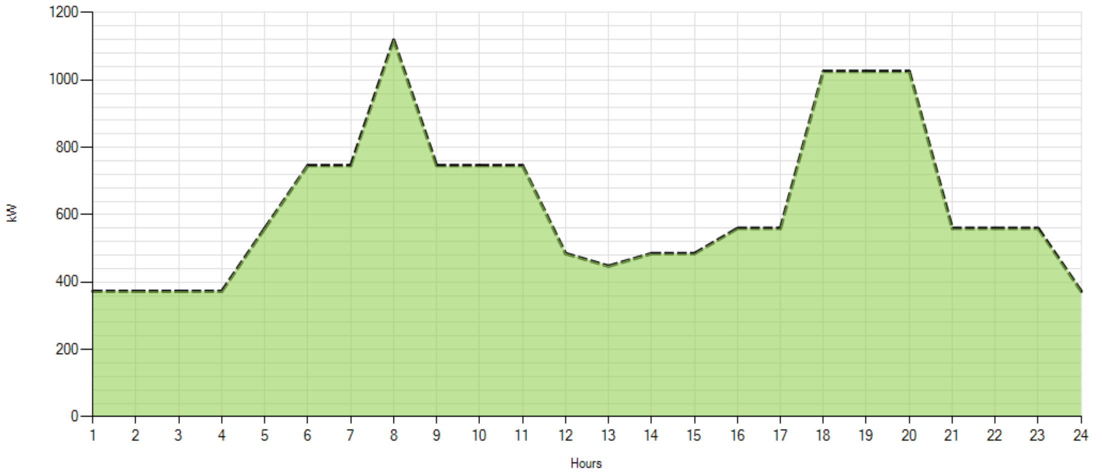


Figure.3.5 Residential feeder weekday profile

In comparison to the industrial feeder, the demand for the residential feeder is slightly declined during the weekend, so the demand pattern for the feeder remains almost similar during the whole week. The weekend load profile of the residential feeder is shown in Fig.3.6 below.

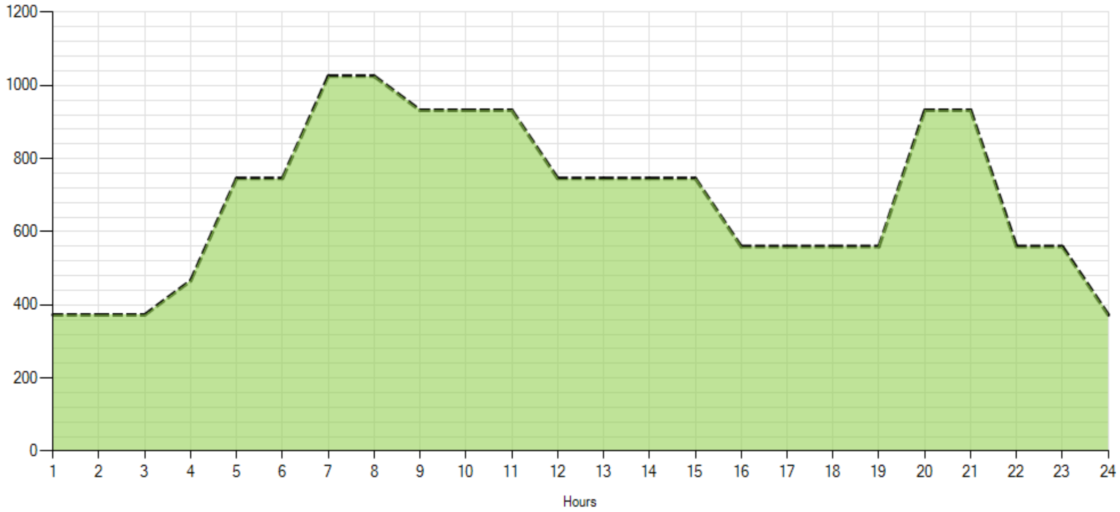


Figure.3.6 Residential feeder weekend profile

The peak demand on the residential feeder usually occurs during the summer season with the inclusion of an inductive load of air conditioners and fans. The peak load profile is visualized below in Fig.3.7.

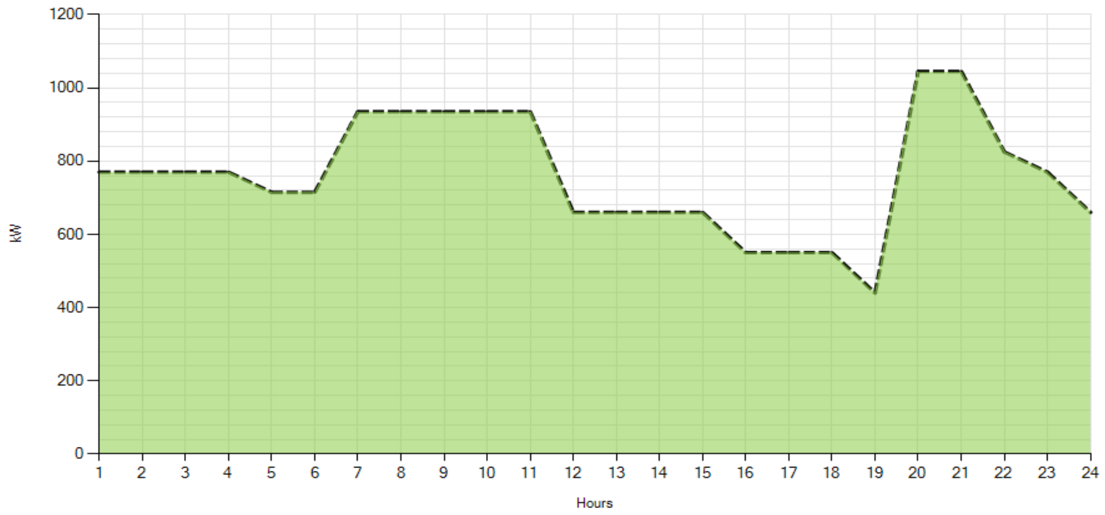


Figure.3.7 Residential feeder Peak profile

3.2.3 DER and Utility Tariff Data

The capital cost of DG installation includes the cost of PV, batteries, and static switch, which varies from region to region. In this case study, the market available typical solar PV panel is selected without any subsidy. The cost of PV is expected to reduce further with technological advancement. The technical and economic parameters include efficiency, lifetime, and cost for VPP modeling is shown in Table.3.2 below:

Table 3.2 Technical parameters of VPP

PV cost($/kW)	$1200
PV lifetime	25 Years
PV inverter cost 100kW	$500
PV maximum efficiency	14.9%

Table 3.2 Technical parameters of VPP (Continued)

Battery cost($/kW)	218
Battery lifetime	5 years
Efficiency charge (%)	90%
Efficiency discharge (%)	90%
Max charge rate(%/hour)	30%
Max discharge rate(%/hour)	30%
Static switch cost($/kW)	$75
Static switch lifetime	10 years

The Time of Day (TOD) tariff used for this study is taken from PSPCL energy tariff 2018-19 [114]. The main purpose of this tariff is to reduce the load in peak hours by encouraging consumers to shift their load from on-peak to off-peak hours and these ultimately deferred the utility investment in the generation capacity. The main features of this tariff are shown in Table 3.3 below:

Table 3.3 PSPCL ToD tariff

Period	Time	Cost/kW (1$=74 INR)
1-4-18 to 31-5-18	06:00 AM To 06:00 PM	$0.0907
	06:00PM To 10:00 PM	
	10:00 PM To 06:00 AM	$0.0713
1-6-18 To 30-9-18	06:00 AM To 06:00 PM	$0.0907
	06:00PM To 10:00 PM	$0.1220
	10:00 PM To 06:00 AM	$0.0907
1-10-18 To 31-3-19	06:00 AM To 06:00 PM	$0.0907
	06:00PM To 10:00 PM	
	10:00 PM To 06:00 AM	$0.0713

3.2.4 Generation Data Assessment

The influence of solar PV on the demand profiles is evaluated by analyzing various consumers' data, which installed DERs on their rooftop. The detailed analysis of the solar profiles is tabulated in Table 3.4. Both generation and load profiles of domestic, commercial, and industrial are studied for a particular time duration. The daily average generation of solar panels per kW is found to be 2.96 kWh. The maximum capacity of solar capacity is capped at 80% of the connected load.

Table 3.4 Typical solar generation

Account and category	**Sanction load (SL) and Solar Capacity (SC)**	**Solar generation (kWh)**	**Energy export kWh**	**Average generation/day (kWh)**	**Average generation /day/kWh/kW**	**Duration of measurement**
Domestic 1	SL: 9.09 kW SC: 5 kW	210	158	15	3	12-9-18 to 26-9-18
Domestic 2	SL: 4.6 kW SC: 3.2 kW	552	230	8	2.61	11-8-18 to 18-10-18
Domestic 3	SL: 10 kW SC: 8 kW	700	693	12	1.5	15-6-18 to 18-8-18
Industry 1	SL: 498 kW SC: 100 kW	14440	4026	451	4.51	5-4-18 to 7-5-18
Commercial 1	SL: 350 kW SC: 600 kW	38400	1300	1037	2.96	27-3-18 to 3-5-18

3.3 Potential Effects of High Penetration of DER on Utility

3.3.1 Reverse Power flow

The demand following with the renewable energy resources is not an easy task, the high penetration results in reverse power flow, especially in industrial feeders during weekends. Fig.3.8 reveals the reverse power flow in the industrial feeder on weekends:

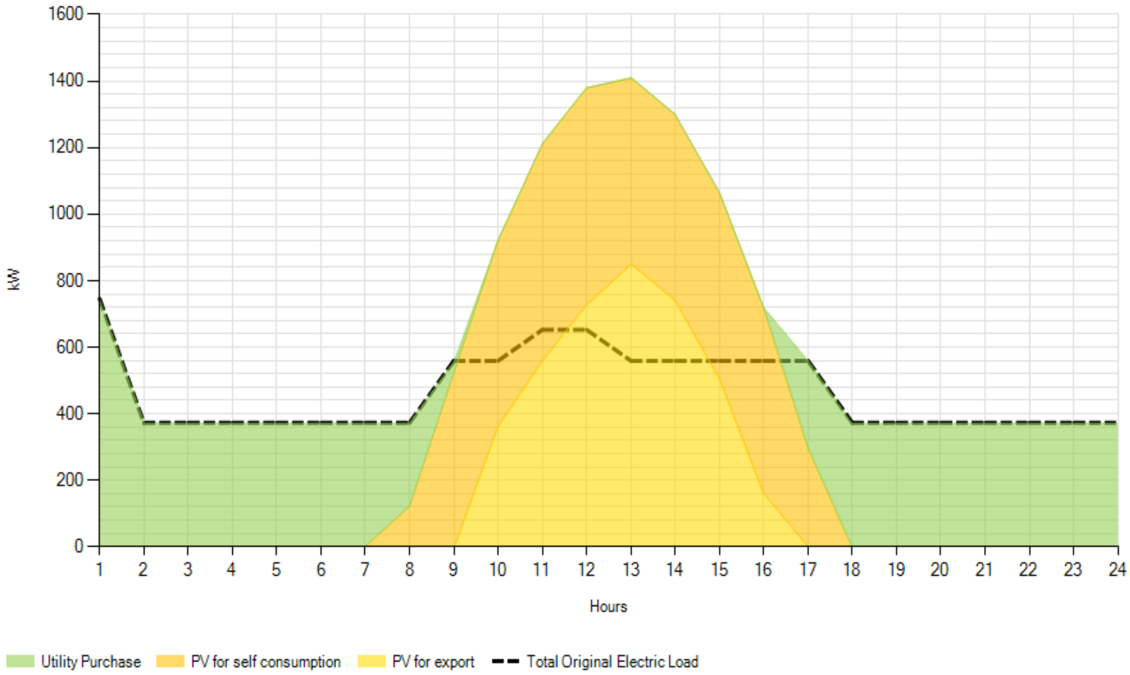


Figure 3.8 Reverse power flow in industrial feeder during the weekend

The reverse power flow in the feeder is due to the sudden switch off the industrial load during the weekend with the closure of industries. This reverse power results in un-utilized energy from solar generation, voltage fluctuations, and potential adverse effects on the protection system.

3.3.2 Effect on Utility Revenue

Without effective utilization of solar generation, the utility peak load still escalates, so to reduce the peak load, the demand response and aggregation of consumer profiles are needed. An in-depth analysis of solar energy on the utility is evaluated in Table 3.5. The consumption with solar has been reduced, however in some cases, the growth in demand also increases consumption, so the consumption with solar is not only the basic indicator of solar effectiveness. The reduction in utility imports is the deciding factor to determine whether it is beneficial of integrating DER in the utility network for consumers and utility itself.

Table 3.5 Impact of solar generation

Profile	Domestic 1	Domestic2	Domestic 3	Industry 1	Commercial 1
Consumption without solar	1027 kWh	933 kWh	4014 kWh	31165 kVAh	124766 kVAh
Date & duration	26-8-17 To 31-9-17 = 36 days	19-8-16 To 26-10-16= 68 days	10-5-17 To 13-7-18 = 64 days	3-6-15 To 28-6-15 = 25 days	31-05-17 To 25-6-17 = 25 days
Consumption with solar	5007 kWh	670 kWh	3814 kWh	37311 kVAh	156120 kVAh
Date & duration	12-9-18 To 18-10-18 = 36 days	11-8-18 To 18-10-18 = 68 days	15-6-18 to 18-8-18 = 64 days	9-06-2018 To 4-7-18 = 25 days	09-6-18 To 04-07-18 = 25 days
NET utility import	4594 kWh	337 kWh	3119 kWh	28355 kVAh	129120 kVAh
Utility export	953 kWh	219 kWh	693 kWh	444 kVAh	40 kVAh
Solar self-consumption	1366 kWh	333 kWh	7 kWh	8956 kVAh	26960 kVAh
Solar generation	2319 kWh	552 kWh	700 kWh	9400 kVAh	27000 kVAh
Consumption % ↑or↓	↑ 487%	↓ 28.18%	↓4.98%	↑ 19.7%	↑ 25.1%
NET Utility demand. % ↑or↓	↑447.3%	↓ 63.87%	↓22.29%	↓ 9.01 %	↑ 3.48 %
Red in utility import %	8.90%	49.70%	18.20%	24.00%	17.20%

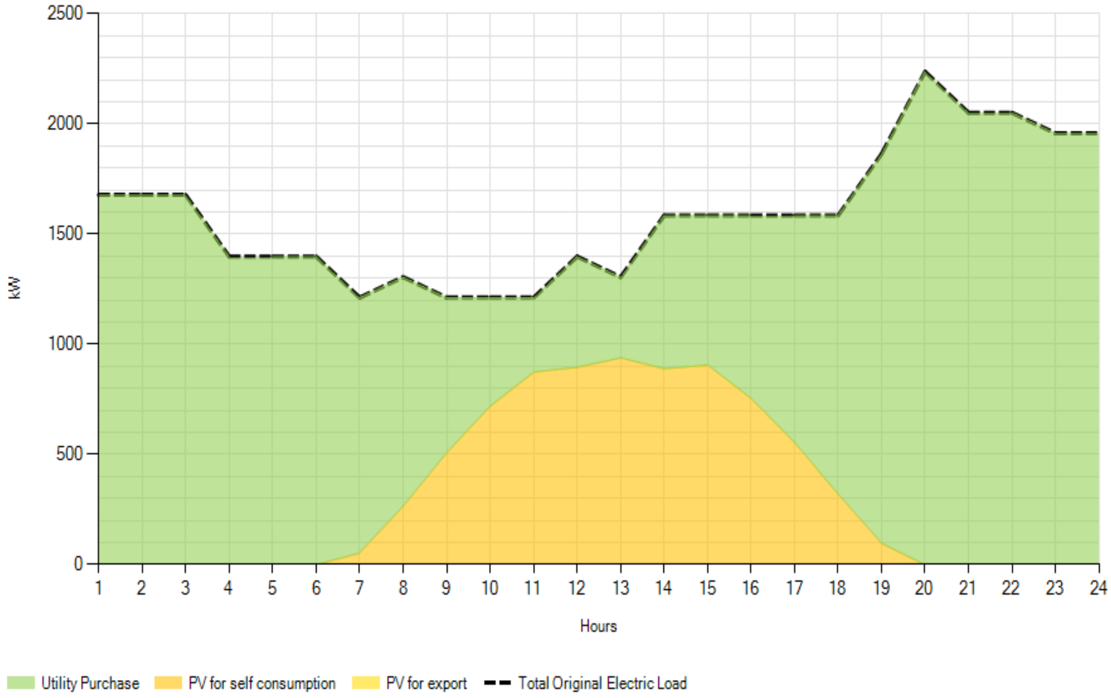


Figure.3.9 Peak demand with high integration of DERs

The above Fig.3.9 illustrates that peak load remains the same even with the integration of DER, which ultimately gives no benefits to the utility and even consumer as there is no reduction in demand charges. The electrical storage and DR is necessary to effectively penetrate the DERs.

3.3.3 Grid Integrated DERs During an Outage

During fault on the distribution network, the generation of DERs is of no use, as they forcibly shut down for the prevention of islanding. The un-utilized energy of solar generation could be used for storage and self-consumption within the healthy network or the isolated region within the VPP framework using battery storage and isolators.

3.4 Pilot Study of DER High Penetration With VPP Model

The area is selected with high demand consumers having unique demand patterns and supply priorities. The supply fed to the consumers is taken from the same feeder and which makes generation exchange possible between the consumers.

3.4.1 Mathematical Formulation

This section gives brief details of the Mixed Integer Linear Programming (MILP) based Distributed Energy Resource Customer Adoption Model (DER-CAM) tool and its techno-economic parameters. The main objective function is to minimize the capital and operational cost of DER annually. Continuous and discrete generation technologies like solar PV and internal combustion respectively are used. The optimal investment solution calculates by utilizing the complete set of tariff and economic data. The mathematical formulation of DER-CAM describes below.

Input Variables

c continuous generation technologies: solar photovoltaic panels (PV)

i all technologies generation or storage (j - k)

j all generation technologies (c only)

k storage technologies: battery storage (ES),

p tariff period (on-peak, mid-peak, off-peak)

s season (winter, summer including paddy season)

u end-use load: electricity only (eo)

m, d, h month (1, 2,3 ..., 12), day type (1, 2, 3), hour (1, 2,3 ..., 24) $load_{m,d,h.u}$ consumer load at time m, d, h for end-use u [kW]

Tariff Data

$TP_{s,p}$ Maximum demand charges under the PSPCL tariff for season s and period p [\$/kW]

$TE_{md,h}$ Energy tariff for electricity consumption charges at time m, d, h [\$/kWh]

TF_m Tariff for fixed charges for using utility infrastructure in month m [\$]

$TEx_{m.d.h}$ Energy tariff for electricity export at time m, d, h [\$/kWh]

Generation and Storage Technology Data

$MaxP_g$ rated capacity of generation technology g : PV [kW]

$MinL_g$ minimum acceptable load for generation technology g: PV [kW]

Lt_i expected lifetime of technology i [years]

$CCDP_g$ turnkey capital cost of generation technology g [\$/kW]

$FCC_{(c,k)}$ fixed capital cost of generation technology c or storage technology k [\$]

$VCC_{(c,k)}$ variable capital cost of generation technology c or storage technology k: battery storage [\$/kW]

$VCSC_{(c,k)}$ variable capital cost of battery storage technology k [\$/kWh]

$\boldsymbol{OMF_i}$ fixed annual operation and maintenance costs of technology i [\$/kW]

Decision Variables

- $InvGen_i$ number of units of technology i installed by the customer
- $GenL_{i,m,t,h,u}$ generated power by technology i during hour h, type of day t, month m, and for end-use u to supply the customer's load (kW);
- $DRLoad_{m,t,h,u}$ electricity imported from PSPCL by the consumer during hour h, type of day t, and month m for end-use u (kW).
- OMV_i variable operation and maintenance costs of technology i [\$/kWh]
- $MaxH_j$ maximum number of hours technology j can operate during the year [hour]
- $VC_{j,m}$ generation cost of technology j during month m [\$/kWh]
- $S_{(j)}$ set of end-uses that can be met by technology j [electrical only]
- SCE_k charging efficiency of battery technology k [%]
- SDE_k discharging efficiency of battery technology k [%]
- φ_k losses due to decay/self-discharge in battery technology k [%]
- MCE_k minimum state of charge of battery technology k [%]
- SPE_c theoretical peak solar conversion efficiency of generation technology c [%]

- $\mathrm{SRE}_{\mathrm{c.m.h}}$ solar-radiation conversion efficiency of generation technology c, in month m, and hour h [%]
- $ECap$ energy capacity of storage tech. k [kWh]
- SOC k,m,d,h state of charge of storage technology k at time m, d, h [kWh]
- SIn k,m,d,h energy input to storage technology k, at time m, d, h [kW]
- $SOut$ k,m,d,h,u energy output from storage technology k, at time m, d, h for end use u [kW]
- sb k,m,d,h binary charge/discharge decision of storage technology k at time m, d, h [b]
- psb m,d,h binary decision of purchasing or selling electricity at time m, d, h [b]

Financial Parameters

- IR interest rate on DER investments [%]
- An_i annuity factor for investments in technologies i
- $SI_{m,d,h}$ solar insolation at time m, d, h [kW/m²]
- SA available area for solar technologies [m²]
- BAU total base case energy costs without integrated DER investment disabled [$]
- PBP maximum payback period allowed on the integrated DER investment decision [years]

Economic Objective Function

$$min\ c\ = \Sigma_{m} TF_{m} + \Sigma_{m} \Sigma_{d} \Sigma_{h} \Sigma_{u} UL_{m,d,h,u} \cdot TE_{m,d,h} + \Sigma_{m} \Sigma_{\mathrm{m} \in s} \Sigma_{p} TP_{s,p} \cdot max(\Sigma_{u \in eo}\ UL_{m,(d,h) \in p,u})$$

$$+ \Sigma_{j} \Sigma_{m} \Sigma_{d} \Sigma_{h} (GS_{j,m,d,h} + \Sigma_{u} GU_{j,m,d,h,u}) \cdot (VC_{j,m} + OMV_{j}) + \Sigma_{g} IG_{g} \cdot MaxP_{g} \cdot (CCD_{g} \cdot An_{g} + OMF_{g}) + \Sigma_{i \in c,k} ((FCC_{i} \cdot Pur_{i} + VCC_{i} \cdot Cap_{i} + VCSC_{k} \cdot ECap_{k}) \cdot An_{i} + Cap_{i} \cdot OMF_{i}) - \Sigma_{j} \Sigma_{m} \Sigma_{d} \Sigma_{h} GS_{j,m,d,h} \cdot TEx_{m,d,h} \quad (1)$$

Network constraints

$$Load_{m,d,h,u} + (SI_{nk,m,d,h})/SCE_{k} = SOut_{k,m,d,h,u} \cdot SDE_{k} + \Sigma_{j} GU_{j,m,d,h,u} + UL_{m,dh,u,} \forall\ m,d,h{:}\ k = \{ES\} \wedge u = \{eo\}\ [\mathrm{kW}] \quad (2)$$

$$RG_{g,m,d,h} \cdot MinL_{g} \leq \Sigma_{u} GU_{g,m,d,h,u} + (GS_{j,m,d,h} \leq RG_{g,m,d,h} \cdot MaxP_{g} \quad (3)$$

$\forall\, g, m, d, h$ [kW]

$$\Sigma_{m} \Sigma_{d} \Sigma_{h} \left(\Sigma_{u} GU_{j,m,d,h,u} + GS_{j,m,d,h}\right) \leq IG_{g} \cdot MaxP_{g} \cdot MaxH_{g} \quad \forall\, g, m, d, h \text{ [kW]} \tag{4}$$

$$Cap_{i} \leq Pur_{i} \cdot M \;\forall\, i \in \{c, k\} \text{ [kW]} \tag{5}$$

$$\Sigma_{u} GU_{j,m,d,h,u} + GS_{j,m,d,h} \leq Cap_{c} \cdot SRE_{c,m,h} / SPE_{C} \cdot SI_{m,d,h} \;\forall m, d, h : c \in \{PV\} \text{ [kW]} \tag{6}$$

$$\frac{\Sigma\, Capc}{cSPE_{c}} \leq SA : c \in \{PV\} \;[m^{2}] \tag{7}$$

$$SOC_{k,m,d,h} = SInk_{k,m,d,h} - \Sigma_{u} SOut_{k,m,d,h,u} + SOC_{k,m,d,h} - 1 \cdot (1 - \varphi_{k}) \forall k, m, d, h \neq 1 \text{ [kWh]} \tag{8}$$

$$SOC_{k,m,d,1} = SOC_{k,m,d,24} \forall\, k, m, d \text{ [kWh]} \tag{9}$$

$$SOC_{k,m,d,h} \geq ECap_{k} \cdot MSC_{k} \;\forall\, k, m, d, h \text{ [kWh]} \tag{10}$$

$$SOC_{k,m,d,h} \leq ECap_{k} \;\forall\, k, m, d, h \text{ [kWh]} \tag{11}$$

$$SInk_{k,m,d,h} \leq Cap_{k} \;\forall\, k, m, d, h \text{ [kW]} \tag{12}$$

$$\Sigma_{u} SOC_{k,m,d,h} \leq Cap_{k} \;\forall\, k, m, d, h \text{ [kW]} \tag{13}$$

$$SIn_{k,m,d,h} \leq sb_{k,m,d,h} \cdot M \;\forall\, k, m, d, h \text{ [kW]} \tag{14}$$

$$\Sigma_{u} SOC_{k,m,d,h,u} \leq (1 - sb_{k,m,d,h}) \cdot M \;\forall\, k, m, d, h \text{ [kW]} \tag{15}$$

$$\Sigma_{u} UL_{m,dh,u,} \leq psb_{m,d,h} \cdot M \;\forall\, m, d, h : u = \{eo\} \text{ [kW]} \tag{16}$$

$$GS_{j,m,d,h} \leq (1 - psb_{m,d,h}) \cdot M \;\forall\, j, m, d, h \text{ [kW]} \tag{17}$$

$$An_{i} = \frac{IR}{1 - \frac{1}{(1+IR)^{Lt_{i}}}} \forall\, i \;[1,2,3\ldots] \tag{18}$$

$$C \leq BAU + \Sigma g IG_{g} \cdot MaxP_{g} \cdot CCDP_{g} \cdot An_{g} + \Sigma_{i \in c,k}(FCC_{i} \cdot Pur_{i} + VCC_{i} \cdot Cap_{i} + VCSC_{k} \cdot ECap_{k}) \cdot An_{i} - \frac{\Sigma g IG_{g} \cdot MaxP_{g} \cdot CCP_{g} + \Sigma_{i \in c,k}(FCC_{i} \cdot Pur_{i} + VCC_{i} \cdot Cap_{i} + VCSC_{k} \cdot ECap_{k}}{PBP} \;[\$] \tag{19}$$

The above Eq.(1) shows the objective function and includes all the economic components like DER capital cost, storage cost, operation cost, and utility charges, etc. The network constraints for this objective function are as follows:

- Eq.(2) forced a balanced constraint between load and generation.
- Eq.(3) forced generation and energy export constraint.
- Eq.(4) forced constraint of maximum DER generation.

- Eq.(5) forced constraint of generation and consumer energy purchased, where M = arbitrarily large number.
- Eq.(6) forced solar PV generation constraint.
- Eq.(7) forced solar PV area constraint.
- Eq.(8-15) forced battery capacity and investment constraints.
- Eq.(16) forced energy purchased or selling constraint.
- Eq.(17) forced energy export constraint.
- Eq.(18) annuity rate calculation factors.
- Eq.(19) forced payback constraint

3.4.2 Load Assessment of Study Area

The load is fed up from the SCADA integrated 66/11kV substation that is located within the boundary of the division. The 11kV distribution feeders leaving the substation are moving along the residential, commercial, and industrial areas of the city. In this case study, the DER installed residential and commercial buildings are selected for load assessment. The load specification data of these buildings collected from the respected distribution subdivision is shown in Table 3.6.

Table 3.6 Load specification

Load type	**Grocery store**	**Residential Apartment**	**Secondary school**	**Hospital**	**Aggregated**
Average demand	117 kW	109 kW	102 kW	60 kW	388 kW
Peak demand	191 kW	254 kW	233 kW	96 kW	635 kW
Annual energy demand	1010264 kWh	923512 kWh	987752 kWh	546726 kWh	3468255 kWh
Peak month	June	July	July	July	July

From the above table, it is concluded that there is a significant difference between average demand and peak demand. The average daily load profile of aggregated load is shown in Fig.3.10

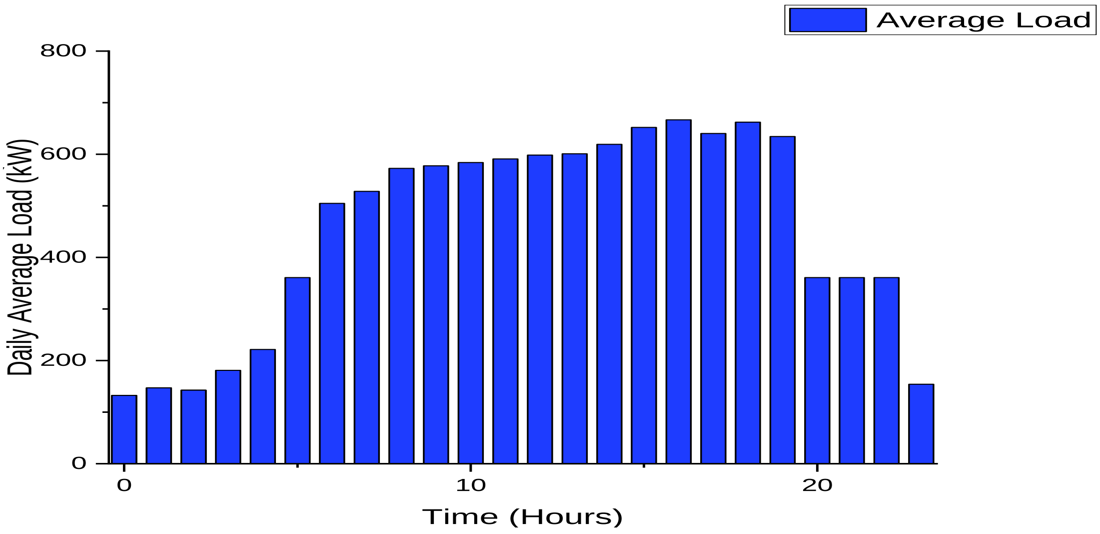


Figure.3.10 Typical average daily load profile

With the introduction of the TOD tariff, the variable cost of energy encourages the consumer to shift their consumption from peak hours to off-peak hours or during PV generation time. Depending upon the load profile, the flexible load is shifted to save on energy bills. The schedulable load which can be scheduled during peak, week and weekend days are shown in Table 3.7. It is to be noted that a load of the hospital is critical, so there is no possibility of shifting that load at any time of the day. The maximum possibility of load shifting is found in residential apartments.

Table 3.7 Load shifting data

Load	%Schedulable Peak	%Schedulable week	%Schedulable weekend	Maximum load in an hour (kW)
Grocery store	12	15	10	50
Residential Apartment	32	28	15	85
Secondary school	15	15	15	30
Hospital	0	0	0	0

3.4.4 Load Curtailment Parameter

In the period of fault on the feeder or grid failure, the reliability of VPP is a matter of concern. The VPP has the potential to continue supplying the portion of a load directly from batteries and the remaining portion is curtailed depending upon the priority level. The maximum load curtailed, maximum curtailment time, and cost is shown in Table 3.8. below:

Table 3.8 Priority level and maximum curtailment of load

Load	Priority level	Variable cost ($/kWh)	Maximum curtailment of load (%)	Maximum curtailment time (hours)
Grocery store	Low priority	15	15	8
Grocery store	Medium priority	21	18	5
Grocery store	High priority	43	10	2
Residential Apartment	Low priority	0.5	35	12

Table 3.8 Priority level and maximum curtailment of load (Continued)

Residential Apartment	Medium priority	2	40	8
Residential Apartment	High priority	8	25	4
Secondary school	Low priority	2	20	3
Secondary school	Medium priority	7	27	2
Secondary school	High priority	10	18	1
Hospital	Low priority	Emergency service	0	0
Hospital	Medium priority	Emergency service	0	0
Hospital	High priority	Emergency service	0	0

3.4.5 Financial Parameters

The financial inputs for decision making in the VPP model are shown in Table 3.9. To compute the savings from VPP, the base case cost is calculated, which is the cost incurred without implementing the VPP concept or any DER investment.

Table 3.9 Financial parameters of VPP

Discount Rate	3 %
Maximum Payback Period	10 Years
Base Case Cost	\$329000

3.4.6 Results and Discussion

After feeding all the VPP inputs and constraints, the DER-CAM simulation is launched. The model obtained includes the interconnection of different loads with their designated DER. The aggregated load and DER into one profile is used to decide for investment. Fig.3.11 shows the detailed VPP model.

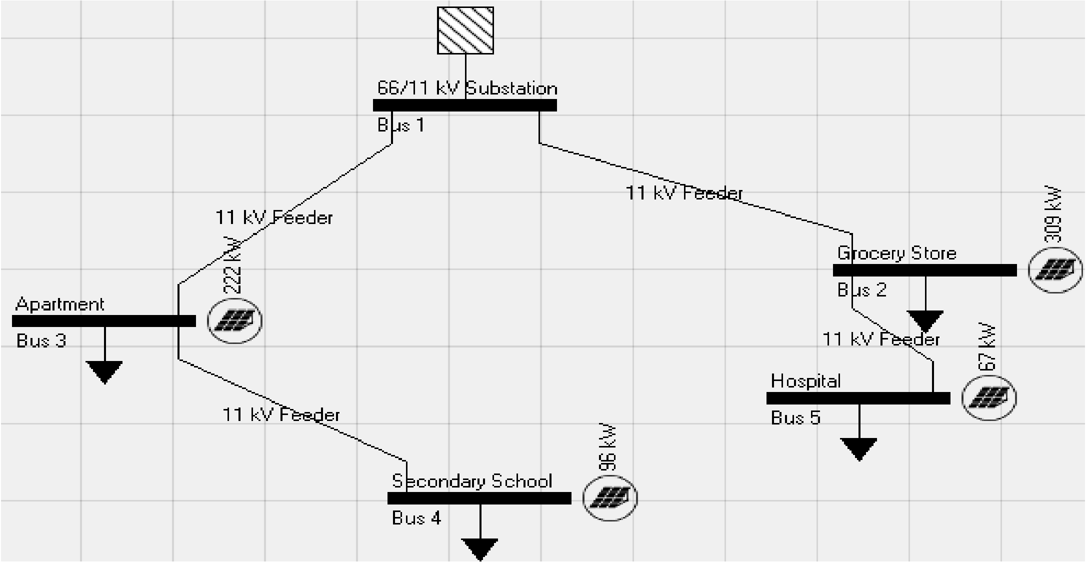


Figure.3.11 VPP aggregated model with LS

The VPP aggregate the generation and load profile of DERs located at a different position on the feeder into a single operating profile. The comparison between the three cases, the base case without DER investment, the base case with DER investment, and the base case with DER investment and Load Shifting (LS) is shown in Table 3.10. It is clearly observed from the result that considering load shifting, the investment of solar PV capacity of 693 kW is suggested. The maximum PV installation capacity of 309 kW is advised for the grocery store and a minimum capacity of 67kW is advised for the hospital. The DER investment with LS comes to be the most economical configuration which gives 31.45% saving on annualized energy cost and without LS it comes to be 28%. The operational cost is also significantly reduced by DER investment and helps in saving of 44% with LS and 41% without LS. From these results, it is noticed that apart from DER, the LS also has great potential to reduce electric cost and a peak load of the utility. In both cases of the DER investment, the capacity of solar PV for the aggregated profile is the same.

Table 3.10 VPP aggregated profile

Investment	**Aggregated Model**		
	Base case without DER investment	**Base case with DER investment**	**Base case with DER investment and LS**
PV capacity	-	693 kW	693 kW
Storage	-	-	-
Electricity sales from PV	-	12478 kWh	12478 kWh
Total annual energy costs (incl. annualized capital costs and electricity sales)	$329456	$237809	$225545
Annual savings	$329456	$133892	$146156
Optimized operational cost	$329456	$195108	$182844
Total electric costs	$327948	$207024	$195469
Total annual electricity purchase	3468255 kWh	2121169 kWh	2121169 kWh
Total annual on-site generation	-	1489651 kWh	1489651 kWh
Share of renewable in total electric load	-	43%	43%

The result shows that the load shifting could be an effective technique to reduce the utility peak load when the investment in DER is considered. The comparison of aggregated load dispatch with and without LS while considering DER investment is shown in Fig.3.12 and Fig.3.13.

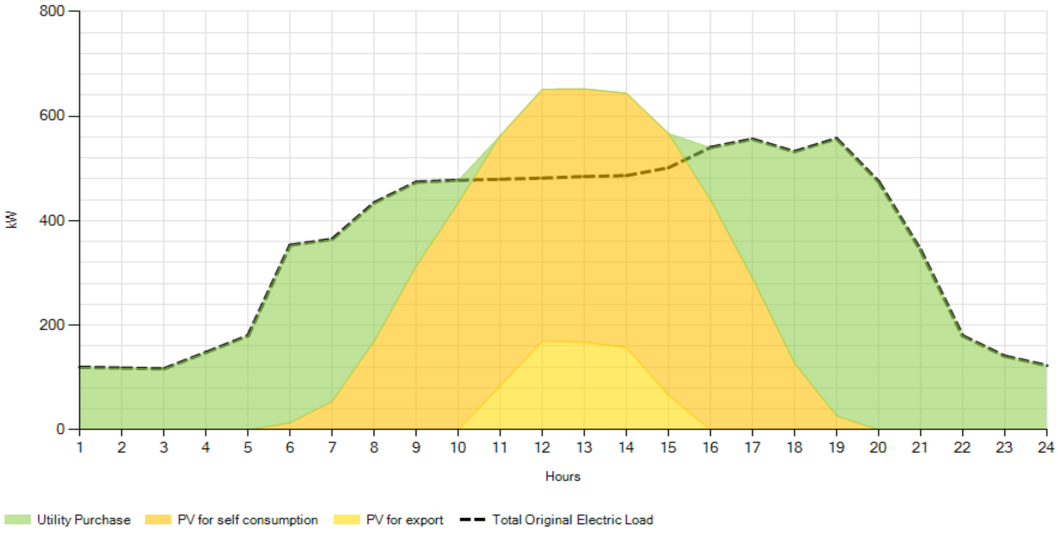


Figure.3.12 Aggregated electrical dispatch of the system with LS

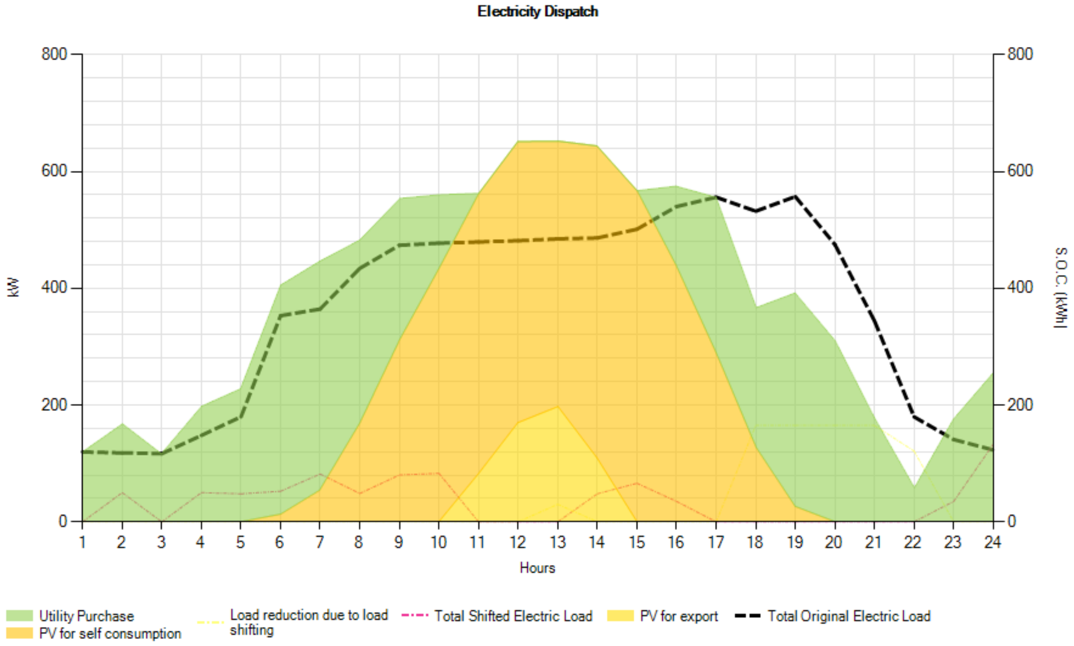


Figure.3.13 Aggregated electrical dispatch of the system without LS

To understand the VPP model in more detail, the bus wise analysis is done in Table 3.11. With LS more capacity of DER can be integrated into the grid while maintaining reliability.

Table 3.11 Bus wise profile

Investment	**Grocery store**			**Apartment**		
	Base case Without investment	**With DER investment**	**With DER investment and Load shifting**	**Base case Without investment**	**DER investment**	**With DER investment and load shifting**
PV capacity	-	216 kW	309 kW	-	139 kW	222 kW
Storage	-	-	-	-	-	-

	Secondary school			**Hospital**		
	Base case Without investment	**DER investment**	**With DER investment and DR**	**Base case Without investment**	**DER investment**	**With DER investment and DR**
PV capacity	-	70 kW	96 kW	-	268 kW	67 kW
Storage	-	-	-	-	-	-
On site DER generation	-	150370 kWh	206528 kWh	-	574918 kWh	142937 kWh

The electrical dispatch of a grocery store with a PV capacity of 309 kW is shown in Fig. 3.14. The major part of the grocery store's peak load is fed up by PV generation and only a small portion of demand is imported from the grid or other VPP agents. The excess generation of PV from 12:00 to 15:00 hrs is exported to the grid. It is clearly observed that with DER installation, the peak load and energy export is considerably reduced.

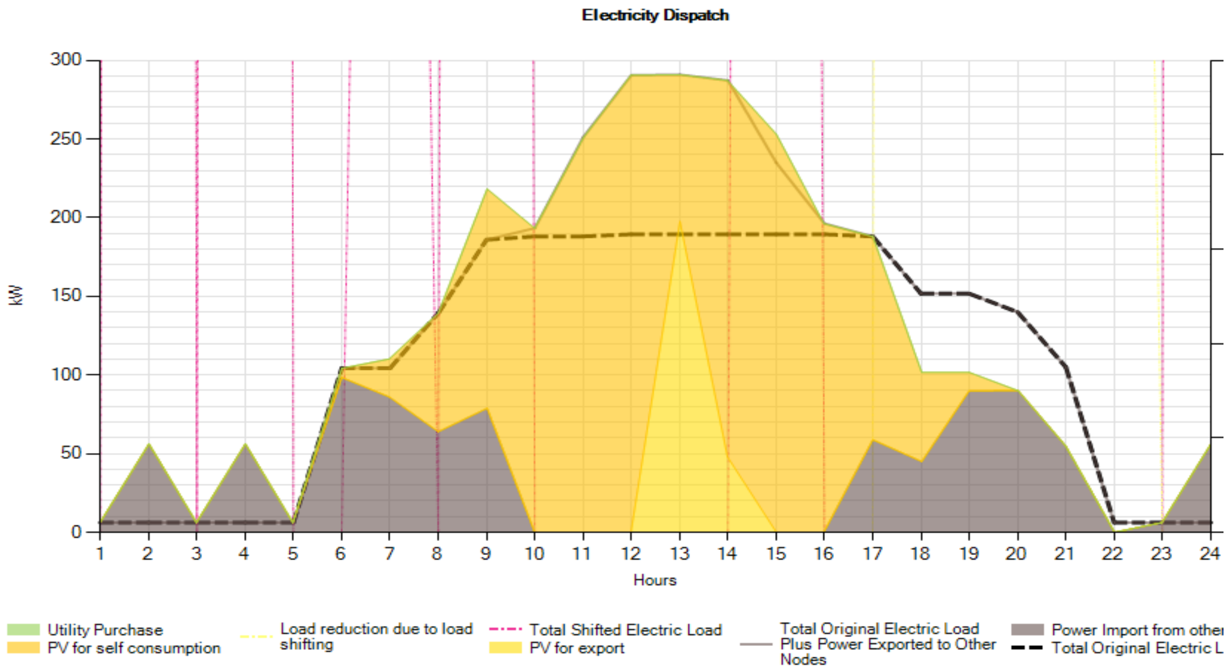


Figure.3.14 Grocery store electricity dispatch with LS

A load of the residential apartment is coincided with the utility peak load, in order to reduce the peak load and demand charges the load is shifted to an off-peak period or

PV self-consumption period. The detailed electrical dispatch is shown in Fig.3.15.

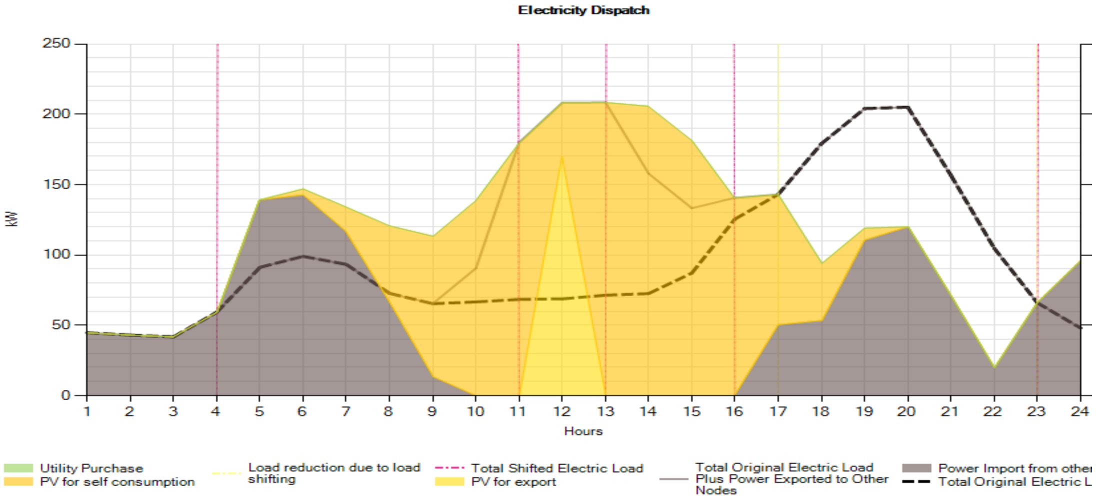


Figure.3.15 Residential apartment electricity dispatch with LS

The peak load of secondary school coincides with the PV generation period, which helps to reduce the peak load and the energy charges. The schedulable load is less in comparison with other loads that are discussed before, so the load shifting does not play a significant role in this electricity dispatch. The electricity dispatch of secondary school is shown in Fig.3.16.

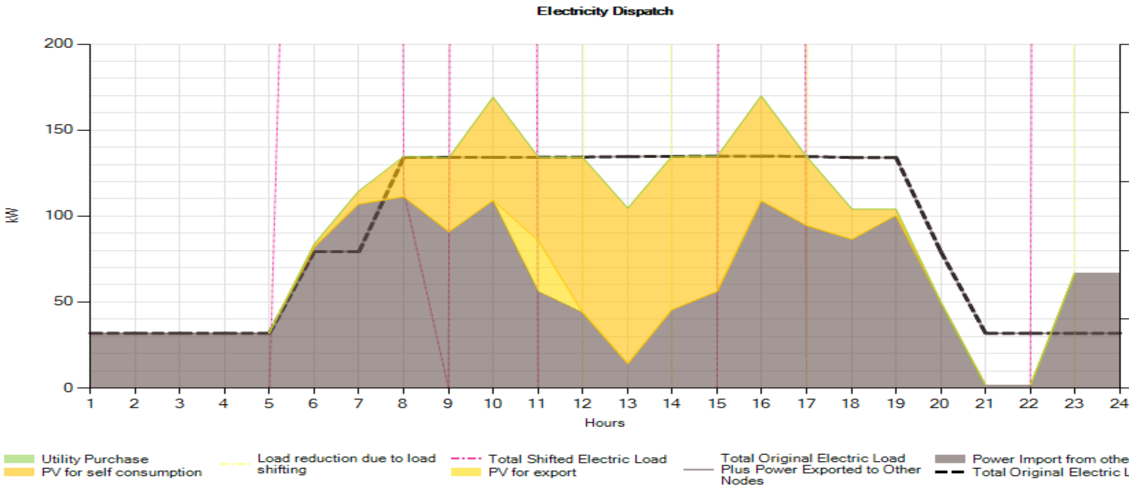


Figure.3.16 Secondary school electricity dispatch

Due to the 24 emergency service, the load of the hospital is critical and hence cannot be shifted or curtailed. The PV generation still shows a reduction in peak load and reduction of energy charges. The excess generation from PV is also exported to the grid for a small duration. The detailed electrical dispatch of the hospital without LS is shown in Fig.3.17

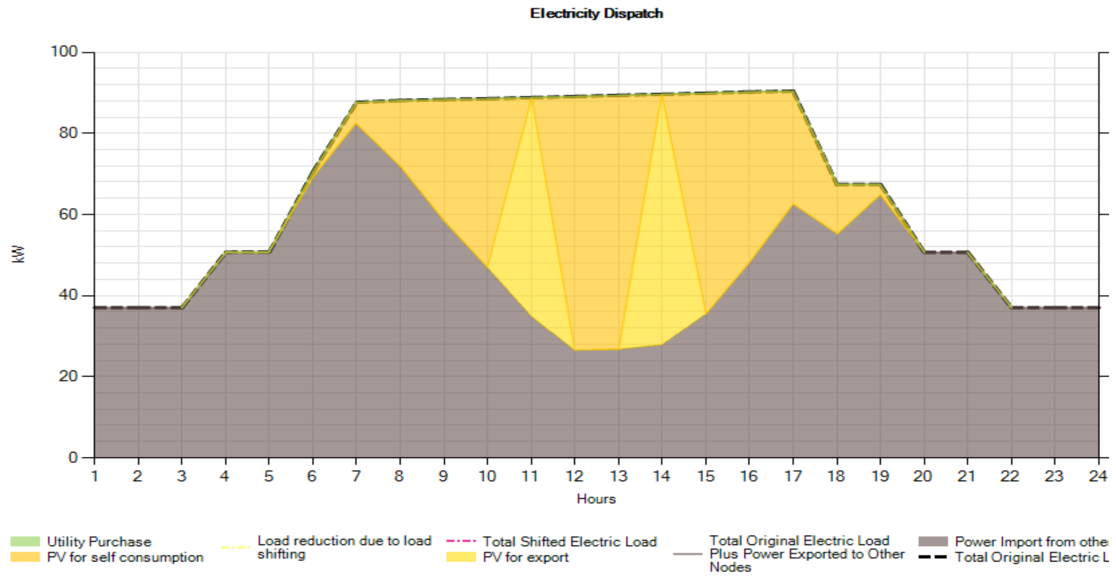


Figure.3.17 Hospital electricity dispatch without LS

3.4.7. VPP Reliability

The VPP improves the reliability of electricity dispatch in the selected area and reduced the dependence of the network on the utility grid. In the period of outage, the VPP can feed up its load by DER and battery storage system. On the other hand, in the worst-case scenario, the VPP can use the load curtailment technique to maintain stability. The outage data of feeder tripping due to faults and scheduled maintenance is collected from the 66/11kV substation. The data regarding the utility of normal and emergency days (outages) is shown in Table 3.12. In the comparison of VPP without storage, this VPP needs investment in a battery storage system with a capacity of 755 kWh, which results in increased annual energy cost ($268243), and the annual saving is reduced to 18.47% from 31.5%.

Table 3.12 Utility normal and emergency days

Month	**Peak days**	**Weekdays**	**Weekend days**	**Emergency days of the week**	**Emergency days of peak**	**Emergency days weekend**
January	2	21	5	1	0	2
February	2	19	5	0	1	1
March	2	19	7	1	0	2
April	2	20	5	0	1	2
May	2	21	5	1	0	2
June	2	18	7	1	0	2
July	2	17	7	2	1	2
August	2	18	6	2	1	2
September	2	18	6	1	1	2
October	2	21	5	1	1	1
November	2	19	6	1	1	1
December	2	19	6	1	1	2

In the peak month period, the numbers of emergency days are the maximum, which results in reduced reliability of the utility grid. With the VPP integration into the distribution grid, the reliability of the particular area is significantly improved. Fig.3.18 shows the electrical dispatch during the emergency outage period of a weekday in January.

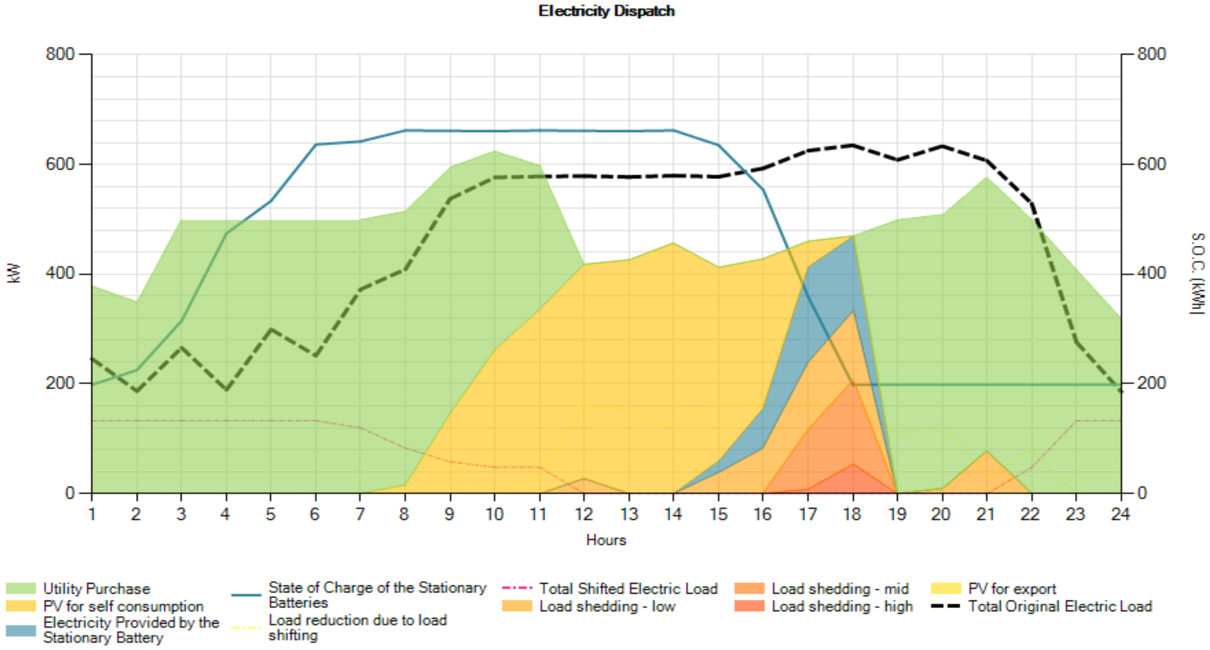


Figure.3.18 Electrical dispatch of VPP during an outage

From the above figure it is concluded that during the period of outage, the load could be dispatched from the combination of PV generation and battery storage. The remaining part of the load can be curtailed or shifted, which depends upon the priority of the load. The need for load shedding can be further reduced with an increase in battery storage capacity.

3.5 Summary

In general, the results indicated that the VPP is a promising solution for the integration of DER resources, which reduces both demand and energy charges from the consumer point of view. On the utility side, it can enhance the network reliability and provide relief to feeders from peak load, which ultimately deferred the investment in network augmentation. The four different aggregate load profiles are analyzed to determine the VPP implication. The DER investment alone gives a significant decline in electrical energy cost and its functionality can enhance by implementing load shifting, which reduces energy cost and peak load at the same time. The utility outage due to any fault results in loss to industrial production and other commercial works. The impact of these outages can decrease by investing in a battery storage system and implementing a load curtailment program. The battery storage is also used to store excess PV generation and limit the reverse power flow into the grid. The storage also improved utility reliability and reduced the peak load to the lowest value. The combined dispatch of DER and DR founds to be the most economical scenario of VPP, but the small investment in the storage system can be easily justified due to reliability improvement.

CHAPTER-4

RELIABILITY & FLEXIBILITY EVALUATION WITH VPP

4.1 Introduction

The smart grid revolutionizes the present grid infrastructure with large scale integration of small rating grid-connected DERs installed at consumer premises. The power generation from this DER is often clean and low cost especially in the case of renewable-based DER such as roof-top PVs, which gives hopes of a sustainable energy future as well. However, there are still some issues associated with DER power generation, which limits its application in reliability improvement[115],[116]. The theory of VPP takes full advantage of DER by integrating their generating profiles into a single operating profile, which is easy to control and dispatch[78], [112]. During the unscheduled outage due to any fault in the radial network, the entire grid-connected consumers are at the risk of interruption, which results in production loss and adversely affects the national economy. In the present grid infrastructure, the automatic reclosers are mostly used in the radial feeder to isolate the faulty feeder section during a fault condition and restore the supply of the remaining consumers, which slightly improves the overall reliability of the feeder. However, to get substantial improvements, the concept of VPP needs to be implemented in the distribution network. The power supply can be restored through the VPP during an outage by creating intentional islanding and dispatch the aggregate generation of rooftop PV's and shifting or interrupting the load of low priority. This strategy makes it possible to meet emergency load in case of grid unavailability and even reduces the load stress during feeder reconfiguration. This interconnected DER and DR as the components of VPP can only be put into operation through automatic recloser as during fault the unhealthy section must be isolated from the healthy portion. The remaining faulty portion can be energized through VPP and the main grid depending upon the fault location. The generation profiles of DERs are integrated into one operating profile and load is dispatched optimally and securely by optimal control strategy. In order to calculate the reliability, the analytical method of reliability evaluation is undoubtedly simple and less time consuming, but lack of accuracy due to its fixed average value limited its use in practical applications. The probabilistic method such as Monte Carlo Simulation (MCS) provides numerous possible values through its probability distribution and gives realistic results in comparison to the simple analytical method as the utility distribution system is stochastic in nature [117]. The MCS predicts the behavior of the system accurately and classified into two categories: sequential and non-sequential. The sequential MCS is used in this study as it simulates the system in the chronological order of time and models the system components more realistic, especially the time-varying loads. The various reliability indices are calculated after simulating artificial failure history of the various components and overall system reliability is determined.

4.2 Load and Reliability Specifications

For load evaluation, the Industrial feeder is selected on which, the major load of furnace and punching is connected. A part of the one-line diagram of 90 bus 11kV industrial feeder designed in ETAP is shown below in Fig.4.1 It includes major components such as transmission lines, transformers, solar PV, and step-down substation. The load and generating profiles are aggregated at a low voltage level and connected to 11 kV feeder through a distribution transformer. It is assumed that all the transformers installed on the feeder having grid-connected solar PV, but not more than 20% of its power rating.

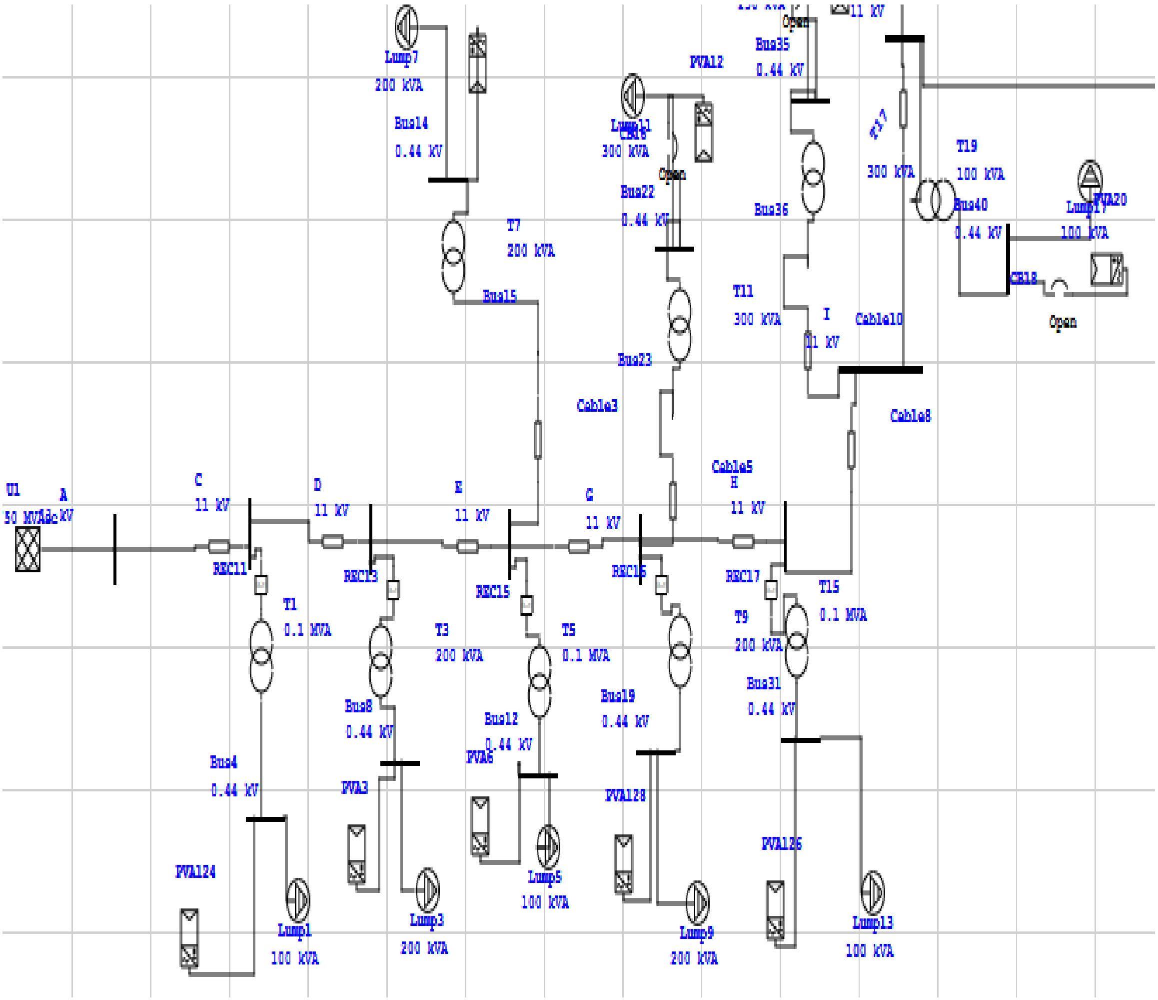


Figure.4.1 90 bus 11 kV Industrial feeder

To determine the influence of VPP, the numerous grid integrated DER are installed at various consumer premises located at different points of the feeder and further connected to the feeding distribution transformer of their locality. The demand and generation profiles are aggregated at the feeding transformer level and the bi-directional flow of power takes place. The typical load Profile including week, weekend, and peak day for November of this feeder is illustrated in Fig.4.2

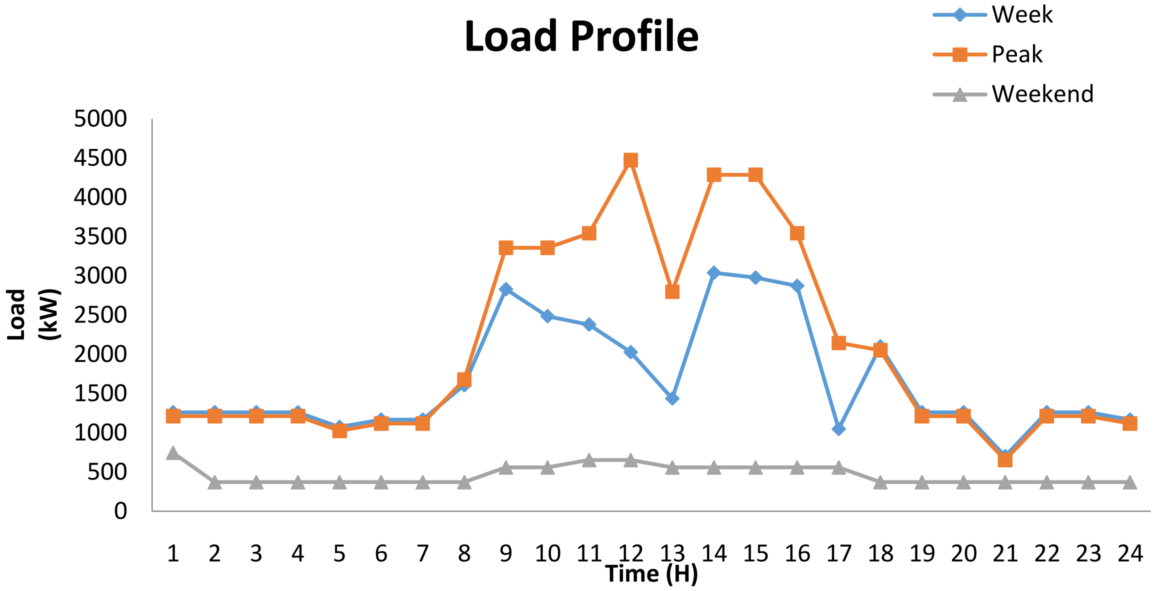


Figure.4.2 Load profile of Industrial feeder

The loading and reliability parameters of the Industrial feeder are shown below in Table 4.1.

Table 4.1 Industrial Feeder Technical Parameters

Loading Parameters		**Reliability Parameters**	
Average demand	1033 kW	No. of transformers	47
Peak demand	4288 kW	Transformer failure rate/yr (λ)	0.15
Annual energy demand	9718850 kWh	Transformer mean time to repair (MTTR)	0.5 hr
Peak month	November	No. of sectional lines	41

Table 4.1 Industrial Feeder Technical Parameters (Continued)

Total consumers	257	Sectional lines failure rate/yr (λ)	0.5
Length	2.174 KM	Sectional lines mean time to repair (MTTR)	1.5 hr
Current capacity	254 Amp	No. of substations	1
Connected load	9228 kVA	Substation failure rate/yr (λ)	0.6
Maximum demand	290 Amp/5518 kVA	Substation meantime to repair (MTTR)	4 hr

4.3 VPP Components Data

The VPP investment includes the capital cost of solar panels, inverter, and a static switch. In this research, the market available PV panel is considered without any government subsidy [118]. The various technical and financial specifications of the VPP components are tabulated in Table 4.2.

Table 4.2 Specification of VPP components

Solar panel price ($/kW)	$ 1150
Solar panel Lifetime	20 Years
Inverter price (100kW)	$500
Peak eff.	14.9%

4.3.1 Tariff Data

The Time of Day (TOD) tariff used for this study is based on the power tariff 2019. The prime objective of this tariff is peak shaving and to obtain a near-flat load profile, which results in the deferral of utility network augmentation and also declines consumer's demand charges. The main features of this tariff are shown in Table 4.3 below [114]:

Table 4.3 TOD tariff

Date	Duration	Price/kWh (1$=74 INR)
1-4-18 to 31-5-18	06:00 am To 06:00 PM	$0.0907
	06:00PM To 10:00 PM	
	10:00 PM To 06:00 AM	$0.0713
1-6-18 To 30-9-18	06:00 AM To 06:00 PM	$0.0907
	06:00PM To 10:00 PM	$0.1220
	10:00 PM To 06:00 AM	$0.0907
1-10-18 To 31-3-19	06:00 AM To 06:00 PM	$0.0907
	06:00PM To 10:00 PM	
	10:00 PM To 06:00 AM	$0.0713

4.3.2 Flexible Load Data

The flexible or controllable load follows the generation, which provides flexibility to the distribution grid with high penetration of DER. The PSPCL is encouraging the consumers to shift their demand to off-peak periods by giving rebates through TOD tariff [14], [100], [119]. The maximum possibility of load shifting is found at weekends. The demand which could be controlled during various days is summarized in Table 4.4.

Table 4.4 Schedulable load data

Feeder	Controllable load(percentage of aggregated load) during Peak day	Controllable load(percentage of aggregated load) during Weekday	Controllable load(percentage of aggregated load) during Weekend	Maximum Load Curtailment During peak hours	Maximum Period
Industrial	18%	18%	32%	800 kW	12 hrs

4.4. Methods of Reliability Analysis

System Average Interruption Frequency Index (SAIFI): It reveals the frequency of an average customer interruption for a specific course of time. The SAIFI is given as

$$SAIFI = \frac{Total\ Number\ of\ Customers\ Interrupted}{Total\ Number\ of\ Customer\ Served}$$

With the isolation of a faulty section of the feeder through recloser, this can assist in restoring the supply of a healthy portion and declines the number of customers interrupted.

System Average Interruption Duration Index (SAIDI): it shows the duration of the interruption that an average customer faced in the specified course of time. The SAIDI is given as

$$SAIDI = \frac{Customer\ Interrupted\ Duration}{Total\ Number\ of\ Customer\ Served}$$

The duration of interruption could be reduced with the reclosers for fault isolation and DER for supplying the healthy portion.

Customer average interruption duration index (CAIDI): This reveals the average time needed to restore the supply. The CAIDI is given as

$$CAIDI = \frac{Customer\ Interrupted\ Duration}{Total\ Number\ of\ Customer\ Interrupted}$$

With the fixed number of interrupted consumers, the CAIDI can be reduced with the restoring time by supplying the isolated section of the feeder by the DER.

Average service availability index (ASAI): it indicates the percentage of duration in which an average customer received the electrical supply in the specified course of time. The ASAI is given as

$$ASAI \ = \frac{Customer\ Hours\ Service\ Availability}{Customer\ Hours\ ServiceDemands}$$

The supply of demand through the DER during the fault period can enhance the service availability of the customers and ultimately the ASAI index.

Expected Energy Not Supplied (EENS): It depicts the average electrical demand in the year, which is not met by the system. It is given as

$$EENS \ = Average\ Outage\ Time * Total\ Electrical\ Demand \text{ (kWh / Yr)}$$

The demand is dispatched from the aggregated DER and the main grid after isolating the faulty section can be reduced EENS.

4.4.1 With Analytical Method

This is one of the simplest and fastest methods available for computing reliability indices of distribution networks. In this method, the impact of each component failure on the load points is calculated to determine the frequency and duration of the interruption. The values computed from this method are mean values, which are not much of practical significance as the behavior of the utility network is stochastic, so the results obtained from the analytical method are impractical.

4.4.2 With MCS Method

In MCS, the sequential method is mostly utilized by researchers due to its numerous advantages. In the sequential method, the probability distribution is calculated, which indicates the close range of the reliability indices. The sequential method modeled the system's various characteristics in chronological order as an up or down cycle. The sequential is the only method, which can model time-varying loads.

The basic parts of the MCS method are further elaborated as follows:

A. Artificial Operating History

The generation of failure history of the different components is the basic requirement of MCS. The artificial operating history can be generated by defining the reliability parameters such as failure rate and MTTR of the specific component. The artificial failure history generation is the dual-state model, which means the component stays either in UP state called Time To Failure (TTF) or in downstate, which is known as Time To Repair (TTR)[120], [121]. The switching time between these states is assumed to be zero. In the Matlab environment, the random numbers between 0 and 1 are generated, which represents a component failure in the exponential distribution as the system is random [96], [122], [123]. The calculation of TTF and TTR is given as follows:

$TTF_i = -\frac{\ln(Ui)}{\lambda i} \times 8760$ hours

$TTR_i = -\ln(Ui) \times MTTRi$ hour (λ_i = failure rate, $MTTR_i =$ mean time to repair)

B. Customers Interruption

The system response to the faults that are generated during the artificial failure history indicates the numbers of customers are interrupted due to the specific component failure in that region. The every hour system is assessed for possible faults and their consequence interruption considering the application of reclosers and DER.

C. Types of Faults

The faults consider in this simulation are originated from the failure of the component over their lifetime, in such a way that it shut down the whole system or a section with recloser.

D. System Islanding

In the event of a grid outage, the customers connected to the particular portion of the system faced interruption. However, the supply can be restored by intentional islanding with the implementation of the VPP concept [124], [125]. The faulty area of the feeder is isolated with the help of automatic reclosers and the healthy portion is supplied by DER and the unmet load is either shifted or curtailed.

4.5 VPP Mathematical Modeling

The two major components of VPP are DER and DR, both these components are modeled with other components is as follows.

4.5.1 Solar PV

The solar PV is weather dependent DER, which is quite popular in countries located near the equator due to high solar irradiance throughout the year. The output of a solar cell is well dependent on different variables, which are briefly described below**:**

$PV_t = A * \eta * N * S_t \ \forall\, t \in T$

η = Efficiency of a solar panel (14.9%)

S_t = Solar irradiation (800 W/m^2)

t = Time-step

N = Number of solar panels connected either in series or parallel

A = Area occupied by solar panels

PV_t = Estimated output of solar PV

It is assumed that the PV panels are fully reliable and integrated with an inverter of the same rating. The maximum grid integrated capacity of PV is capped to 20% of transformer capacity due to safety constraints.

4.5.2 Loads

The load is supplied up from SCADA controlled 66/11kV step-down substation that is located within the boundary of the division. In this research, the 11kV industrial feeder on which the DERs are installed is selected for load assessment. The feeder's load profiles are aggregated into a single operating profile and analyzed for different cases. The load data of the feeder is taken from the utility database.

$Load_t = FlexL_t + \ IntrrL_t + \ EmgL_t \ \forall\, t \in T$

$\boldsymbol{Load_t}$ = Total demand on the feeder

$Flex_t$ = Schedulable demand

$Intrr_t$= Non Schedulable demand

Emg_t = Emergency demand

The flexible load can be shifted from peak time to off-peak period, whereas the inflexible demand cannot be scheduled to any other time of day but can be curtailed. The emergency demand is needed to supply at any cost even during a grid outage. The cost of load interruption is taken as \$13.74/kWh, which is the average loss cost incurred by the connected industries in the event of an outage.

Objective function

$$\text{Min}= \Sigma\, Uim \cdot Ttod + \Sigma\, NS \cdot MaxS \cdot CCS + \Sigma\, ICS \cdot Pur + + Cap\,.\,OMC - \Sigma\, Gex.TEx + \Sigma\, EENS\,.\,C_{EENS} \tag{1}$$

Network constraints

$$Loadt = \Sigma\, GU + UL \text{ [kW]} \tag{2}$$

$$OS\,.\,MinL \leq \Sigma\, GU + (Gex \leq OS \cdot Max\mathrm{S} \text{ [kW]} \tag{3}$$

$$\Sigma\, (\Sigma\, GU + Gex) \leq \mathrm{NS} \cdot Max\mathrm{S} \cdot MaxH \text{ [kW]} \tag{4}$$

$$Cap \leq Pur \cdot M \text{ [kW]} \tag{5}$$

$$\Sigma_{\,u} GU \quad + Gex \quad \leq Cap_c \cdot SRE \quad / SPE_C \cdot SI_{m,d,h}\ \forall m,d,h : c \in \{PV\} \text{ [kW]} \tag{6}$$

$$\frac{\Sigma\, Capc}{cSPE_c} \leq SA : c \in \{PV\}\ [m^2] \tag{7}$$

- Eq. (1) explains the objective function and includes all the economical components like DER capital cost, operation cost, utility charges, etc. the network constraints of this objective function are as follows:
- Eq. (2) forced a balanced constraint between load and generation.
- Eq. (3) forced generation and energy export constraints.
- Eq. (4) forced constraint of maximum DER generation.

- Eq. (5) forced constraint of generation and consumer energy purchased, where M = arbitrarily large number.
- Eq. (6) forced solar PV generation constraint.
- Eq. (7) forced solar PV area constraint.

Load Parameters

- $Load$ Consumer demand u [kW]
- Uim Energy imported from the grid (kWh)
- C_{EENS} Cost of not supplying demand ($/kWh)
- $EENS$ Expected Energy Not Supplied (kWh)

Tariff details

- $Ttod$ Energy usage charges [$/kWh]

Technical parameters of solar PV

- $MaxS$ Maximum rating of solar PV [kW]
- CCS Capital cost of solar PV [$/kW]
- ICS Initial capital cost of solar PV [$]
- OMC Fixed annual O&M costs of solar PV [$/kW]
- $Max\ H$ Maximum annual operation hours for technology [hour]

Decision Variables

- NS Number of units of solar PV installed
- OS Number of units of solar PV operating
- GU Power generated by solar PV [kW]
- Cap Rated output of solar PV [kW]
- UL Electricity purchased from utility [kW]
- Pur Consumer purchase binary decision of solar PV [0 or 1]

Assumptions

- The movement of clouds and other external factors that effecting PV output are not considered
- A single TOD tariff applies to the entire load.
- The deterministic approach is followed while gathering the required data.

The workflow for the main body of the algorithm is illustrated in Fig.4.3. below.

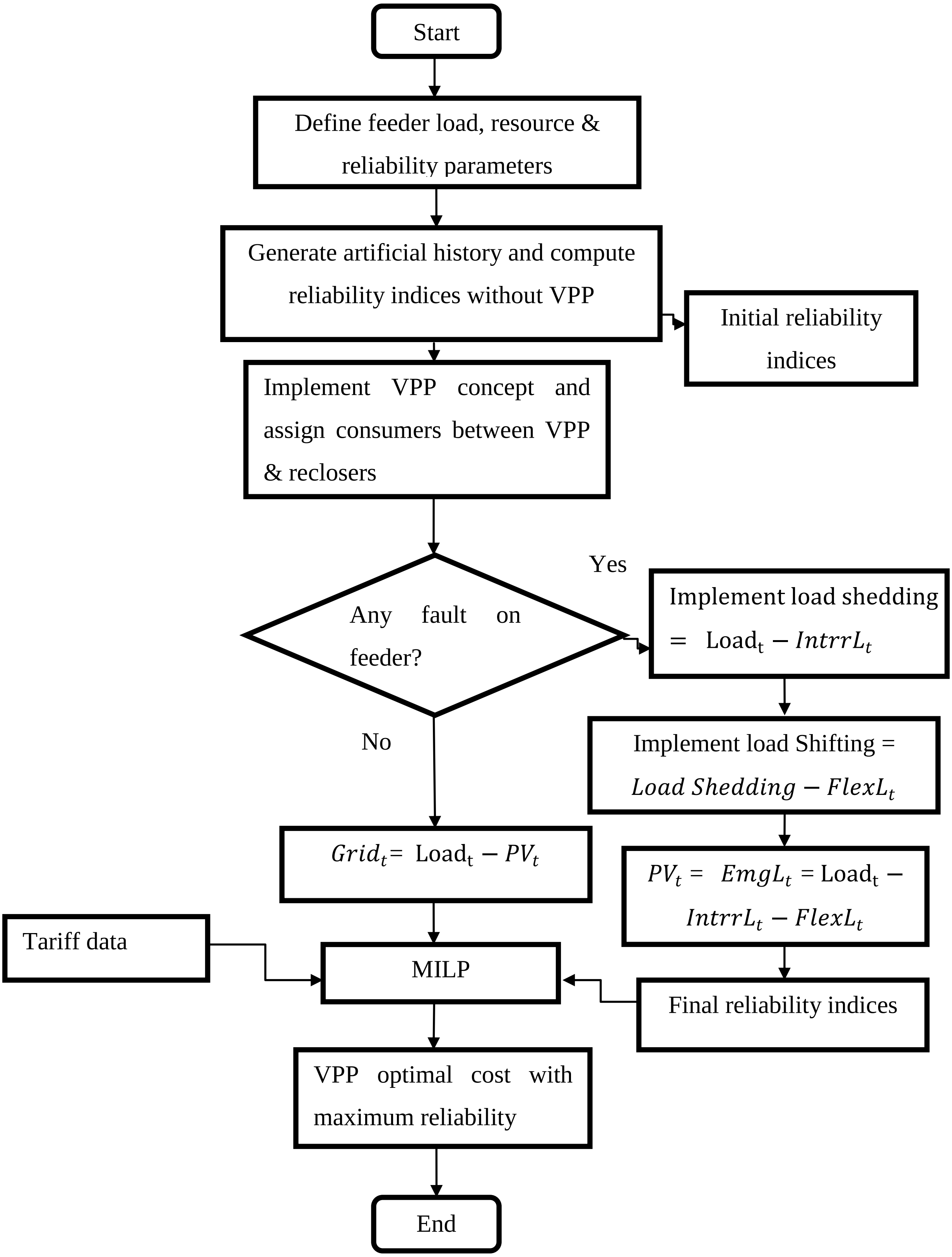


Figure 4.3 Workflow of MILP Optimization

The study is further classified into three major cases for evaluating the reliability assessment with the VPP.

1) **Case 1: Base Case**

For setup reference reliability of the system, the base case is needed to be run. In this case, the VPP investment and reclosers are disabled.

2) **Case 2: With Reclosers**

The two automatic reclosers at different positions on the feeders are installed and the reliability of the system is determined. These reclosers isolate the faulty sections and the remaining portion of the feeder if before the faulty section is energized.

3) **Case 3: With Reclosers and VPP**

To further improve the reliability of the feeder, the DER is installed with the conjunction of automatic reclosers and the overall system reliability is assessed. The faulty portion is isolated and a healthy portion is energized either through the main grid or DER depending upon the location of the fault.

4.6. Results and Discussions

After defining all the utility parameters, the developed model is simulated and the various indices are calculated and assessed in techno-economic terms.

4.6.1 MCS Results

After running the MCS with the 1000 sample years duration, the failures of different components of the feeder are simulated randomly. The prime step of MCS is to generate an artificial failure history of every component connected to the feeder. This failure history simulates the system for each hour of the year to find the possible failure and its consequence on all the load points of the feeder. The overall reliability results are summarized in Table 4.5.

Table 4.5 Reliability results of Industrial feeder

Case	SAIFI	SAIDI	CAIDI	ASAI	EENS
Case1:Base case with initial values	27.686	34.2946	1.2387	0.99609	37045 kWh
Case2:With automatic reclosers	23.6684	31.3868	1.3261	0.99642	33869 kWh
Case3:With automatic reclosers and VPP	9.5266	10.153	1.0657	0.99884	11689 kWh

The above interruptions do not include the outages due to scheduled maintenance or any erection work of the distribution network. The obtained results depict that the integration of reclosers and VPP into the network results in significant improvement in reliability indices such as SAIFI, which is declined by 14.51 % and 65.59 % with cases 2 and 3 respectively. Without reclosers, there is no advantage of installing the DER as the faulty section cannot be isolated from the feeder and results in a complete interruption of consumers. The flexibility of the system is also improved as an alternative supply is available from the DER.

4.6.2 Techno-Economic Analyses

The reliability indices obtained are fed into a MILP based multiobjective model for evaluating the financial implications of VPP in reliability enhancement, which includes calculating annualized and operational energy costs. The detailed techno-economic analyses of VPP are summarized in Table 4.6 below. In comparison to the base case and the case with only reclosers, the PV capacity 1916 kW is utilized as a part of VPP integration, which considerably declines the yearly energy cost by 55.26 % of the feeder by dispatching the load by combining the effect of DER and DR. The optimized operational cost is also reduced by 61% with DER penetration and DR program such as load shifting varies the consumer load pattern to make a balance between demand and supply. The cost of EENS with grid outage is also reduced through the VPP implementation by 68%. The case in which the reclosers and VPP are included is found to be most economical in comparison to other configurations.

Table 4.6 Techno-economic analysis

	Base case	**With reclosers**	**With reclosers and VPP**
PV capacity	-	-	1916 kW
Total annual energy Costs	$1891000	$1846614	$846016
Annual savings	0	$44386	$1044984
Optimized operational cost	$1891000	$1846614	$737578
Total electric costs	$1890513	$1846051	$725280
Total annual electricity purchase	9718850 kWh	9718850 kWh	6511797 kWh
Total annual on-site generation	-	-	3602959 kWh
Load curtailment cost	$508998	$465360	$160606

4.7 Flexibility with VPP

The modern energy system values reliability and flexibility as its main parameters while drafting energy policy to meet the high expectations of consumers in the present scenario. The utilities adopting VPP in the distribution network to enhance the grid flexibility in event of grid outage by supplying the high priority demand through DER locally and low priority load is curtailed or shifted to the remaining part of the day. The VPP also aggregates and coordinates the numerous grid-connected DER and storage devices into a single operating profile[112], [126], [127]. This one operating profile is much simple and easier to control in real-time situations in comparison to managing numerous resources at a time. A case study of utility is evaluated to study the implication of VPP on grid flexibility considering the grid outage. The DER-CAM is utilized in this study for finding an optimal solution, which is a far more sophisticated and accurate model than present tools. The modeling of combined dispatch of DER, DR, and storage has been done in DER CAM and optimal sizing of DER and storage is determined.

After running various configurations in DER CAM, the optimal sizing of DER and storage is determined, which is comes around PV capacity of 1916 kW and 9511 kWh. To minimize the energy cost and to maintain the security of the distribution network, the DER CAM founds optimal electrical dispatch. The optimal electrical dispatch during the outage weekday of January is illustrated in Fig.4.4 below. The sudden loss of grid supply is compensated by DER generation, storage, load shifting, and load curtailment. In the event of an outage, the DER generation is given first priority for dispatch and the storage is utilized when PV generation is limited. The load shifting and load-shedding program are used when none of the supply resources is sufficient to meet the full demand.

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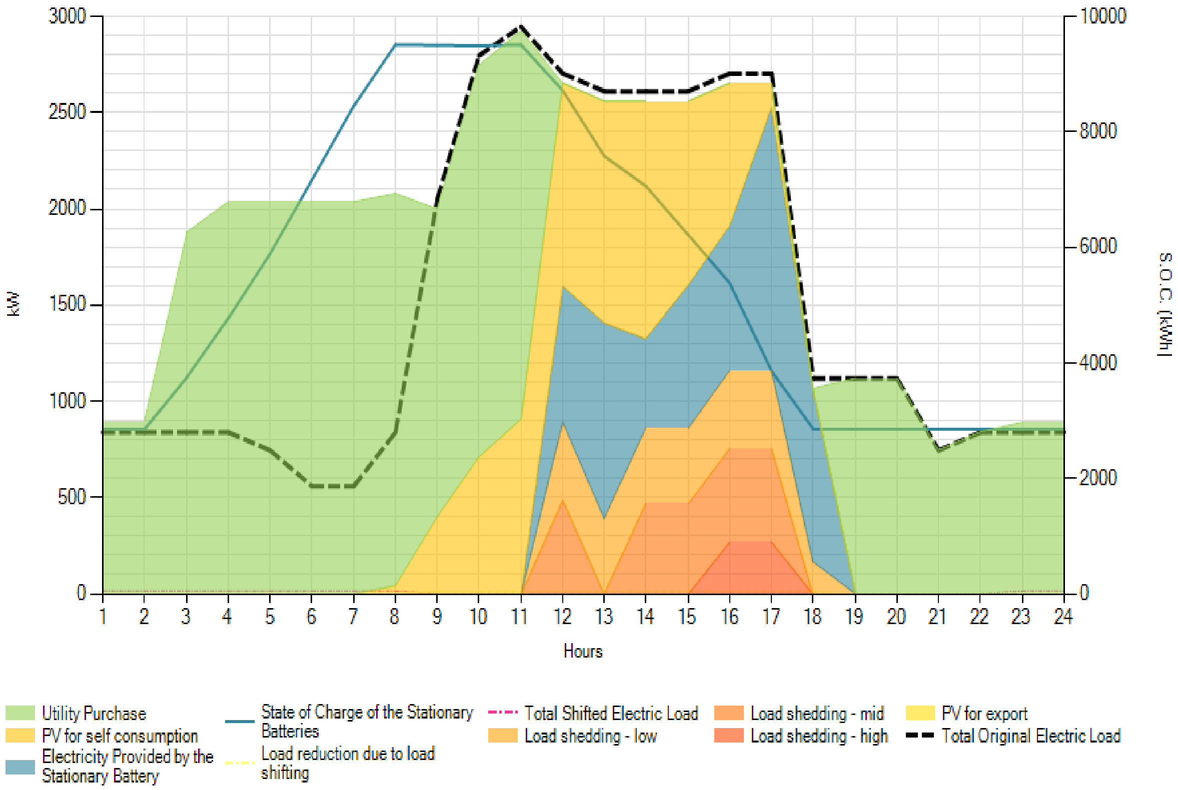

Figure.4.4 Electrical dispatch during an outage

4.8 VPP Modes of Operation

The VPP can operate in dual mode one is a grid-connected mode to minimize the energy cost and on the other side, it can operate autonomously during the outage period and supply the maximum possible demand. The electrical dispatch of the selected feeder by the grid-connected VPP concept for November month is illustrated in Fig.4.5 below. The significant demand of the feeder is coinciding with the solar peak generation period, hence it is possible to supply a major part of load through VPP during that period.

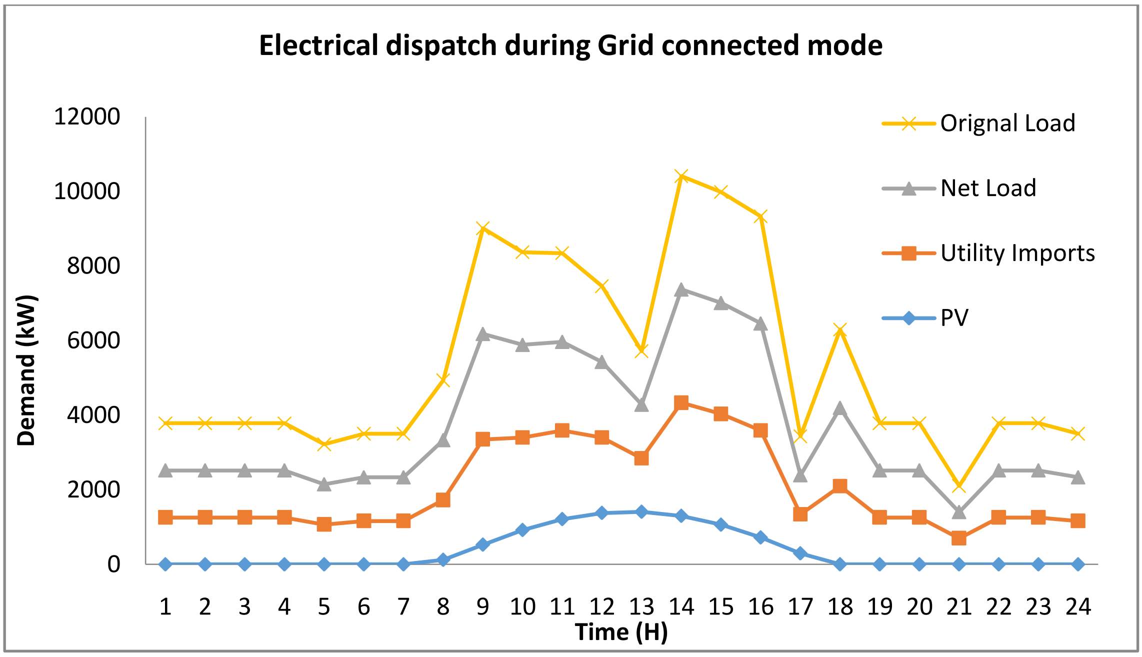

Figure.4.5 Electrical dispatch with VPP during an outage (grid-connected mode)

The VPP plays a major role in the enhancement of reliability during the period of the outage as part of load which is emergency load is supplied my network of small-scale rooftop PVs and remain load is shifted or interrupted based on the priority. Also, the load shifted to the off-peak period to lessen the strain on the feeder during intentional islanding. For instance, the outage of an hour from 09 to 10 hrs is considered on the weekday of September and the electrical dispatch with VPP during an outage (Islanding mode) is illustrates in Fig.4.6.

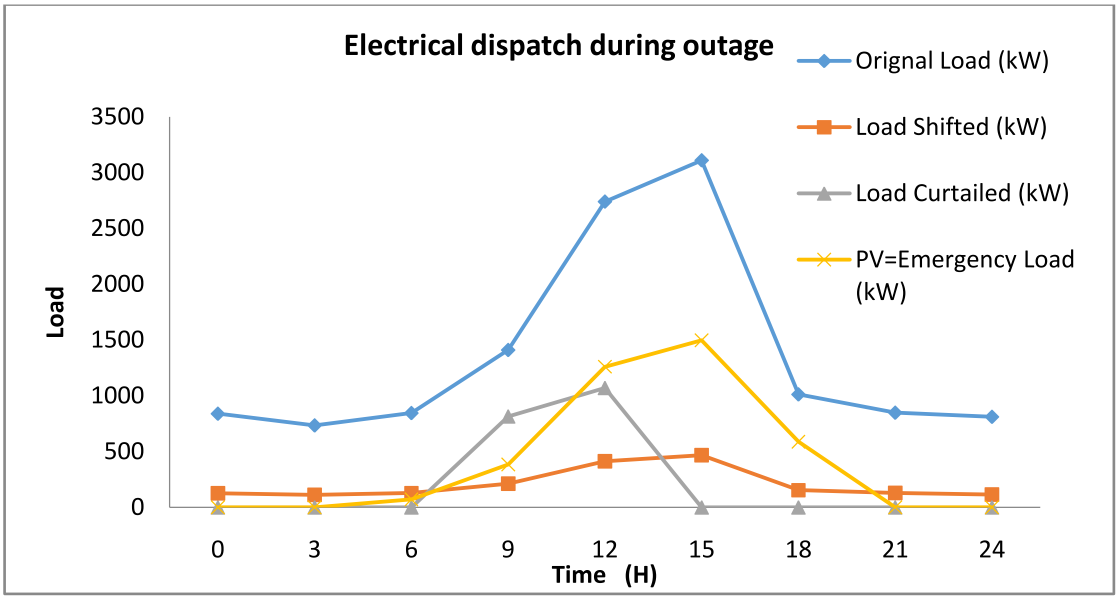

Figure.4.6 Electrical dispatch with VPP during an outage (Islanding mode)

During the outage of one hour, the demand of 211 kWh is shifted, 815 kWh curtailed and 384 kWh of emergency demand is met by PV, which considerably reduces the EENS and hence improved the overall reliability. To further analyze the demand implication of autonomous VPP on the feeder, the section-wise main length of the feeder is assessed in Table 4.7 below. The branches of feeder are not considered in this evaluation and an outage of an hour is analyzed at various sections of feeders while assuming preceding sections of feeder are isolated.

Table 4.7 VPP section-wise autonomous response

Feeder Section	**Connected Load (kW)**	**Running Load (kW)**	**PV (kW)**	**Flexible Load (kW)**	**Load Shed (kW)**
0-A	9228	4401	884	660	2857
A-B	9128	4354	874	653	2827
C-D	8928	4258	854	1339	2065
D-E	8528	4067	833	1279	1955
E-F	8328	3972	813	1249	1910

Table 4.7 VPP section-wise autonomous response (Continued)

F-G	**8128**	**3877**	**793**	**1219**	**1865**
G-H	7898	3767	770	1184	1813
H-I	6878	3280	670	1031	1579
I-J	6678	3285	650	1001	1634
J-K	6578	3137	640	986	1511
K-L	6378	3042	620	956	1466
L-M	5378	2565	522	806	1237
M-N	5178	2469	502	776	1191
N-O	4678	2231	483	701	1047
O-P	4478	2136	462	671	1003
P-Q	4278	2040	441	641	958
Q-R	4178	1992	430	626	936
R-S	3778	1802	388	566	848
S-T	3678	1754	377	551	826
T-U	3478	1659	356	521	782
U-V	2978	1420	304	446	670
V-W	2778	1325	283	416	626
W-X	2578	1229	262	386	581
X-Y	2115	1008	214	317	477
Y-Z	1615	770	163	242	365
Z-A1	1552	749	156	232	361
A1-A2	1489	710	149	223	338
A2-A3	889	424	88	133	203
A3-A4	263	125	66	39	20
A4-A5	200	94	50	30	14
A5-A6	100	47	23	15	9

4.9 Experimental Validation

The results received from the developed Matlab code have clearly defined the suitability of VPP in the reliability enhancement of the distribution network. However, to validate the Matlab results, the IEEE 34 node test system is selected and simulates in the MCS using already created Matlab code. The IEEE 34 node test system is shown in Fig.4.7 below. The DERs are inserted in the nodes between 832 and 840 with automatic reclosers at suitable positions.

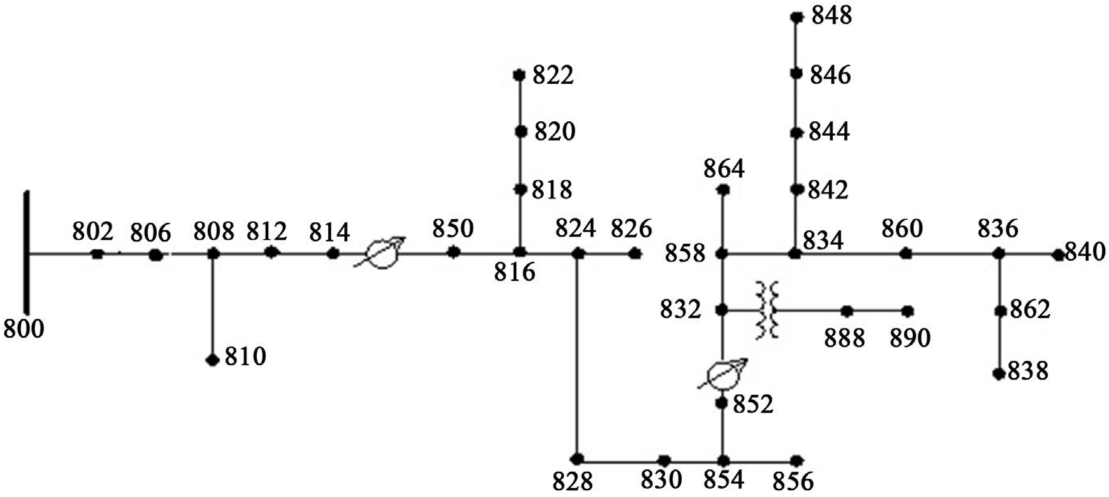

Figure.4.7 IEEE 34 node test system

This test system is run in Matlab and the results obtained are tabulated in the given Table 4.8. The overall reliability indices of the IEEE 34 bus test system are improved by 57%, which is quite an attractive figure.

Table 4.8 Reliability results of IEEE 34 node system

Case	SAIFI	SAIDI	CAIDI	ASAI	EENS
Case 1: Base Case	18.811	43.2923	2.3014	0.99506	68142 kWh
Case 2: With Automatic Reclosers	14.9521	34.1843	2.2858	0.9961	53793 kWh
Case 3: With Automatic Reclosers and VPP	8.2658	18.9415	2.2915	0.99784	27946 kWh

A well-established optimization technique such as a proprietary derivative-free algorithm (HOMER Optimization) is further used to validate and compare the proposed optimization results. Both optimization techniques are implemented on the

90 bus industrial feeder VPP model to calculate the optimal operation cost. The results of the optimization are compared below in Table 4.9.

Table 4.9 Comparison of Different Optimization Techniques

Optimization algorithm	Optimal Operational cost	Execution time
Only Grid	$1891000	00 Sec
Proprietary Derivative Free	$888571	03.6 Sec
Proposed MILP	$737578	15.1 Sec

Despite the long executing time, the proposed MILP is more effective and provides the minimum optimal operating cost.

4.10 Summary

The prime objective of this research is to enhance distribution network reliability considering the financial implication of the grid outage and minimize the energy cost. A case study of state power utility has been studied for the feasibility of VPP integration, which is facing revenue loss due to frequent outages in its distribution network. The VPP model, which is based on MILP is developed for evaluating the reliability of the grid with the inclusion of reclosers, DER, and DR. The results acquired from the MCS revealed that there are significant improvements in the system reliability index of SAIFI and SAIDI by 65.59 % and 70.39% respectively in the case of VPP deployment in the comparison to the base case. The techno-economic analysis of the proposed model revealed that the operational cost is declined by 61% and shows significant reductions in need of load curtailments, which further limit the load curtailment cost by 68%. The results obtained through the optimization technique are compared with other popular technologies such as Homer optimization, which also witnessed the effectiveness of the proposed optimization technique. It can be noticed that the VPP concept is found to be beneficial for both consumers and utility in the techno-economic prospectus.

CHAPTER-5

PEAK LOAD SHAVING USING VPP

5.1. Introduction

The DER is now becoming the focus of energy policymakers for shifting the paradigm of the monopoly system to the competitive energy market. The participation of consumers in the energy market by injecting their surplus generation and varying their consumption patterns makes the distribution network more efficient and competitive [62]. The small-scale DER in the form of residential or industrial rooftop PV is widely popular in India due to the competitive energy market [2] and considering the current pace of its growth, the DERs are expected to dominate the energy generation sector in the upcoming years. At present, the government incentives and subsidies facilitate the high integration of renewable-based DER such as solar PV due to favorable weather conditions [4]. The grid integration of the DER undoubtedly brings utility benefits such as a reduction in line losses, voltage drop, and network augmentation. However, at an equivalent time, due to weather dependence, the intermittent generation from large scale DER penetration causes numerous challenges for the grid operator to maintain system security and demand following [29]. Furthermore, in the absence of sufficient control and energy management, these DERs undesirably influence the utility network through voltage instability, reverse power flow, and utility revenue drops [115], [116]. To permit the high penetration of DER in the grid, without violating the technical and economical constraints, the VPP concept can be an effective solution to address all these challenges.

VPP is the advancement of the well-established concept of microgrid and performs the autonomous operation through two-way communication between the grid operator and consumers. The VPP has four main components, which are DERs, storage devices, flexible loads, and communication technologies [46], [6]. The small-scale DERs can be renewable or conventional ones and are located at various points on the utility network. In the case of DERs having intermittent generation, the storage devices can play a game-changing role in smoothens the variations and to provide a continuous supply. To further enhance the efficiency of VPP and accommodate the higher rating of DERs in the grid, the flexible load is seen as an effective way to maintain the balance between demand and generation. It also relieves demand congestion during peak hours through the change in consumer demand patterns by giving them monetary incentives [54], [100] Similarly, the communication technology made possible consumer participation in the grid and further allows them to act as prosumer [5]. With the application of smart grid technologies such as smart meters, there is two-way communication between consumer and utility, which makes it possible to certain the PV generation and demand of the consumer. The VPP provides various benefits such as self-supply, reduction of losses, and peak load reduction which will benefit both consumers and utility. The model of VPP schedules the generation of small scale DERs and demands between various consumers or agents of VPP [78], [112]. It provides aggregation of small DER installed at various points in the utility network to form a single operating profile [48], which is similar to the working of the central level load dispatch center.

The current literature survey gives more attention to the marketing aspect of VPP and checks the VPP performance only on the standard test feeders. The main goals of these researches are limited to the cost minimization and designing optimal bidding strategies models of VPP considering market constraints. The potential applications of VPP such as utility peak load reduction and mitigating serious side effects like reverse power flow are not part of these studies. Also, there is only small stress given on the implication of utility advantages like investment deferral. Moreover, the application of refined models such as DER CAM for VPP scheduling is still unexplored. The main goal of this chapter is to fill the research gap and ascertain the practicability of VPP with optimal energy dispatch for real-time distribution network from each economic and technical point of interest. The chapter proposes novel VPP applications in a distribution network such as peak load shaving and network augmentation deferral. It also introduces the solar tariff as part of DR to limit the reverse power flow in the network.

5.2 DER-CAM Formulation

The DER-CAM model is designed by Lawrence Berkeley National Laboratory, USA applied to find the optimal investment solution and DER dispatch [128]. DER-CAM finds its key application in VPP and microgrid operations, specifically in the planning phase. The base of the DER CAM optimization process is Mixed Integer Linear Programming (MILP).

5.2.1 Mathematical Modeling

This sub-section provides a brief description of the mathematical problem, which describes various input data and decision variables. The objective function is to minimize the annual energy and operating cost of the deterministic model with DER integration [129] without violating technical and economical constraints. The key generation technologies for DER-CAM can be discrete technologies and continuous technologies like internal combustion engine and solar PV respectively. The end-user load can be electrical, cooling, or heating load, but due to feasibility and market trend, the only electrical load is considered and continuous technology like solar PV without storage is utilized in this model. The complete description of the modified DER-CAM mathematical model is explained below [130]:

Objective function

$$\text{Min C} = \Sigma\, TF + \Sigma\, UL \cdot TE + \Sigma\, TP \cdot max(\Sigma\, UL + \Sigma\,(GS + \Sigma\, GU) \cdot VC + OMV + \Sigma\, IG \cdot MaxP \cdot CCD \cdot An + OMF + \Sigma\, FCC \cdot Pur + VCC \cdot Cap \cdot An + Cap\,.\,OMF - \Sigma\, GS.TEx \tag{1}$$

Network constraints

$$Load = \Sigma\, GU + UL \text{ [kW]} \tag{2}$$

$$RG\,.\,MinL \leq \Sigma\, GU + (GS \leq RG \cdot MaxP \text{ [kW]} \tag{3}$$

$$\Sigma\,(\Sigma\, GU + GS) \leq IG \cdot MaxP \cdot MaxH \text{ [kW]} \tag{4}$$

$$Cap \leq Pur \cdot M \text{ [kW]} \tag{5}$$

$$\Sigma\, GU + GS \leq Cap \cdot SRE/SPE \cdot SI\{PV\} \text{ [kW]} \tag{6}$$

$$\frac{\Sigma\, Cap}{SPE} \leq SA\ \{PV\}\,[m^2] \tag{7}$$

$$\Sigma\, UL \leq psb \cdot M \text{ [kW]} \tag{8}$$

$$GS \leq (1 - psb\ ) \cdot M \text{ [kW]} \qquad \textbf{(9)}$$

$$An \ = \frac{IR}{1-\frac{1}{(1+IR\ )^{Lt}}} \qquad \textbf{(10)}$$

$$C \leq BAU + \Sigma gIG \ \cdot MaxP \ \cdot CCDP \ \cdot An \ + \Sigma \ (FCC \ \cdot Pur \ + \qquad \textbf{(11)}$$

$$VCC \ \cdot Cap \ ) \cdot An \ - \frac{\Sigma IG \ \cdot MaxP \ \cdot CCP \ + \Sigma \ (FCC \ \cdot Pur \ + VCC \ \cdot Cap}{PB} \text{ [\$]}$$

- Eq. (1) explains the objective function and includes all the economic components like DER capital cost, operation cost, utility charges, etc. The network constraints of this objective function are as follows:
- Eq. (2) forced a balanced constraint between load, PV generation, and utility imports.
- Eq. (3) forced constraint of minimum and maximum DER generation during self-consumption and energy export mode.
- Eq. (4) forced constraint of maximum DER operating hours for energy generation for self-consumption and export.
- Eq. (5) forced constraint of generation capacity of solar and consumer energy purchasing decision, where M = arbitrarily large number.
- Eq. (6) forced solar PV balanced constraint between solar generation for self-consumption/export and solar capacity considering conversion efficiencies.
- Eq. (7) forced solar PV area constraint.
- Eq. (8) forced constraints between utility energy purchased and the energy import/export decision where M = arbitrarily large number.
- Eq. (9) forced maximum energy export constraint.
- Eq.(10) annuity rate calculation including factors such as interest rate and technology lifetime.
- Eq. (11) forced payback constraint considering capital and operating costs.

  Consumers load
- *Load* Consumer demand u at time month, day, hour [kW]

Tariff details

- TP Peak demand charges in accordance with utility tariff [$/kW]
- TE Energy usage charges [$/kWh]
- TF Fixed charges for utilizing utility infrastructure[$]
- TEx Energy export prices [$/kWh]

Technical parameters of solar PV

- $MaxP$ Maximum rating of solar PV [kW]
- $MinL$ Minimum allowable demand for solar PV [kW]
- Lt Lifetime of technology anticipated [years]
- $CCDP$ Turnkey capital cost of solar PV [$/kW]
- FCC Fixed capital cost of solar PV [$]
- VCC Variable capital cost of solar PV [$/kW]
- OMF Fixed annual O&M costs of solar PV [$/kW]
- OMV Variable O&M costs of solar PV [$/kWh]
- $Max\ H$ Maximum annual operation hours for technology [hour]
- VC Generation cost of technology j [$/kWh]
- SPE Peak solar conversion efficiency of solar PV panels [%]
- SRE Solar radiation conversion efficiency of solar PV [%]

Financial Data

- IR Interest rate [%]
- An Annuity rate
- SI Available solar radiations [kW/m²]
- SA Vacant area for solar PV installation [m²]
- BAU Total reference energy cost of system without any investment[$]
- PB Maximum payback period [years]

Decision Variables

- IG Number of units of solar PV installed
- RG Number of units of solar PV operating

- GU Power generated by solar PV for self-consumption [kW]
- GS Power generated to export by solar PV [kW]
- Cap Rated output of solar PV [kW]
- psb Binary decision of importing or exporting energy [0 or 1]
- UL Electricity purchased from utility [kW]
- Pur Consumer purchase binary decision of solar PV [0 or 1]

Assumption

- The load on the feeder is considered aggregated while calculating the optimum solution.
- The uniform tariff is applicable for the aggregated load.
- The deterministic approach is followed while collecting the required data.

5.2.2 DER-CAM Optimization Workflow

The DER-CAM is a sophisticated simulation tool that handles complicated interactions between DER, load, storage, and utility tariff with the subject to technical and economic constraints. The stepwise workflow of DER-CAM is shown below in Fig.5.1.

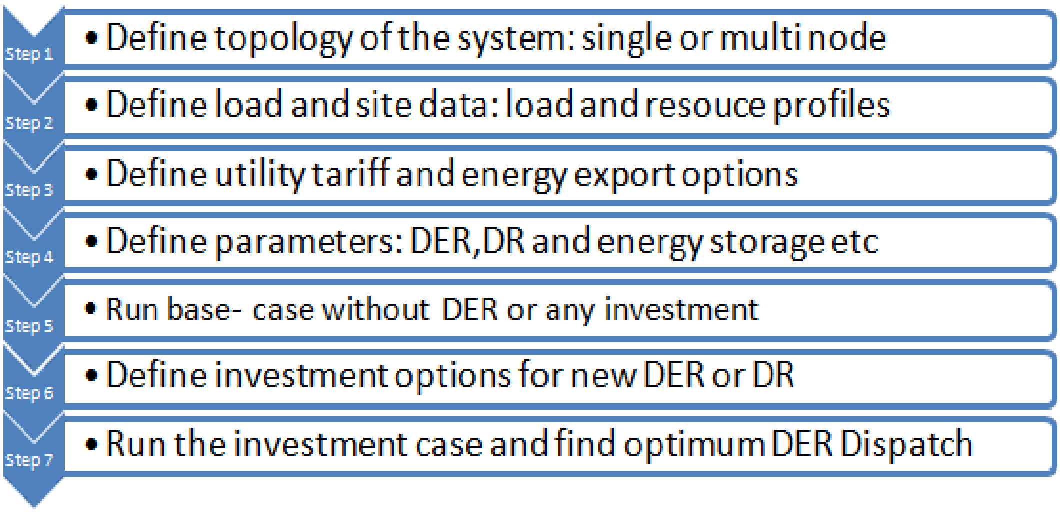

Figure.5.1 DER-CAM workflow

5.3. Case Study of Utility

To study the utility challenges closely and finding a possible solution through the VPP concept, the PSPCL, which is a state government acquired power utility has been selected for this research. Apart from this generation, the DER such as solar PV is now playing a game-changing role in the distribution sector. The installation of small scale DER on the residential, industrial, and commercial building is now common in the state, due to the competitive solar market and government subsidies. Under the PSPCL agreement, a consumer can install PV capacity ranging from 1 kW to 1 MW, and the maximum capacity of DER is capped to 80% of the connected load. At the same time, the aggregated capacity of solar PV is limited to 20% of transformer capacity at present due to technical constraints. These DERs are often grid-connected mode and it can be expected from its current growth that it will boost its energy shares soon. These DERs help the consumers to reduce power bills and reduce dependability on the utility grid, however at the same time, it shrinks utility revenue and causes other undesirable effects such as reverse power flow without proper planning. The concept of VPP can be an effective solution for efficiently and securely integrate these grid integrated DERs without any negative effect. At present, the major issue faced by the PSPCL is the peak load, which surpassed the current capacity of the feeder conductor and needs major investment in the distribution sector for network augmentation. For this VPP can aggregate DER generation and loads into one profile, which provides peak shaving and flexibility to the utility grid. The deferral on investment through a reduction in the peak load can compensate for the revenue loss of utility due to the high share of DER. The prospective of VPP in PSPCL for a selected area is analyzed in this case study and for the techno-economic analysis; it is further classified into four separate cases for DER-CAM simulation.

- Base case: Without DER or DR investment.
- Only DER: With investment in DER installation (solar PV), but without any DR.
- Both DER & DR: With DER investment and implementation of DR programs (load shifting).

- DER, DR & solar tariff: With DER investment and solar tariff-based DR program.

5.3.1. Resource Data Assessment

The site chosen for the research is under the control of the PSPCL distribution division East, which is located (31.3260° N, 75.5762° E) in Jalandhar city (India).

5.3.2. Load Data Assessment

The load is supplied up from SCADA controlled 66/11kV step-down substation that is located within the boundary of the division. In this research, the 11 kV feeders such as Industrial and Residential feeder on which the DERs are installed are selected for load assessment. The feeder's load profile is aggregated into a single operating profile and analyzed for different cases. The load data of both feeders, which are made available by PSPCL, is categorized into three different profiles: weekday, weekend, and peak day. On weekends, the load on the industrial feeder is sharply declining to quite a low value as, during this period, most of the industries are shut down. Both are 24 Hrs supply feeders with the least interruption and are interconnected with the Ring Main Unit (RMU). The load of one feeder can also be shifted to another feeder during peak load, outage period, and on an event like reverse power flow. The load data of these feeders are shown in Table 5.1.

Table 5.1 Load characteristic data

Load type	**Industrial Feeder**	**Residential Feeder**	**Aggregated**
Average demand	1033 kW	930 kW	1963 kW
Maximum demand	4288 kW	2050 kW	5105 kW
Annual energy demand	9718850 kWh	8338764 kWh	18057614 kWh

5.3.3 Feeder Configuration

To determine, the effect of peak demand on the need for investment in the distribution network, the feeders load data for the last six years is studied, which is shown in Fig.5.2 below.

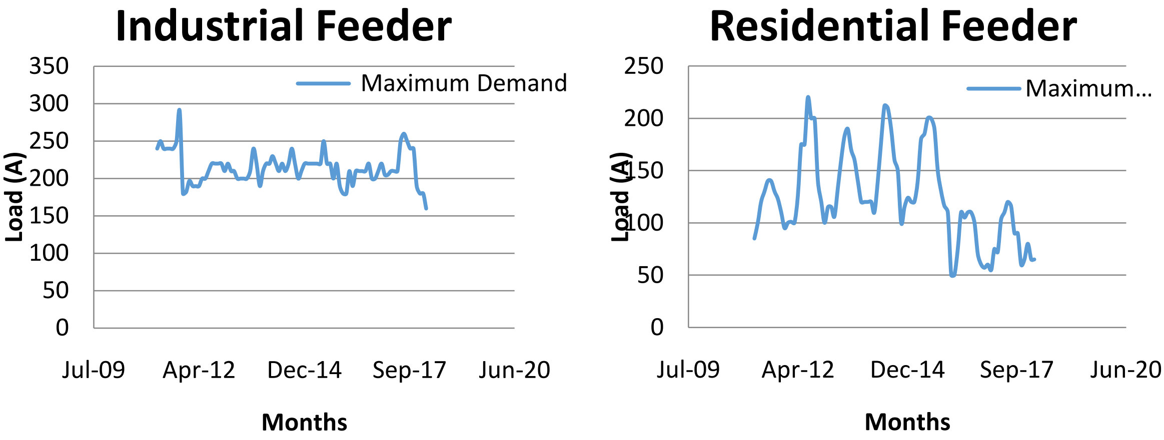

Figure.5.2 Feeder load data

The PSPCL recently invested hefty funds on the augmentation of feeder capacity by bifurcation of the current feeders or by creating parallel circuits. The investment includes the cost of the conductor, 11 kV breaker, poles, insulators, labor, and other accessories, but with the annual 4% growth of connected load [131], the peak demand is still increasing and surpassed the distribution network capacity. Further augmentation in the distribution network is limited due to the financial condition of utility and line congestion in this particular area with an increase in population. The overloaded feeders are resulting in more frequent faults, increased losses, and voltage instability, which reduced the overall reliability of the system. The complete technical configurations of the distribution feeders are shown in Table 5.2.

Table 5.2 Feeders technical configurations

Configuration	**Industrial feeder**	**Residential feeder**
Voltage level	11 kV	11 kV
Length	2.174 KM	1.47 KM
Conductor	ACSR	ACSR
Conductor size	65 mm^2	48 mm^2

Table 5.2 Feeders technical configurations (Continued)

Current capacity	254 Amp	197 Amp
KVA capacity on 11 kV	4839 kVA	3753 kVA
Maximum demand	290 Amp/5518 kVA	220 Amp/4186 kVA
Connected load	9579 kVA	5316 kVA
Peak time	11:15 AM	7:40 PM
Utilization factor	0.477	0.5619
The average cost for laying a new feeder (including conductor, cable, poles, insulators, and other accessories)	$7800/KM	$700/KM
11 kV Circuit breaker 400 Amp	$3570	$3570

The time at which peak load occurs is different for both feeders, thereby there is a possibility to shift demand or generation according to the situation of the grid. The peak demand for industrial feeder coincides with solar generation during weekdays however, on weekends the demand is negligible. On the other side, the load on the residential feeder is comparatively higher on weekends, which makes the combined dispatch of these feeders more economical and flexible than dispatching alone. Solar generation can be effectively utilized with combine dispatch as the excess solar generation can be shifted during a low demand period on a particular feeder.

5.3.4. DER Data

The DER technology selected for this study is solar PV due to favorable weather conditions. For this study, the easily available non-subsidized solar PV panel is selected. There is a lot of variation in the cost of solar panels with different geographical regions and its cost is expected to diminish with technological improvement in the near future.

5.3.5. Reverse Power Flow

The popularity of small scale DER results in their high penetration in a utility network, consequently, on a low demand period, the adverse effects of the reverse power can be noticed. The solar generation export is significantly higher especially on the weekends when there are considerably less demand and reduced solar consumption due to shut down of the industrial load. This reverse power can potentially affect the working of the circuit breakers during the fault period and hence the reliability of the system is at the stake. Moreover, PV continuously generates power in this time and with the insufficient load, the available power is back feed to the grid and causing serious challenges to the grid operator to utilize this generation. Fig.5.3 illustrates the reverse power flow at the solar peak on the weekend of November month, while considering PV penetration of 20% of the connected load.

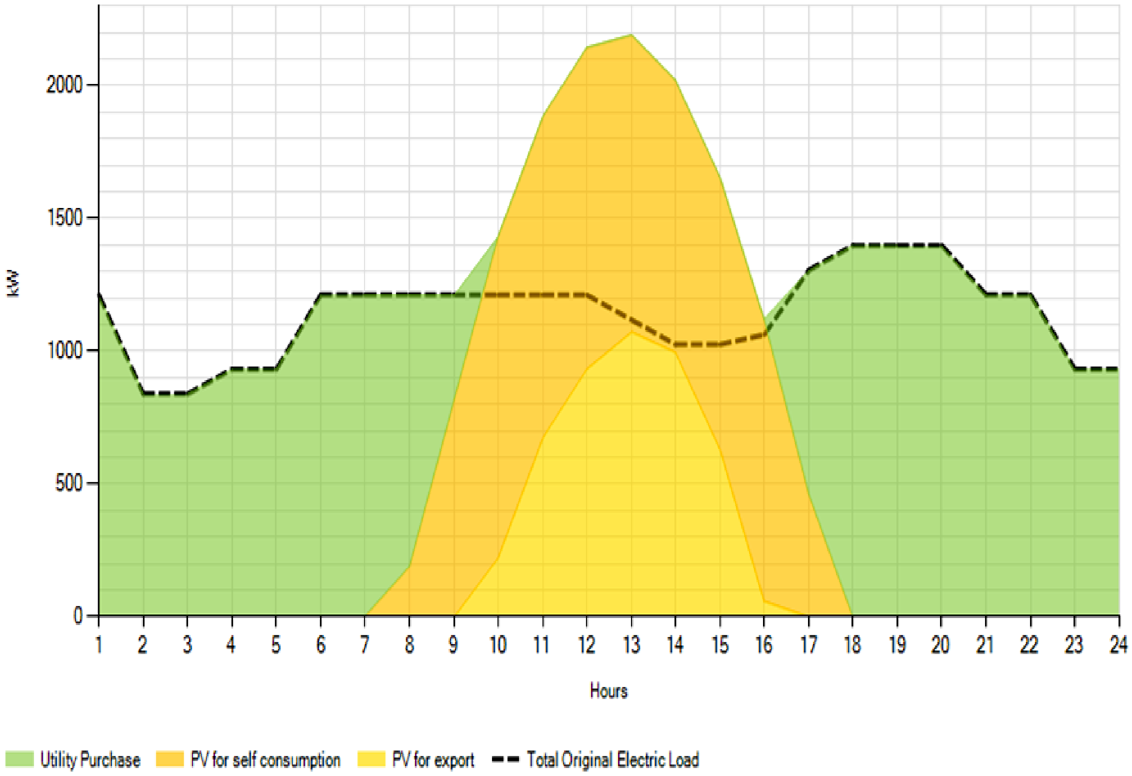

Figure.5.3 Reverse power flow on November weekend

The reverse power flow of 1080 kW is noticed around 1 PM when there is solar peak generation, while there is little demand on the feeders.

5.3.6. Tariff Data

The PSPCL introduces the TOD tariff for peak shaving and flattening the load profile which is also applicable in this study [114]. In this tariff, the demand is curtailed on-peak hours by motivating the consumer to shift their load to a low demand period, which results in the utility investment deferral in capacity augmentation. The export of excess generation from DER causes reverse power flow from the feeders to the substation during the low demand period, especially on the weekend in the winter season. To eliminate this effect, the solar tariff is purposed in this chapter, which is applicable on weekends and provides a rebate on energy tariffs to the consumer to shift their flexible demand to the solar peak generation period. The technical details of this tariff are also given in Table 5.3.

Table 5.3 Solar Tariff

Period	**Time**		**Cost (I$ = 74 INR)**
Summer season June to September	Week	06:00 To 18:00	$0.0907/kWh
		18:00 To 22:00	$0.1220/kWh
		22:00 To 06:00	$0.0907/kWh
	Peak	06:00 To 18:00	$0.0907/kWh
		18:00 To 22:00	$0.1220/kWh
		22:00 To 06:00	$0.0907/kWh
	Weekend	22:00 To 08:00	$0.0907/kWh
		08:00 To 18:00	$0.0713/kWh
		18:00 To 22:00	$0.1220/kWh
Winter season October to April	Week	06:00 To 18:00	$0.0907/kWh
		18:00 To 22:00	$0.0907/kWh
		22:00 To 06:00	$0.0713/kWh
	Peak	06:00 To 18:00	$0.0907/kWh
		18:00 To 22:00	$0.0907/kWh
		22:00 To 06:00	$0.0713/kWh
	Weekend	22:00 To 08:00	$0.0907/kWh
		08:00 To 15:00	$0.0713/kWh
		15:00 To 22:00	$0.0907/kWh

5.3.7. Load Shifting Data

The controllable load can be shifted from high to low demand period or during the solar generation period so that the need for augmentation distribution infrastructure can be deferred. There can be significant savings on electricity bills by the TOD tariff. The potential of load shifting is more in residential feeders than in the case of industrial feeders as the priority of load is low. The various parameters relating to the controllable load are summarized in Table 5.4.

Table 5.4 Controllable load parameters

Feeder	Controllable load(percentage of aggregated load) during peak day	Controllable load(percentage of aggregated load) during the weekday	Controllable load(percentage of aggregated load) during the weekend	Maximum load curtailment during peak hours	Maximum period
Industrial	18%	18%	32%	800 kW	12 hrs
Residential	22%	20%	22%	650 kW	12 hrs

The study considers only load shifting, which can be done through the consumer side voluntarily by changing their consumption pattern and in return, the significant rebates on energy tariff are given by utility to the consumer. The data regarding maximum load and time during, which this load can be scheduled is taken from the feeding substation, which registered average demand variation between the period when the TOD tariff and the normal tariff are enforced.

5.4. Results and Discussion

After running different configurations with DER capacity ranging from 10% to 30% of the connected load in DER-CAM simulation the major results are obtained. From the result analysis, the PV capacity of 1916 kW and 1063 kW is advised for Industrial and Residential feeder respectively. The feeders are interconnected through RMU which makes the load exchange possible during the outage and surplus PV generation period. The peak load of the feeders is reduced significantly with DER installation and with DR programs. The individual electrical dispatch of the feeder during peak load with 20% DER capacity is illustrated in Fig.5.4 and Fig.5.5

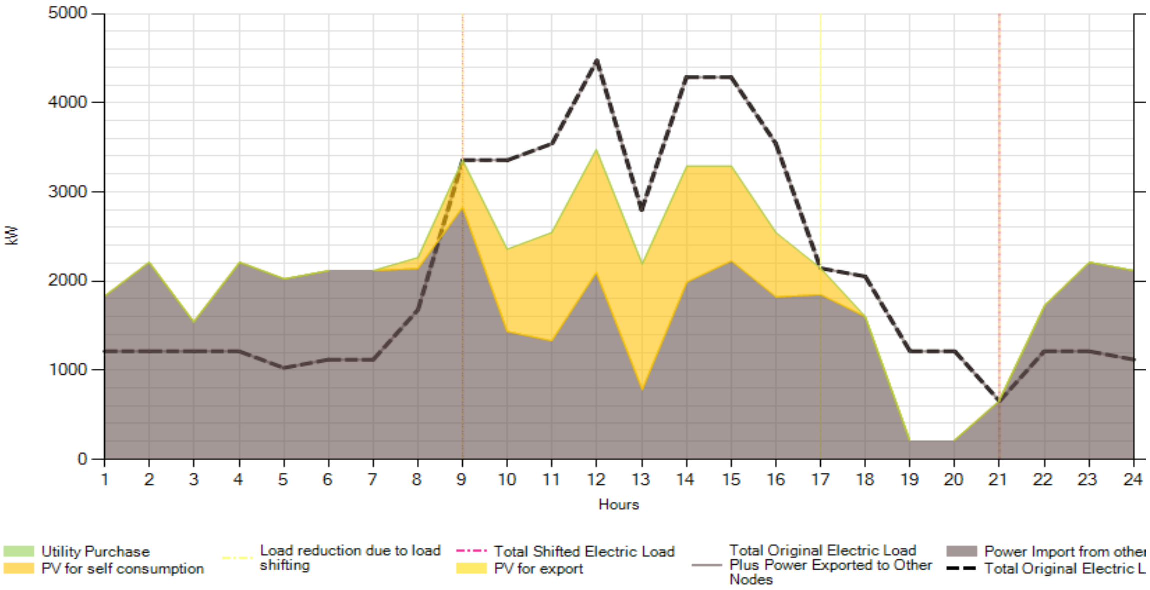

Figure.5.4 Industrial feeder peak load dispatch

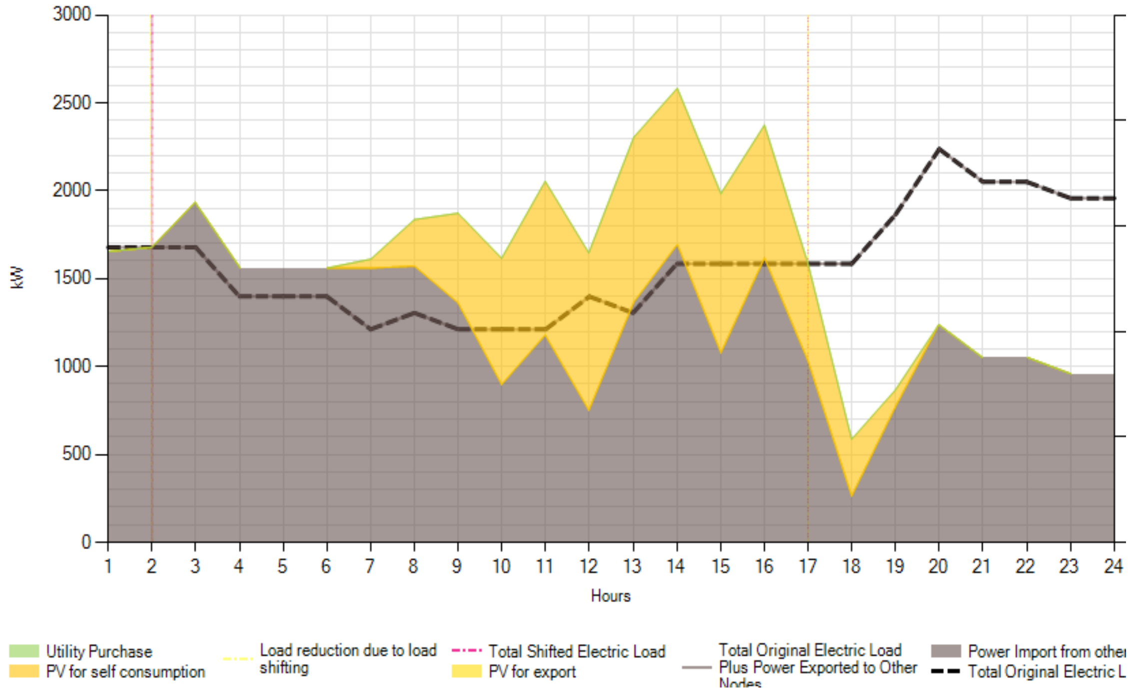

Figure.5.5 Residential load peak load dispatch

5.4.1 VPP Scenarios

The VPP can aggregate the DERs generation and consumer demand profiles, which are located at different positions on the feeder into a single operating profile [132]. The single aggregated profile of the feeders is analyzed for peak load reduction while considering different VPP cases. The detailed comparison of VPP scenarios for November month is discussed below:

5.4.1.1 Scenario 1: Base Case

For setup reference cost of the system, the base case is needed to be run in DER-CAM. In this case, all the DER investment and DR programs are not considered for this simulation. The electrical dispatch of the base case of the peak day of November month is illustrated in Fig.5.6 The feeders are overloaded while dispatching the peak load.

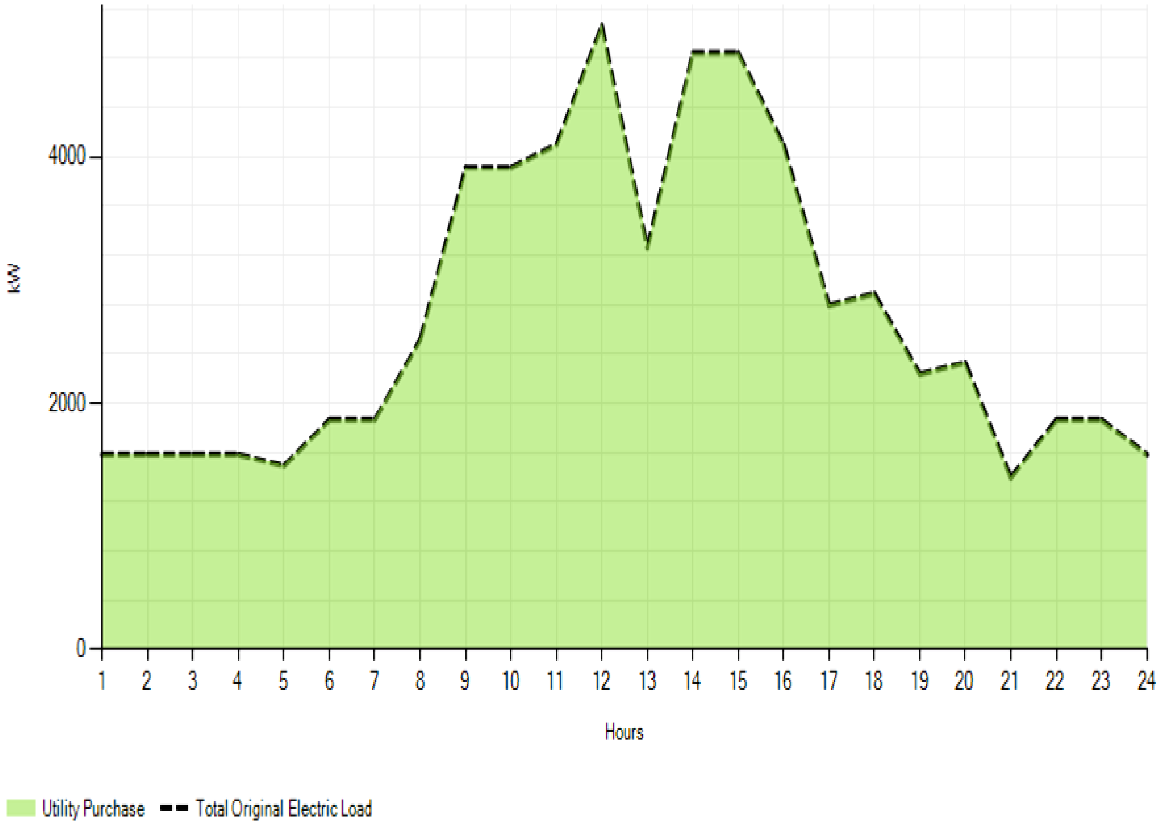

Figure.5.6 Base case electrical dispatch of peak day of November month

5.4.1.2 Scenario 2: Only DER

The investment in DER such as rooftop PV on the consumer place is a viable way to lower the demand on the feeders at the time of peak load. Fig.5.7 illustrates the electrical dispatch of the Peak day of November month, which visualized the DER dispatch for peak load reduction. The export from solar generation during this period is zero as most of the solar generation is consumed by the industrial load.

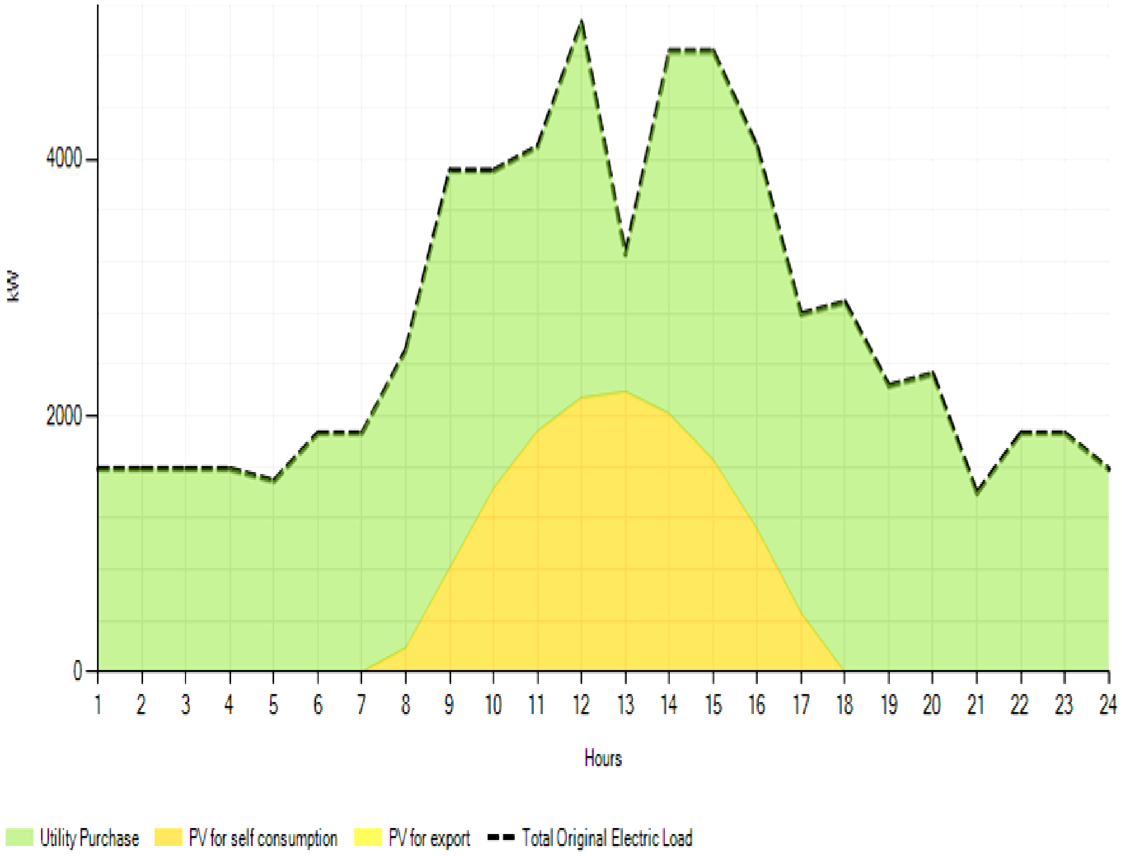

Figure.5.7 DER electrical dispatch of Peak day of November Month

5.4.1.3: *Both DER & DR with TOD Tariff*

To further flatten the load profile and enhancing DER capabilities, the DER and DR are dispatched simultaneously. The DR program based on the TOD tariff effectively reduces the peak demand on the feeders. The DER & DR electrical dispatch is visualized in Fig.5.8 for the Peak day of November month.

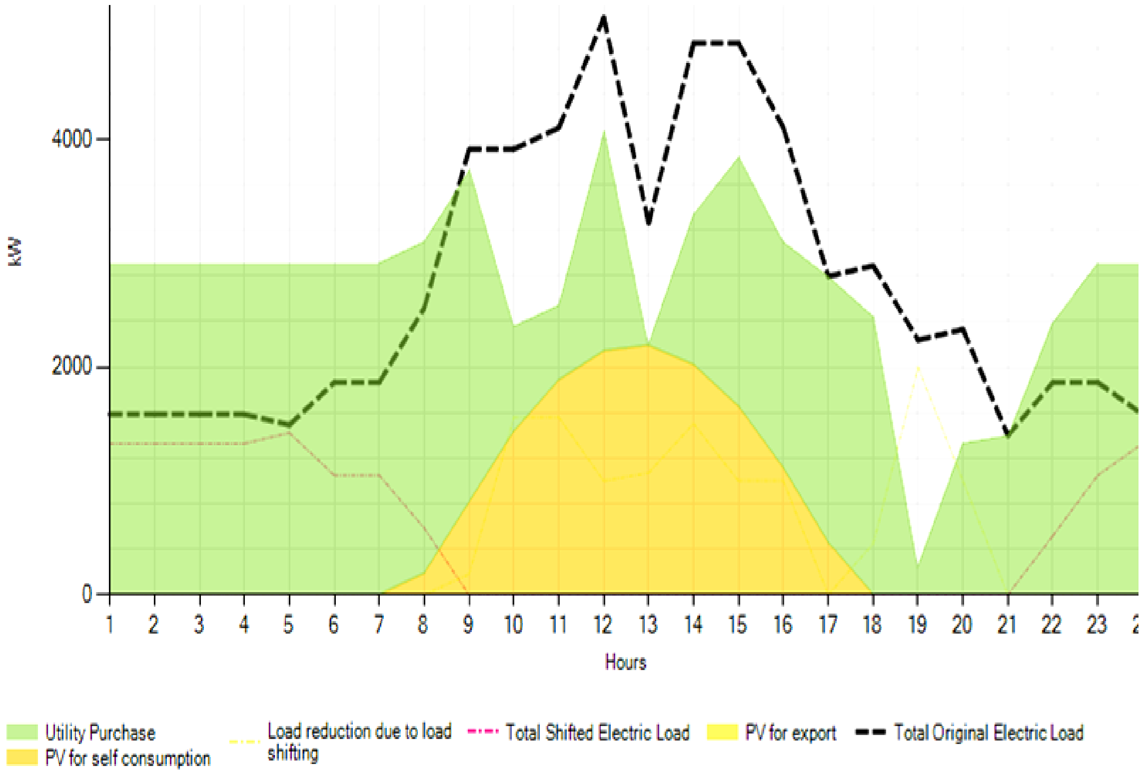

Figure.5.8 DER & DR electrical dispatch of Peak day of November month

5.4.1.4: DER & DR With Solar Tariff

The grid penetration of DER can be an effective solution for a reduction in peak load, but this high penetration can also lead to undesirable consequences like reverse power flow. To limit the PV export to the grid, the load shifting program can be used to schedule the demand from the peak or off-peak period to the solar peak generation period. The special tariff proposed in this chapter refers to the solar tariff, which gives consumer rebates on energy bills using their solar generation, and hence the undesirable effects can be limited during solar peak generation. Fig.5.9 visualizes the electrical dispatch with the solar tariff during solar peak generation on the weekend of November month.

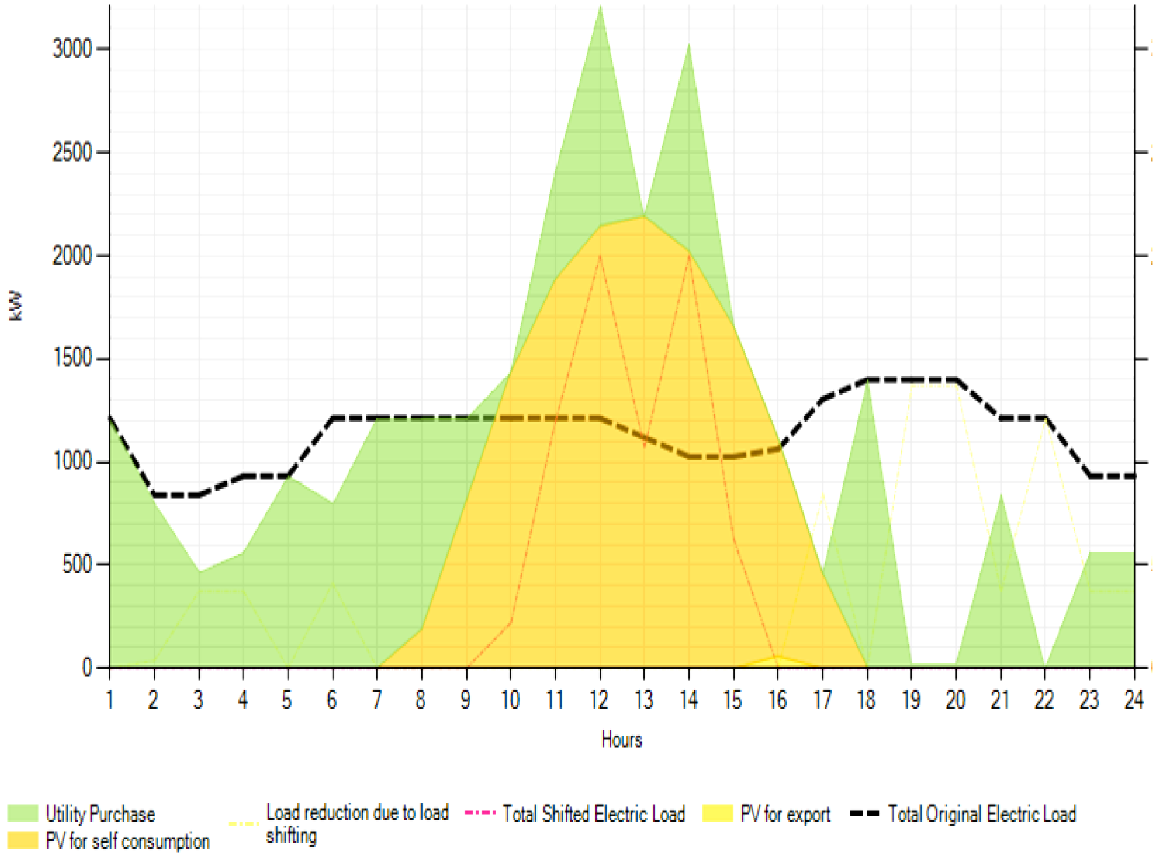

Figure.5.9 Electrical dispatch with the solar tariff of the weekend of November month

The reverse power flow can be eliminated with a solar tariff, which offers lower energy rates for weekends, specifically during the solar peak generation period, and drives the consumer to change their load pattern. In this way, this DR based solar tariff is more effective in comparison with other methods for tackling reverse power flow in the grid. It also is noticed that with DR based on a simple TOD tariff can even increase the reverse power flow in comparison to dispatch without DR, due to the low energy rates during nighttime.

5.4.2 Techno-Economic Assessment

The topology of the VPP is illustrated in Fig.5.10 below. The aggregated capacity of solar PV selected for evaluation is 2979 kW. The electrical dispatch with VPP shows that peak load is significantly reduced by 37.25% and 42.78% with DER and combined DER & DR respectively. The energy exported from PV for electricity sales is found the maximum in the case of DER and DR as there is low demand on the feeder with the shifting of load on the off-peak hours. The peak load of the Industrial and Residential feeder reduced to 45% and 53% of their original value respectively and hence the current is now flowing within the limits of the feeder capacity. With the load shifting based on the solar tariff, the energy consumption of PV is increasing and this reduced the energy export to the grid largely. The most economical scenario of the VPP is found to be the combined scheduling of DER and DR, but at the same time, the marginal cost increase can be allowed to limit the reverse power flow by utilizing solar tariffs. The solar tariff also reduced the grid import and ultimately reduced the total electricity cost of the system including demand charges.

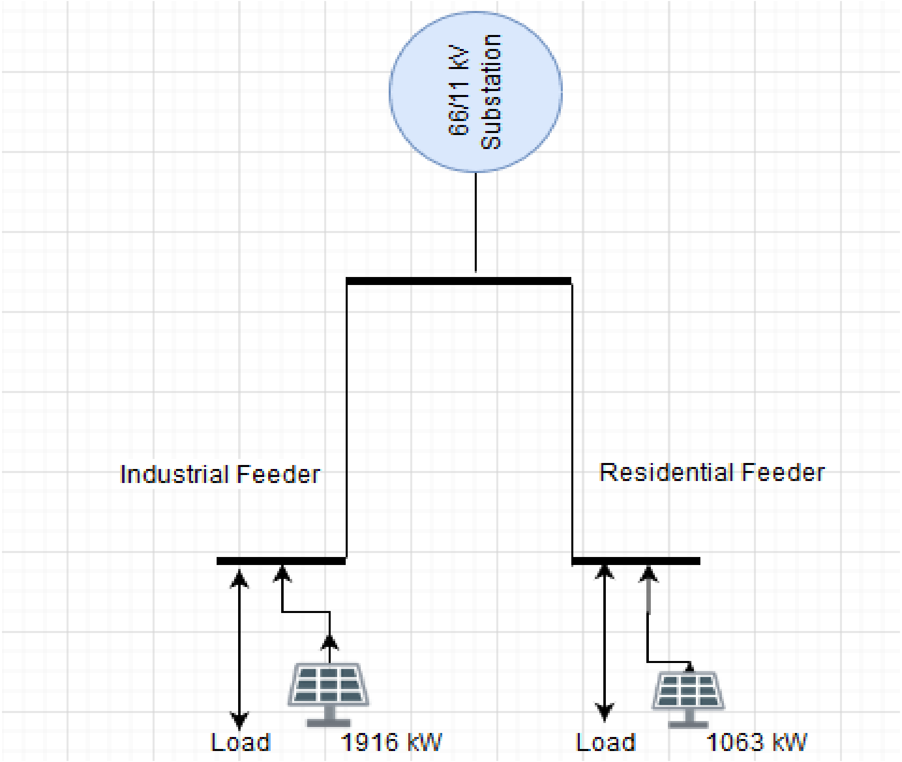

Figure.5.10 Topology of the VPP

The results of the Techno-economic assessment are tabulated in Table 5.5.

Table 5.5 Techno-economic assessment

	Aggregated profile			
	Base case: no investment	**Only DER**	**DER and DR with TOD tariff**	**DER & DR with solar tariff**
PV rating	-	2979 kW	2979 kW	2979 kW
Peak load	5105 kW	3203 kW	2921 kW	2921 kW
Reverse power flow (during solar peak generation on weekend)	-	1080 kW	2200 kW	0 kW
Electricity sales from PV	-	25676 kWh	50849 kWh	8627 kWh
Total annual energy costs	$2171000	$1374000	$1289000	$1300000
Annual savings	-	$797000	$882000	$871000
Optimized operational cost	$2171000	$1231000	$1171000	$1144000
Operational saving	-	44%	48%	48%
Total savings	-	36.7%	40.63%	40.12%
Total electric costs Including volumetric and demand charges	$2171000	$1194976	$1134871	$1103627
Total annual electricity purchase	18057614 kWh	12766092 kWh	13008441 kWh	12543855 kWh

The above results depict the financial benefits through the implementation of the VPP concept, the renewable penetration of 20% of the total connected load of the feeder is considered. At this DER grid integration level, a substantial amount of power is dispatched through the VPP especially in the industrial feeder, where the peak load is coinciding with the solar peak generation. This power dispatched by the PV directly influences the annual energy and operational cost. The DR program is also helping to flatten the load profile and provides a more appropriate environment for DER penetration in the grid. The challenge of reverse power flow due to the increased share of grid integrated DERs is also addressed by the DR through the specifically designed solar tariff. It encourages the consumer to shift their demand in the solar peak generation period through the rebates in the energy tariff. Overall, the combined dispatch of the DER and DR as VPP brings the energy cost significantly down to emerge as an attractive option for both utility and consumer.

5.5. Utility Investment Deferral

With the peak load reduction by DER investment and DR programs, the utility investment in augmentation of distribution networks can be deferred. The investment includes the cost of conductor, insulator, labour and other accessories, etc. The limited space for laying new feeders is also the technical constraint imposed on utility for further construction of distribution networks specifically in the city areas. The estimated utility investment deferral for both feeders on the account of bifurcation or laying of the new feeder is shown in Table 5.6.

Table 5.6 Utility investment deferral

Industrial feeder	No.	Cost of replacement
Conductor overloaded	1.3 km	$1250
11kV Circuit breaker 400 Amp	1	$3570
Auxiliary materials and labor charges		$24000
Residential feeder		
Conductor overloaded	0.6 km	$3420
11kV Circuit breaker 400 Amp	1	$3570
Auxiliary material and labor charges		$11076
	Total investment deferral	$46886

This network deferral is not only aided the utility's financial condition but also helps in the congestion management in the area, where there is limited space for new construction. These savings also compensate for the revenue loss of the utility due to less import of grid energy.

5.6. Comparison of Results with Homer Pro

HOMER Energy is a well-known simulation tool for designing microgrids and can be used for the economic analysis of VPP. In contrast to the DER-CAM model, the peak load profile is not utilized in the HOMER Pro software. The same data that was entered in DER-CAM is now fed into HOMER pro and the particular configuration with 20% DER investment without DR is simulated. The optimization results of HOMER software annually are tabulated below in Table 5.7.

Table 5.7 HOMER optimized cost

Component	Capital Cost	O & M Cost	Total
Grid	$0.00	$10,87,440	$10,87,440
Industrial feeder PV	$1,08,381	$1,34,120	$2,42,501
Industrial feeder PV Dedicated Converter	$31,125	$0.00	$31,125
Residential feeder PV	$60,130	$74,410	$1,34,540
Residential feeder PV Dedicated Converter	$17,119	$0.00	$17,119
System	$2,16,756	$12,95,970	$15,12,726

The annual cost of energy including capital and operational costs is increased to 10% with HOMER optimization, which shows that DER-CAM optimization is not only more versatile but also cost-effective at the same time. Moreover, the DER-CAM is sophisticated software that comprehensively includes the utility parameters such as fixed charges, TOD tariff, and other technical parameters, which are not in the case of HOMER. The DER-CAM also includes the reliability parameters such as reliability indices and scheduled/ unscheduled outages to accurately model the VPP in case of grid unavailability.

5.7. End remarks

The overall results indicated that DER investment is a viable solution for peak load reduction, which does not only reduce consumer demand charges and volumetric charges but also defer the utility investment for network augmentation. The combined dispatch of DER and DR further enhance this functionality and made it possible to increase the PV capacity for penetration into the grid. From the demand profile of the industrial feeder, it is observed that the peak load of the feeder coincides with the solar peak generation and is found to be an effective way to flatten the demand profile while aggregating with residential feeder load.

It is also observed that the cost of energy is reduced with PV consumption, but the negative consequences like reverse power flow to the grid during the low demand period are present under VPP. This reverse power flow can be eliminated by replacing the current TOD tariff with the solar tariff while compromising a slight decline in annual savings. The peak load reduction results in a reduction in the loading of the feeder, which can help the utility to defer the investment in the laying of the new feeder or bifurcation of present feeders. The results obtained from DER-CAM are compared with HOMER optimization with the same data and it is found that DER-CAM results are more cost-effective which makes it preferable over HOMER while designing microgrid or VPP.

5.8. Summary

The chief purpose of this research is to find an effective way to securely dispatch the electricity demand with high penetration of DER through coordination and scheduling of small DER and DR. The VPP applications describe in previous studies are limited to the commercial aspect of the energy system, whereas in this chapter both technical and commercial points of VPP are considered. In this study, the potential of VPP is investigated in PSPCL, which is facing high penetration of solar-based DER. The numbers of configurations are simulated in DER-CAM and the optimal solution with the least annualized energy cost is determined. The utility peak load is also reduced significantly by dispatching DER with flexible load simultaneously and provides a monetary benefit to both utility and consumer. In this study, to limit the initial capital investments and other technical constraints, the DER capacity is limited to 20% of the consumer connected load. The VPP implementation declined the operational cost by 44% and results in total savings of 36.70 % through DER investment. The peak load is also reduced by 37.25%, which defer the need for replacement of the feeder conductor. These results are improved further by the implementation of the DR program such as load shifting, which reduces operational cost by 48% and results in total savings of 40.63%. Furthermore, the peak demand is reduced to the lowest value by 42.78% with the combined dispatch of DER and DR. The undesirable effects of high penetration of PV such as reverse power flow can be eliminated to the large extent by the implementation of solar tariff while compromising the minor reduction in total saving.

For the secure and efficient operation of grid-connected PV, the PSPCL needs some amendments in their current policy. There should be a cap on the maximum grid-connected capacity of solar PV such that it can limit reverse power flow. The utility instead of investing a large number of funds on the central power plants such as thermal plants and its long transmission network, should invest in the installation of small scale DER on the consumer premises with long-term contracts and develop distribution infrastructure to support its operation. These investments compensate for the utility revenue loss and create the revenue stream in the long run.

CHAPTER-6

GENERAL VIRTUAL POWER PLANT MODELLING

6.1 Introduction

6.1.1 VPP Concept

The modernization of the present grid infrastructure through the implementation of smart grid technologies is now one of the top priorities of various nations of the world. In the last decade, the biggest change that the current distribution network had witnessed is the introduction of the VPP. The VPP is the big forward step taken in the path of the sustainable and robust energy future through its efficient and autonomous operation[6], [112]. The core components of the VPP include Grid interconnected DER, Energy Storage System (ESS), flexible loads, and communication technologies [3]. In VPP, the DERs of small rating and having a low starting period such as solar PV, wind, and gas turbines are utilized. Nowadays these DERs are installed at consumer premises and their generation is aggregated, in such a way that their small rating gets visible to the grid operator as a central power generator. Most of the DERs are utilized in the VPP are renewable ones so, to tackle the intermittent generation issues, the ESS could be an effective way to suppress the variation in their generation and provides dispatchable generation[29]. Another distinctive feature of the VPP is the load following[66], [128], in which certain conditions, the flexible load can be used to follow the intermittent renewable generation through the Demand Side Management (DSM) programs [18], [73], [118], [131][113]. The continuous interaction of the different components of the VPP and the grid is only possible through the Information technologies, which provide real-time data to the grid operator to decide while the dispatching and scheduling of energy[67], [69], [114],.

6.1.2 Literature Gap and Contributions

Most of the reported literature is concerned with the VPP scheduling for cost minimization from the consumer point of view. The positive influence of the VPP on the reliability enhancement and peak shaving has not been taken into account by any reported study. Moreover, with our best knowledge, the autonomous operation of VPP during an outage is still not studied. In addition to that, the optimization of the multi-objective model of VPP with the Particle Swarm Optimization (PSO) algorithm is still missing.

The prime objective of the chapter is to fill the research gap and to propose the novel application of the VPP in enhancing the distribution network reliability with its autonomous operation. In this chapter, a multi-objective VPP model is designed with the objective of cost minimization, peak load reduction, and reliability enhancement while considering both VPP grid-connected and autonomous operation. The modified PSO algorithm is utilized in this research for the optimization of the VPP dispatch strategy while considering benefits and constraints from both utility and consumer point of view. A real-time case study of 90 bus Industrial feeder is selected for the evaluation of the proposed VPP model implementation.

6.2. Case Study

The PSPCL, a government-owned power utility, has been studied for feasibility analysis of the solar grid-based VPP [9]. The PSPCL having a monopoly in the power sector of the state of Punjab (India), however, due to full government control it puts continuous efforts into achieving a sustainable energy future. The company introduces numerous schemes to motivate the consumers to install the grid-connected small scale DERs such as roof-top PV on the premises[118]. The benefits of installing the multiple DERs at different locations are not limited to the consumer, but also for the utility in reliability improvement and peak load shaving. There are limited studies of the VPP application is available for the industrial feeder, so in this case study, an industrial feeder has been taken to analyze the implications of the VPP in techno-economic terms. The VPP illustrated in Fig.6.1 below is based on the 90-bus feeder model, which is designed in ETAP, in which the feeder length is divided into different sections depending upon the location of reclosers. A typical section of the feeder includes the overhead ACSR conductor, a distribution transformer, a lumped load, and aggregated solar PV with a controllable switch. The recloser is also installed at various points of the main length of the feeder for the isolation and autonomous operation of the remaining feeder. In grid-connected mode, the combined solar generation is dispatched with the motive of peak load reduction and reduced utility imports.

However, in order to enhance the reliability, the VPP can be operated in autonomous mode, which fed the load of the particular section of the feeder, while isolating the faulty section of the line with reclosers.

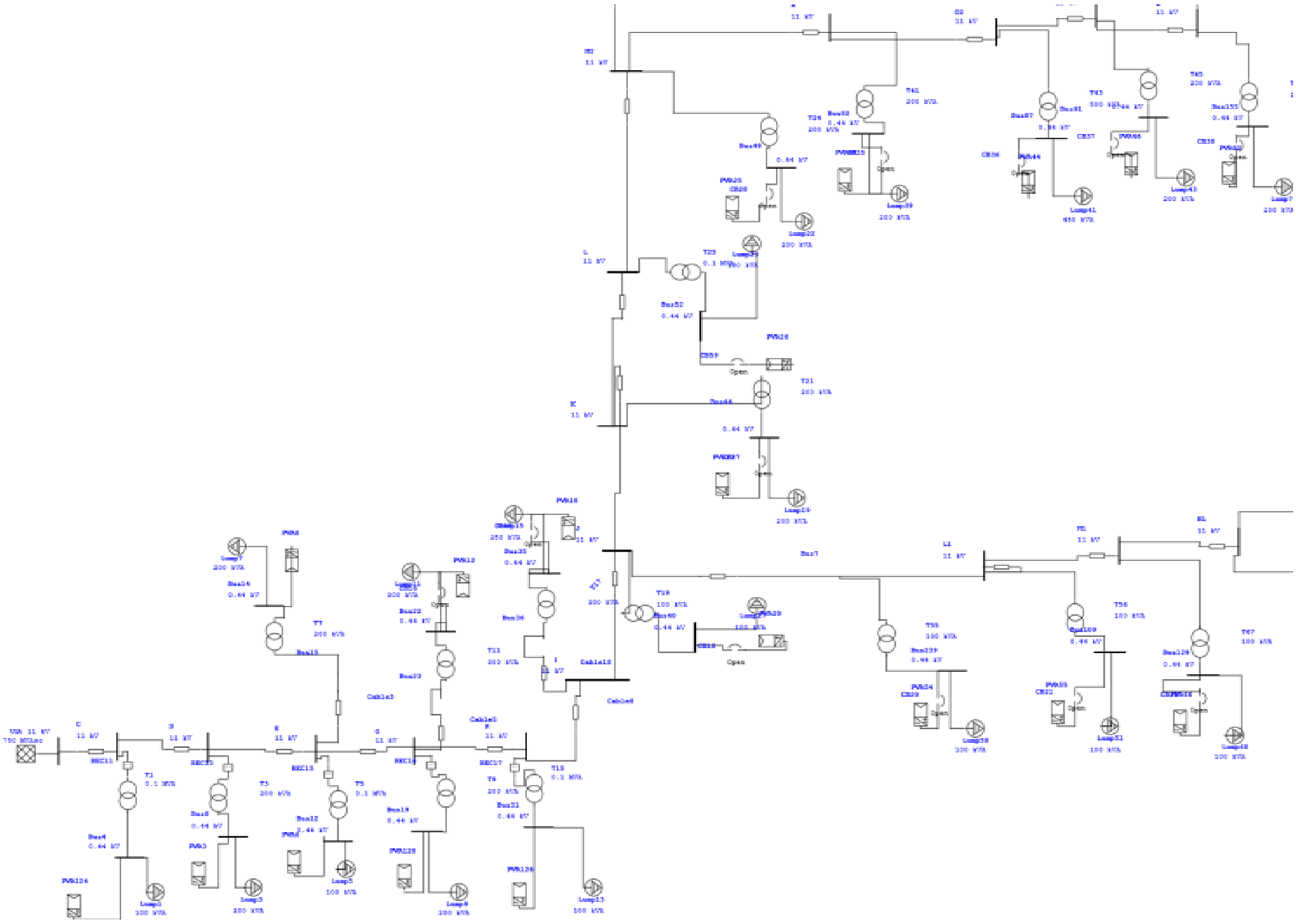

Figure 6.1 90 Bus Industrial feeder

The real-time data of PV generation and demand has been taken from the smart meter installed at a distribution transformer and consumer premises. The study is classified into two operating modes (Grid connected and Autonomous) and further these modes are categorized into three different cases, which are as follows:

1. Base case with DER.
2. Base case with DER and DR.
3. Base case with DER, DR, and Storage.

6.3 VPP Modelling

The individual mathematical modelling of the various components of the VPP is as follows:

6.3.1 Solar PV

It is one of the widely popular DER as most of the regions around the world receiving sufficient solar radiation. The PV technology used in the study is cadmium telluride with a lifetime of 20 years. The solar panel is assumed to install at every industrial consumer and its maximum aggregated capacity is capped to 1916 kW in the feeder. The output of the solar PV is given as:

$$PV_{eo} = A * \eta * N * S_t \ \forall t \in T \qquad (1)$$

η = Efficiency of a solar panel (14.9%)

S_t = Solar irradiation (800 W/m^2)

t = Timestep

N = Number of solar panels connected either in series or parallel

A = Area occupied by solar panels

PV_{eo} = Estimated output of solar PV

It is assumed that the PV panels are fully reliable and integrated with an inverter of the same rating. The maximum grid integrated capacity of PV is capped to 20% of transformer capacity due to safety constraints. The average daily PV generation for the month of November is shown in Fig.6.2 below:

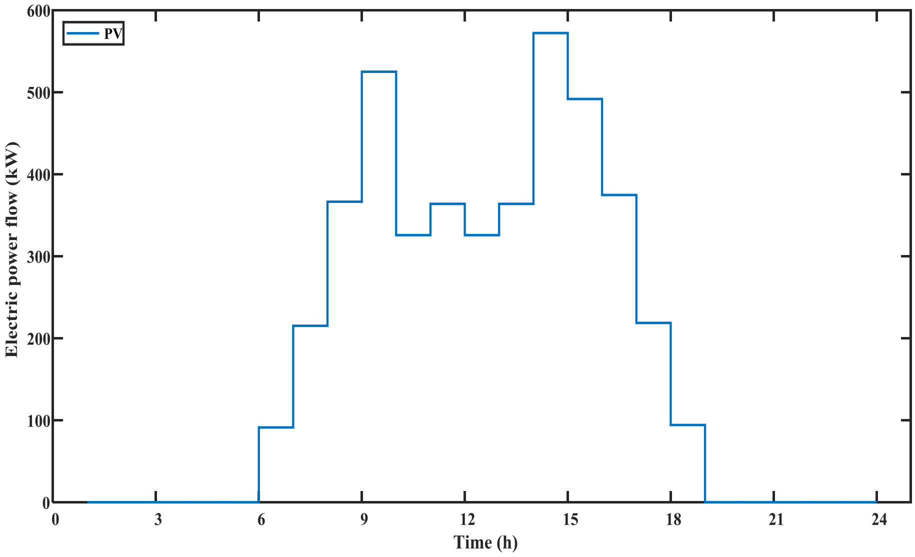

Figure 6.2 Average daily PV generation

The solar radiations are varying with different seasons and cloud movements, which have a direct influence on the PV output. The average solar radiations received by the study area are abundant in comparison of the world average as its location proximate to the equator. The average solar radiation and clearness index data is illustrated below in Fig.6.3.

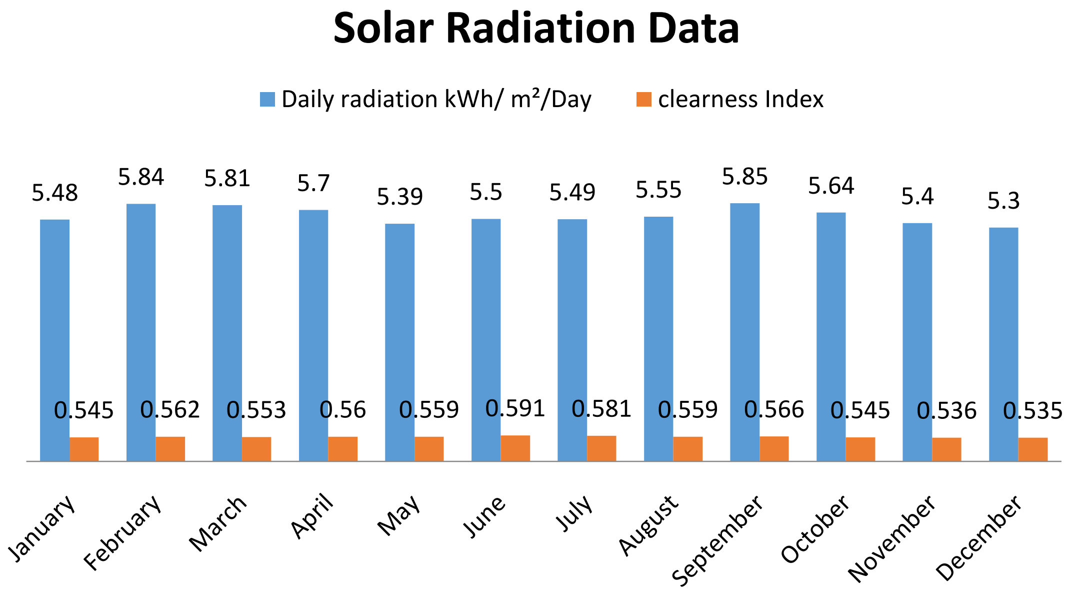

Figure 6.3 Average solar radiation and clearness index

The radiations are maximum in the month of September, however, the clearness index also influences the PV generation during that period.

6.3.2 Battery

The renewable-based DERs usually having highly fluctuated and time-dependent generation, which needs storage technology like batteries to smooth its output variations. It stores the excess energy in a low demand period and releases this stored energy during high demand or low generation period. The operational cost of the battery is given as:

$$\mathrm{P}_{\mathrm{t}}^{\mathrm{bat}} = \mathrm{m}_{\mathrm{t}}^{\mathrm{bat}} * \mathrm{E}_{\mathrm{t}}^{\mathrm{bat}} + \mathrm{d}_{\mathrm{t}}^{\mathrm{bat}} * \mathrm{E}_{\mathrm{t}}^{\mathrm{bat}} + \mathrm{E}_{\mathrm{t}}^{\mathrm{bat}} * \mathrm{pol}_{\mathrm{t}}^{\mathrm{bat}} \ \forall\, \mathrm{t} \in \mathrm{T} \tag{2}$$

$\mathrm{P}_{\mathrm{t}}^{\mathrm{bat}}$ = Operational price of battery in dispatch

$\mathrm{m}_{\mathrm{t}}^{\mathrm{bat}}$ = maintenance coefficient of battery

$\mathrm{E}_{\mathrm{t}}^{\mathrm{bat}}$ = Discharging or recharging of the battery

$\mathrm{d}_{\mathrm{t}}^{\mathrm{bat}}$ = Depreciation coefficient of the battery

$\mathrm{pol}_{\mathrm{t}}^{\mathrm{bat}}$ = Pollution coefficient of the treatment cost

t = Timestep

The battery capacity is taken as 9500 kWh and with a lifetime of 5 years. The battery charging and discharging efficiency is 90%.

6.3.3. Loads

The load is supplied up from SCADA controlled 66/11kV step-down substation that is located within the boundary of the division. In this research, the 11 kV Industrial feeder on which the DERs are installed is selected for load assessment. The feeder's load profile is aggregated into a single operating profile and analyzed for different cases. The modeling of the load is as follows:

$$Load_t = Flex_t + Intrr_t + Emg_t \ \forall\, t \in T \tag{3}$$

$\boldsymbol{Load_t}$ = Total demand on the feeder

$Flex_t$ = Schedulable demand

$Intrr_t$ = Non Schedulable demand

Emg_t = Emergency demand

t = Timestep

The flexible load can be shifted from peak time to off-peak period, whereas the non-flexible demand cannot be scheduled to any other time of day. The emergency demand, which includes high priority loads, is needed to supply at any cost even during a grid outage. The loading and reliability parameters of the industrial feeder are tabulated in Table 6.1.

Table 6.1 PSPCL Load and Reliability data

Industrial Feeder

Loading Parameters		**Reliability Parameters**	
Average demand	1033 kW	No. of Transformers	47
Peak demand	4288 kW	Transformer failure rate/yr	0.15
Annual energy demand	9718850 kWh	Transformer Mean time to repair	0.5 hr
Peak month	November	No. of sectional lines	41
Total consumers	257	Sectional lines Failure rate/yr	0.5

Table 6.1 PSPCL Load and Reliability data (Continued)

Length	2.174 KM	Sectional lines Mean time to repair	1.5 hr
Current capacity	254 Amp	No. of substations	1
kVA capacity on 11kV	4839 kVA	Substation failure rate/yr	0.6
Maximum demand	290 Amp/5518 kVA	Substation Mean time to repair	4 hr

6.3.4. Main Grid

The PSPCL 11 kV distribution network with grid integrated DERs allows both energy import and energy export at different points of the feeder. The net-metering policy makes effective PV utilization possible both with and without the battery storage through the application of smart meter at prosumer premises. The net metering policy and the TOD tariff are utilized for flattening the load profile and the same is used for this study 2018-19 [114]. The main purpose of this tariff is to reduce the load in peak hours by encouraging consumers to shift their load from on-peak to off-peak hours, which ultimately deferred the utility investment in the generation and distribution capacity. The main features of this tariff are shown in Table 6.2.

Table 6.2 PSPCL TOD tariff

Period	**Time**	**Cost/kWh (I$= 74 INR)**
1-4-18 to 31-5-18	06:00 AM To 06:00 PM	$0.0907
	06:00PM To 10:00 PM	
	10:00 PM To 06:00 AM	$0.0713
1-6-18 To 30-9-18	06:00 AM To 06:00 PM	$0.0907
	06:00PM To 10:00 PM	$0.1220
	10:00 PM To 06:00 AM	$0.0907
1-10-18 To 31-3-18	06:00 AM To 06:00 PM	$0.0907
	06:00PM To 10:00 PM	

The equations showing the import and export prices of electricity of the PSPCL :

- $C_{Imp,t}^{VPP} = ToD\left(C_{Imp,t}^{Pspcl}\right)\forall t\epsilon T$ Purchasing cost of energy from the PSPCL (4)
- $C_{Exp,t}^{VPP} = ToD\ (C_{Exp,t}^{Pspcl})\ \forall t\epsilon T$ Selling cost of energy to the PSPCL (5)

The rates for energy import and export are the same, but there is an annual cap on the maximum generation and energy export. The variation in the cost of energy at various time intervals is shown in Fig.6.4

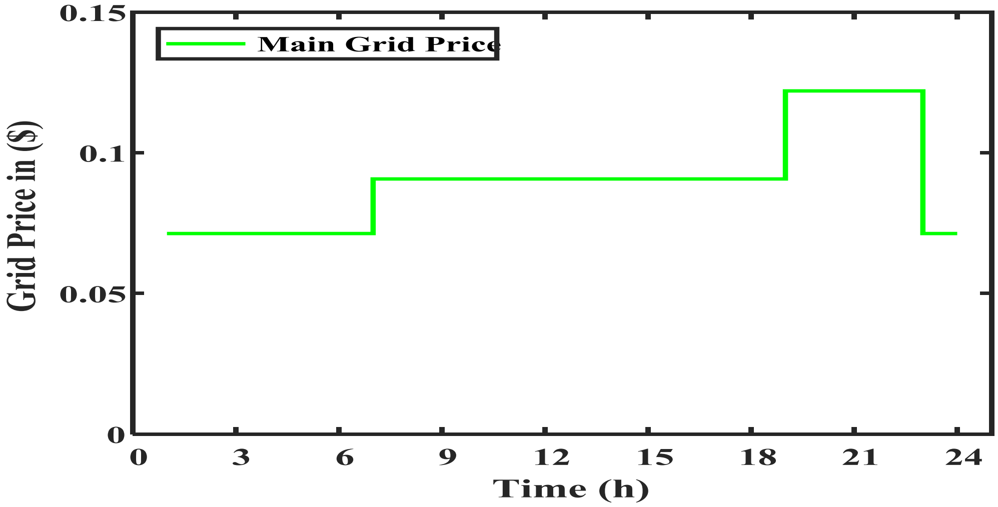

Figure 6.4 Grid price variation

The price variation is based on the different seasons and government policies on consumption and generation patterns.

6.4 Objective Function and Constraints

The objective function of the designed model has three main motives: meet the electrical demand with the least cost, reduce the maximum demand, and enhance the system reliability. In this designed model, the VPP dispatch the various resources according to the minimal cost and its availability.

The objective function of the study is:

$$C_t^{VPP} = C_t^{PV} + C_t^{Batt} + C_t^{Grid} + C_t^{EENS} \tag{6}$$

The eq. (6) above shows the total cost of the VPP which is needed to minimize and it includes the cost of dispatch with PV, batteries, grid, and cost incurred due to Expected Energy Not Supplied (EENS). The factors, which affect the battery and PV output:

$\mathrm{DisR}_t^{\mathrm{bat}}$ = Discharging rate of the battery

$\mathrm{ChrR}_t^{\mathrm{bat}}$ = Charging rate of the battery

$\mathrm{TotCap}_t^{\mathrm{bat}}$ = Total capacity of the battery

$\mathrm{Cap}_t^{\mathrm{bat}}$ = Initial capacity of the battery

$Max\mathrm{S}$ = Maximum rating of solar PV

NS = Number of units of solar PV installed

$Max\ H$ = Maximum annual operation hours for PV technology

The constraints for this objective function are as follows:

- $Load_t = \Sigma\, PV_{eo} + U_{Loadt}^{Imp} + \Sigma \mathrm{TotCap}_t^{\mathrm{bat}}$ [kW] (7)
- $\mathrm{DisR}_t^{\mathrm{bat}} = (\ \mathrm{TotCap}_t^{\mathrm{bat}} /12)*((\ \mathrm{Cap}_t^{\mathrm{bat}} /\ \mathrm{TotCap}_t^{\mathrm{bat}}\ )\ \hat{}\ .5)$ (8)
- $\mathrm{ChrR}_t^{\mathrm{bat}} = (\mathrm{DisR}_t^{\mathrm{bat}} - (\ \mathrm{TotCap}_t^{\mathrm{bat}} /10)\ \ )$ (9)
- $\Sigma\, (\Sigma\, PV_{eo} + U_{Loadt}^{Exp}) \leq \mathrm{NS} \cdot Max\mathrm{S} \cdot MaxH$ [kW] (10)
- $EENS = Load_t - Flex_t - Intrr_t - PV_{eo} - \mathrm{TotCap}_t^{\mathrm{bat}}$ (11)

- The eq. (7) shows balancing between load and PV generation/ utility imports.
- The eq. (8) shows the discharge rate of the battery, which depends on the initial capacity and total capacity of the battery.
- The eq. (9) gives the rate of charging, which is based on the discharging rate and total capacity of the battery.
- The eq. (10) shows maximum PV generation constraint which depends on the number of PV panels and their operating duration.
- The eq. (11) computes EENS during the fault period after utilizing the output from PV, battery, and DR.

Assumptions:

- PV Capacity ≤ 20% of Transformer Capacity
- PV Capacity ≤ 80% of Connected Load
- Battery Maximum Discharge Capacity ≤ 20% of Battery
- The initial capacity of the battery = 500 kWh

6.5 PSO and Dispatch Strategy

The PSO well-known optimization technique which is utilized in numerous optimization problems, which is initially introduced by Kennedy in 1995. It was the simplest version of PSO which is later modified by shi by adding a new parameter inertia weight. Undoubtedly, the effectiveness of this optimization is un-matching, however with inclusions of different variables and constraints, the resultant convergence time is too long [134], [135]. Further, the modification of the Kennedy PSO version is done by limiting the search area by concerning VPP constraints, which keeps its simplicity and results in less convergence time. The three major global variables of the PSO algorithm are:

1) Gbest of each particle

2) Target objective

3) Stopping criteria.

To limit the search space, the information is taken from an experienced member's memories of the swarm and by eliminating the search in the worst places. The flowchart of the PSO algorithm is illustrated in Fig.6.5 below:

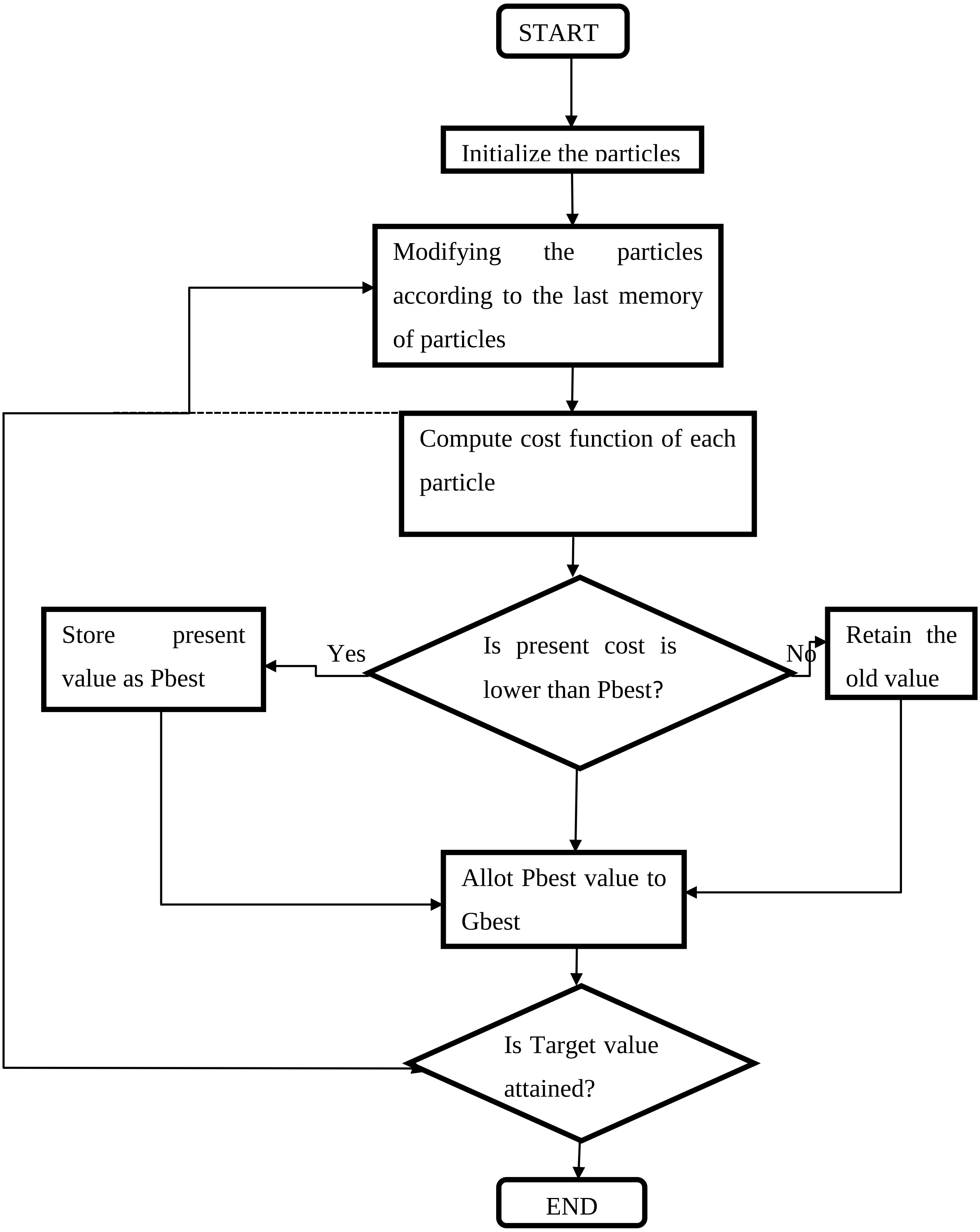

Figure 6.5 PSO algorithm

The size for the population is taken as 25 with learning and the weighting factor is 2 and 0.7 respectively. In the initial step, the technical parameters are defined and generation from the various grid-connected PVs is computed after aggregation. The excess PV generation is used to charge the battery, which further supplies the emergency load during grid outage after shifting or curtailing the low priority demand. On the other hand, in grid-connected operation, the load is dispatched through the grid after utilizing the PV generation. The step-wise workflow of the study is illustrated in Fig.6.6 below

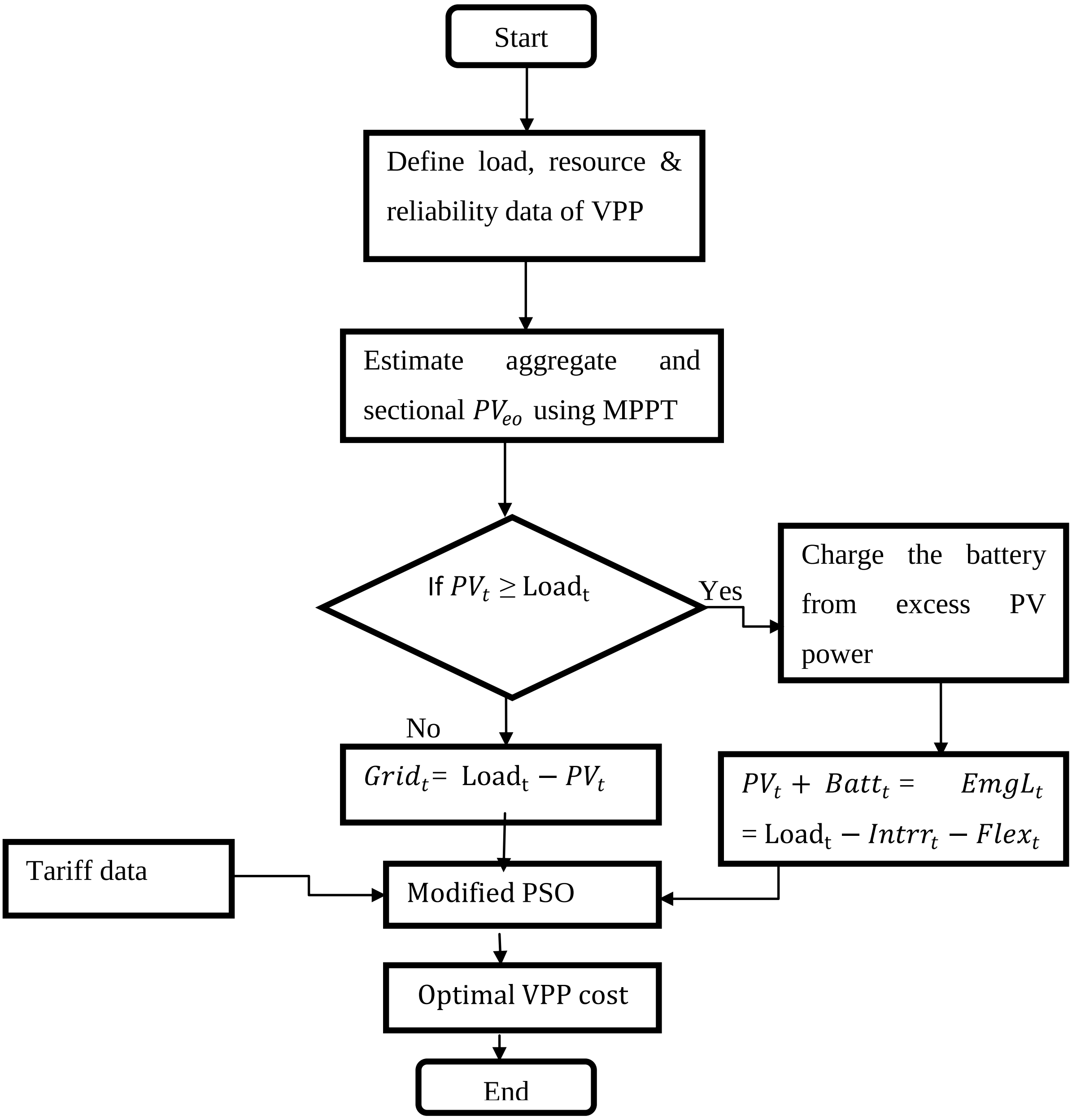

Figure 6.6 Dispatch Strategy of VPP

The economical parameters such as cost of energy and demand charges are fed with technical parameters in the modified PSO for optimal scheduling to minimizing the energy cost.

6.5 Results and Discussions

For the techno-economic analysis; the case study is classified into four separate cases and compared with both technical and financial parameters. In the base case, there is no investment is considered and electrical dispatch is only through the utility grid, which is unreliable and expensive. With the inclusion of DER, the part of the demand is dispatched through PV generation, and the remaining PV output is exported to the grid during low demand. The DER integration declines the operational cost by 11.17 % and EENS of the typical section by 68.66 % in comparison to the base case. The implementation of DR further enhances the effectiveness of the VPP by reducing the operational and loss of load cost. Finally, the best scenario is found to be with the addition of the battery storage, in this case, the operation cost of the VPP is reduced by 31.57 %. The reliability is also increased with the reduction of the EENS and its related loss of load cost by 62.30 %. The detailed VPP techno-economic analysis is tabulated in Table 6.3 below:

Table 6.3 VPP Techno-economic analysis

	Base case	**With DER**	**With DER & DR**	**With DER, DR & Storage**
PV capacity	-	1916 kW	1916 kW	1916 kW
Battery capacity	-	-	-	9511 kWh
Annual savings	$0	$367	$402	$1028
Optimized operational cost	$3284	$2917	$2882	$2247

Table 6.3 VPP Techno-economic analysis (Continued)

Total electricity import	6413 kWh	32085 kWh	32085 kWh	32085 kWh
Peak demand	2945 kW	2582 kW	2582 kW	2250 kW
EENS during autonomous operation for during 10 to 12 hr in typical section TU	3491 kWh	1904 kWh	1579 kWh	1316 kWh
PV output for during 10 to 12 hr in section TU	-	260 kWh	260 kWh	260 kWh
DR (load shifting) for during 10 to 12 hr period in section TU	-	-	324 kWh	324 kWh
Battery output for during 10 to 12 hr in Section TU	-	-	-	262 kWh

6.5.1 Grid Connected Mode:

In this mode, the load is dispatched from the combined scheduling of the main grid and VPP. The detailed analysis of various cases are as follows :

I. Base Case

It is the reference case in, which there is no investment is done and the load is completely dispatched from the main grid. The feeder peak demand is significantly higher than the average load, which mostly occurs in the afternoon. The electrical dispatch with the base case is illustrated in Fig.6.7 below:

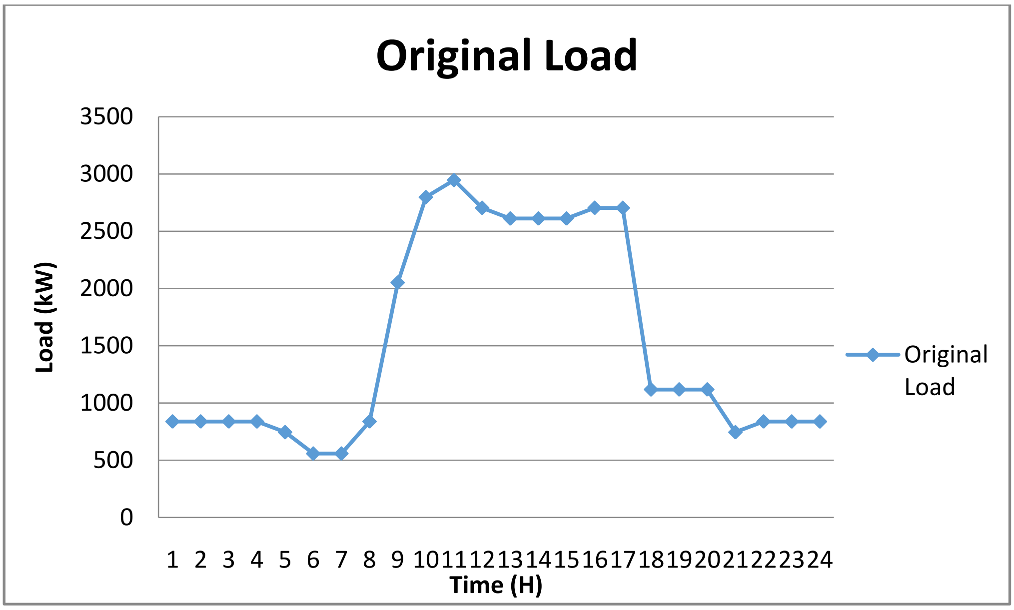

Figure 6.7 Electrical dispatch with the base case

II. Case with DER

The peak load of the industrial feeder is coinciding with the solar generation, which makes the solar PV as an effective DER for peak shaving and minimizing energy cost. The electrical dispatch of with DER is visualized in Fig.6.8 below:

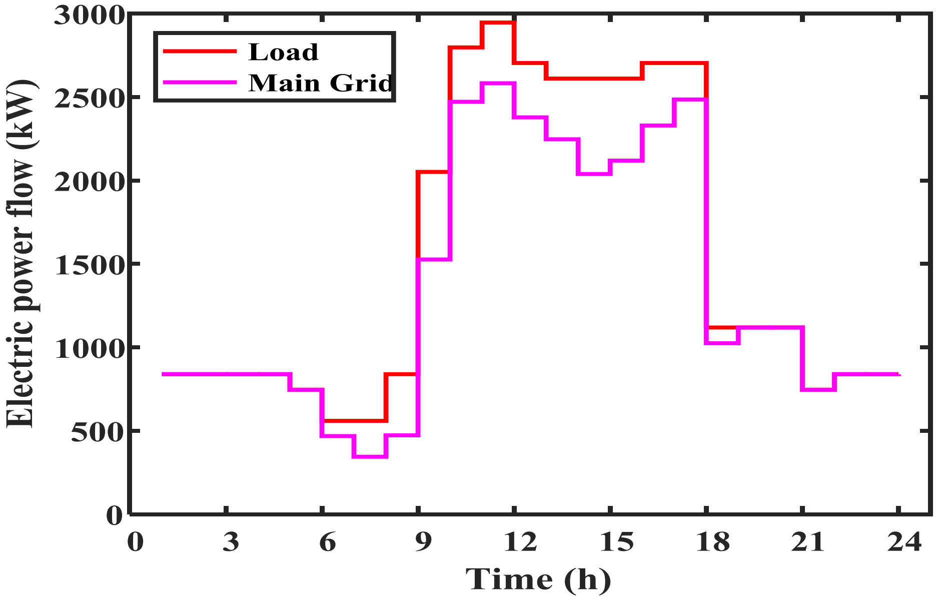

Figure 6.8 Electrical dispatch with DER

III. Case With DER & DR

The addition of DR enhances the utilization of DER having intermittent generation through controlling the load with the generation. The demand is shifted from the peak load period to the off-peak load or peak generation period, which assist in peak shaving and flattening of the demand profile. The electrical dispatch with DER and DR is shown below in Fig.6.9.

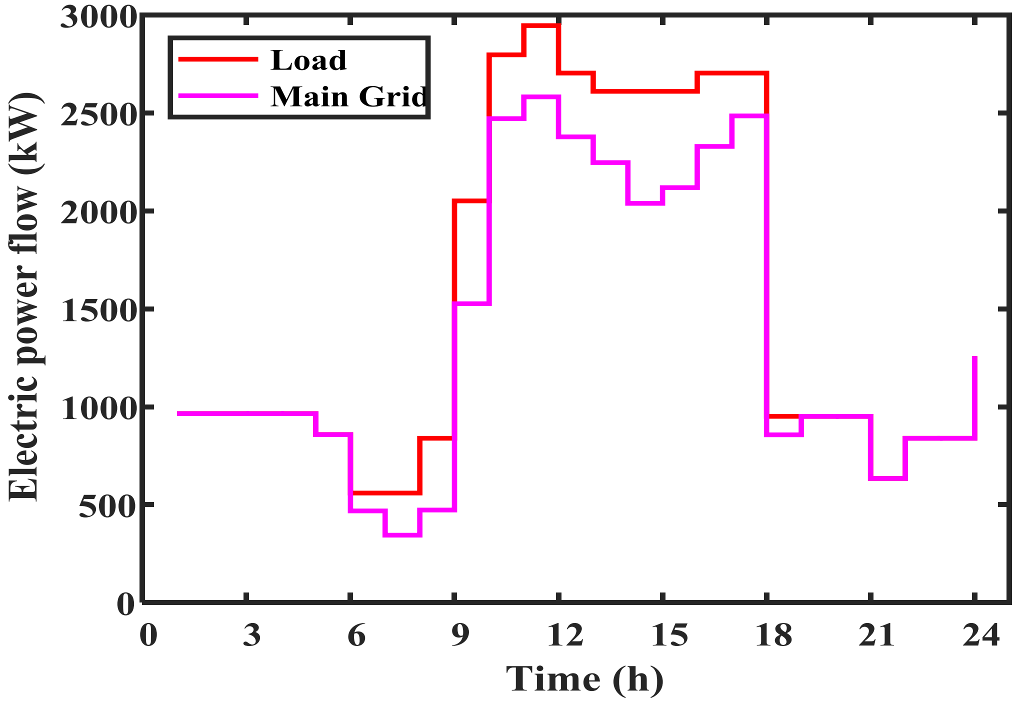

Figure 6.9 Electrical dispatch with DER & DR

IV. Case with DER, DR & Storage

Energy storage is an effective way to integrate intermittent DERs into the grid through supplying and storing the energy in a suitable duration. The rate of charging and discharging of the battery is also the key factor in designing the storage element of the VPP. The energy discharged and recharged by the battery in a single day is shown in Fig. 6.10.

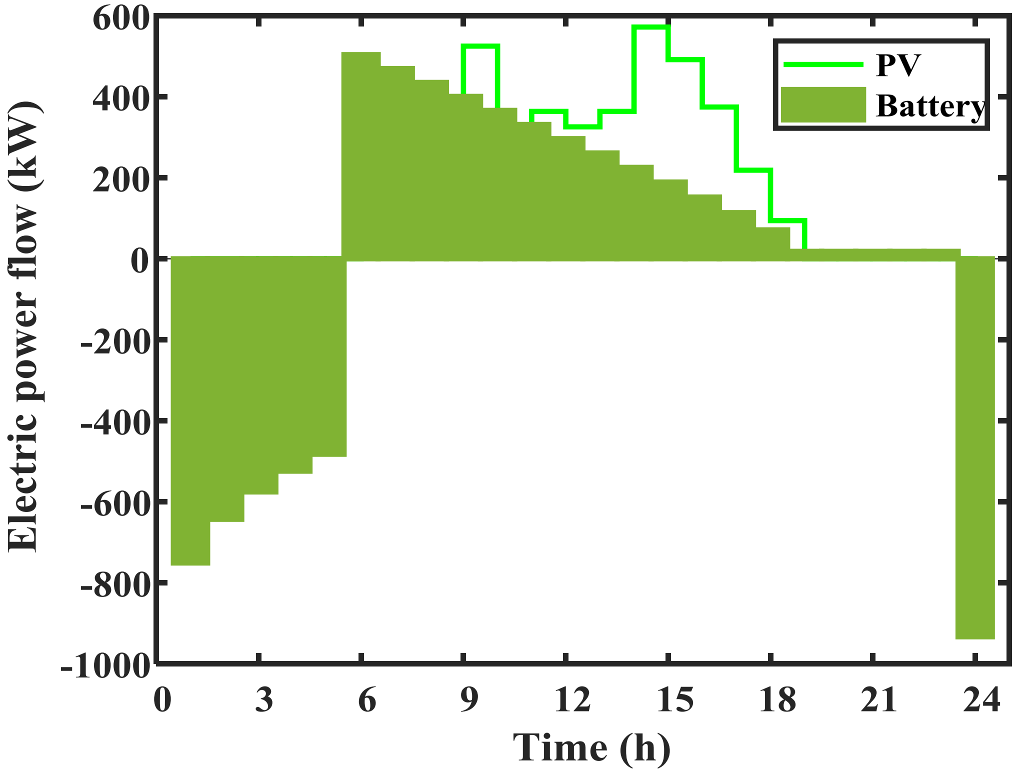

Figure 6.10 Battery discharging and recharging during the day

The combined dispatch of DER, DR, and battery significantly reduces energy cost and peak demand than any other scenario. The electrical dispatch of DER, DR, and battery is shown in Fig.6.11 below. The storage is a dispatchable resource, and its output is utilized during peak periods or during the night when there is no PV generation.

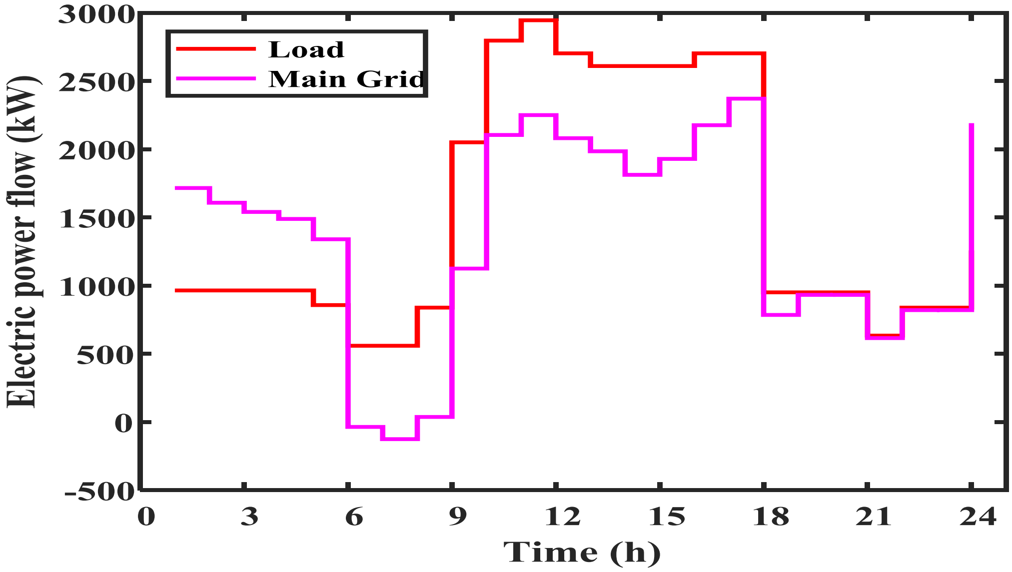

Figure 6.11 Electrical dispatch with DER, DR & storage

6.5.2 VPP Autonomous mode

During the fault period or schedule shut-down, the whole electricity supply is disrupted due to the grid non-availability, however, the VPP could be a viable way to overcome this issue. The electricity supply is dispatched through the available resources within the VPP framework. The different scenarios of the VPP in autonomous mode are discussed below:

I. **Case with DER**

During an outage, an emergency or high priority load is dispatched from the aggregated generation of the grid interconnected DERs. The VPP autonomous operation with DER integration is illustrated in Fig.6.12 below.

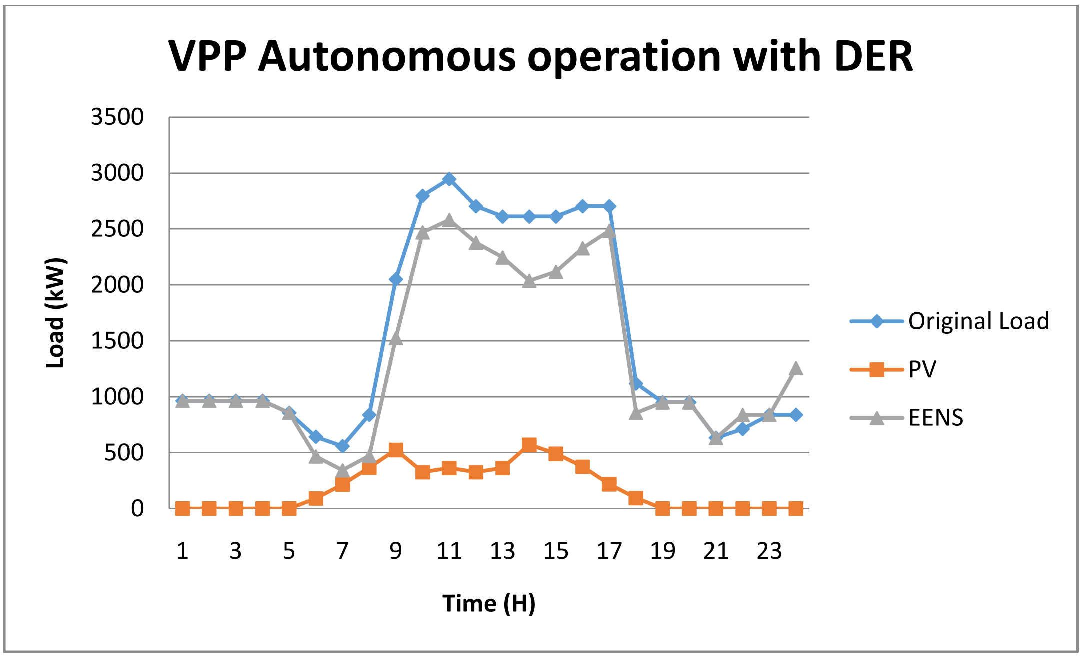

Figure 6.12 VPP autonomous operation with DER

II. Case with DER & DR

In this case, the emergency load is dispatched with DER and the remaining load is either shifted by DR schemes or curtailed depending upon the generation output. The electrical dispatch of VPP operation with DER and DR is shown in Fig.6.13 below.

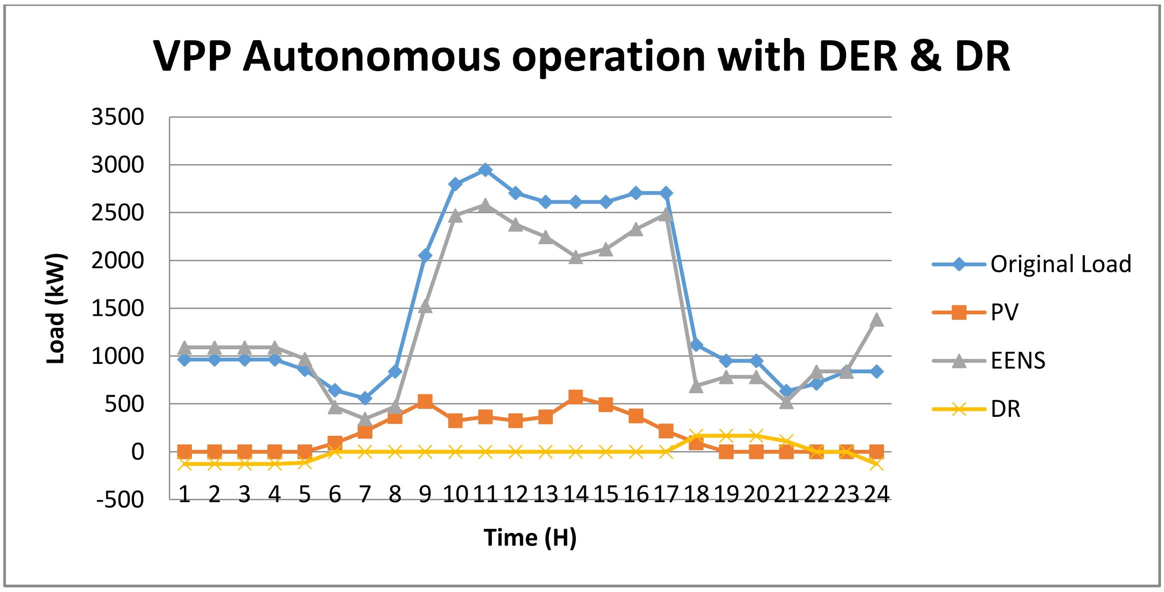

Figure 6.13 VPP Autonomous operation with DER and DR

III. Case with DER, DR & Storage

In order to reduce the EENS significantly, the combined scheduling of all the resources is done. There is a minimum load is shed during the VPP operation with batteries, which represents the highly cost-effective and reliable system for optimal energy scheduling. The electrical dispatch with DER, DR, and storage is shown below in Fig.6.14:

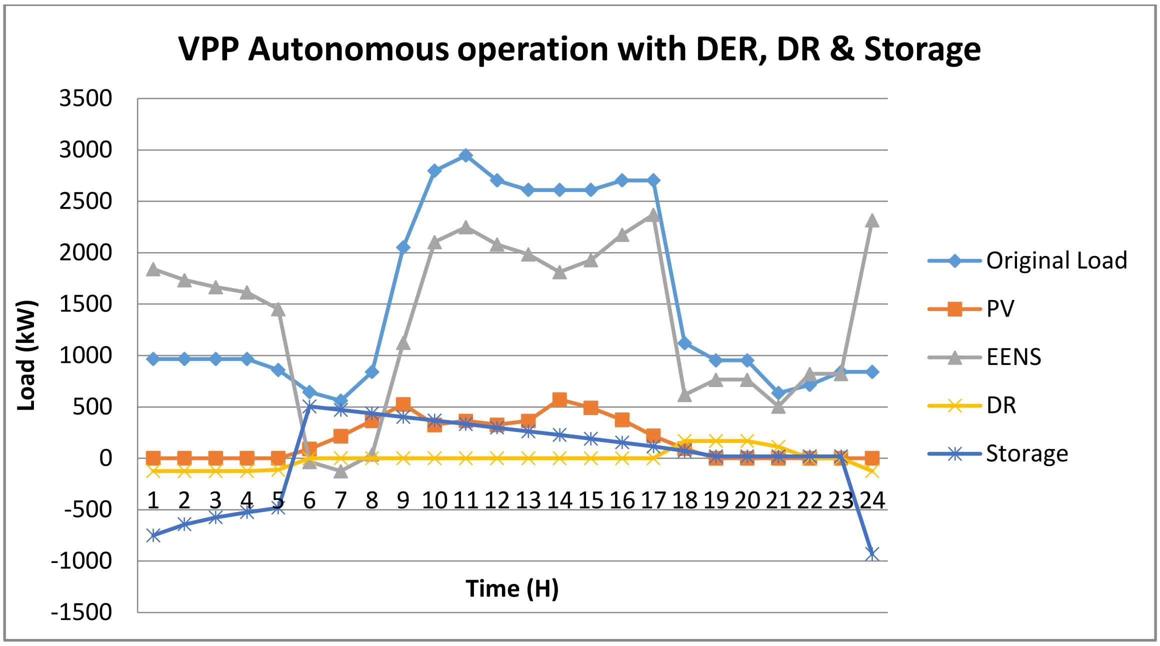

Figure 6.14 VPP Autonomous operation with DER, DR, and storage

6.6 Benefits for Consumers

The industrial unit of the induction furnace having a load of 500 kW has been selected for evaluation for potential benefits of VPP implementation for individual consumers. In this study, a 100 kW solar rooftop plant as grid integrated DER installed on the consumer premises is evaluated. The load profile of the induction furnace during different days is illustrated in Fig.6.15 below. The peak or weekday load is much higher than the weekend load as most of the industries are out of operation during weekends.

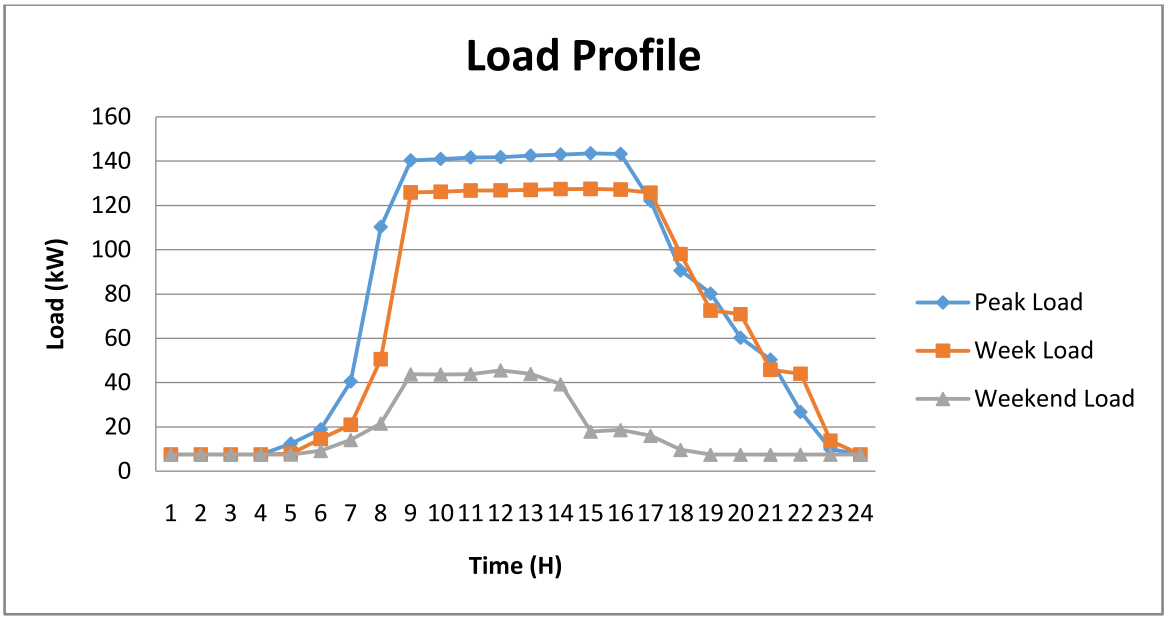

Figure 6.15 Load profile induction furnace industry

6.6.1 Influence of VPP on the Energy Charges

The VPP significantly reduces the energy import from the utility and therefore, the energy charges are significantly declined. The resultant hefty saving in the energy bill will motivate the consumers to install the PVs at their premises and further increase the share of PV in the generation sector. The month-wise saving energy charges of the industry are tabulated in Table 6.4 below:

Table 6.4 Monthly savings in energy charges

Energy Charges with TOD tariff (on = on-peak; mid = mid-peak; off = off-peak)

	Charges in $ Without VPP Implementation			Charges in $ With VPP Implementation		
Month	on	mid	off	on	mid	off
January	637.39	2906.07	137.96	464.95	1480.49	576.54
February	578.47	2673.97	121.38	345.83	1418.59	524.55
March	566.45	3050.77	142.78	312.65	1359.35	593.26

Table 6.4 Monthly savings in energy charges (Continued)

April	**544.19**	**3167.03**	**147.45**	**288.85**	**1468.10**	**591.64**
May	553.85	3215.48	151.89	263.80	1439.22	586.75
June	696.08	3050.88	187.39	180.67	2130.61	78.23
July	752.45	3265.23	197.40	183.74	2202.05	105.45
August	754.69	3289.84	196.13	192.72	2316.59	99.35
September	685.08	3038.58	186.89	166.66	2129.64	101.47
October	545.70	3176.31	150.78	271.22	1526.44	586.59
November	571.03	2760.63	125.46	336.78	1349.21	527.29
December	639.79	2952.88	134.68	459.25	1589.36	577.26

6.7 Experimental Validation

The results of the proposed optimization are compared with other effective optimization techniques for validation. The 90 bus feeder 24 hrs load profile and DER profiles are fed to all the optimization techniques for computing the optimal operational energy cost. All three optimization techniques are simulated on the same computer (Intel i3 4 GB RAM). Table 6.5 gives a detailed comparison of different optimization techniques.

Table 6.5 Comparison of Different Optimization Techniques

Optimization Algorithm	**Optimal Operational Cost**	**Execution Time**
Only Grid	$3284	00 Sec
Proprietary Derivative Free	$2534	03.6 Sec
MILP	$2390	15.1 Sec
Proposed PSO	$2247	10.2 Sec

Our proposed PSO provides the minimal cost of electrical dispatch with 11.32 % and 5.98 % less cost in comparison to Proprietary Derivative-Free and MILP respectively. However, the only downside is its execution time, which is significantly higher than the Proprietary Derivative-Free algorithm.

6.8 Summary

The study evaluated the feasibility of the VPP multi-objective model for different applications in the utility distribution network. A case study of PSPCL 90 bus Industrial feeder with grid integrated DERs is studied for VPP implementation. A multi-objective model based on the PSO optimization algorithm is proposed for optimal scheduling of utility grid, DER, DR, and battery. The main objective of the proposed model is to minimize the operational energy cost, peak shaving, and reliability enhancement subject to various technical constraints. The model is designed after considering the perspectives of both consumers and utility. The result obtained from the model depicts that VPP deployment is beneficial for both consumers and utility as the energy charges are declined by 31.57 % and EENS by 62.30 %. Moreover, the maximum demand for industrial consumers is significantly reduced as their peak demand coincides with a peak generation of solar PV. The VPP with storage comes to be the most cost-effective scenario for the utility network having DER associated with intermittent generation. The overall results advocate the implementation of the VPP for coordination of aggregated generation and optimal scheduling in the distribution network on which several consumers with DERs are present. Lastly, the obtained results are compared and validated with other available optimization techniques, and it is found that the results of the proposed model are more cost-efficient in comparison to other optimization techniques.

CHAPTER-7

CONCLUSION AND FUTURE SCOPE

The modernization of the present grid infrastructure is pacing up with the inclusion of clean and sustainable resources of energy. Smart grid technologies are now widely utilized in distribution network operations to enhance its efficiency and security of the supply. One of the major up-gradations in the distribution network is the inclusion of the DER at the disposal of the demand side. The share of DERs in the utility grid is significantly increased, especially the countries like India where solar-based DERs are widely popular. The integration of DERs provides benefits to both utility and consumer. These DERs are mostly having renewable resources and associated with intermittent generation due to weather dependence. With the increased penetration of DER, the challenges for grid operators are rising as the highly variable generation causes voltage fluctuations, reverse power flow, and utility revenue loss. The VPP concept is an effective way for the high integration of DERs in the utility network in a completely secure and economical manner. The VPP needs four major components for its operation: DER, DR, storage, and communication technologies. In this research, government-owned power utility PSPCL is selected for a case study for VPP implementation. The various parameters of PSPCL including load, generation, reliability, and tariff are studied for designing the VPP model for the various applications.

The previous studies reported the commercial aspects of the VPP ranging from the scheduling of bidding strategies to the optimal dispatch. The technical and economical constraints from both utility and consumer sides are not sufficiently taken into account. Moreover, the VPP applications in utility peak shaving and during an outage are still undiscovered.

7.1 Evaluation of Existing network with High DER Penetration

In chapter 3, the present grid infrastructure of the distribution network is studied and the effects of grid integrated DERs are analyzed without the VPP concept. The individual demand and the connected PV DER generation profile is evaluated. The profiles of residential, commercial, and industrial consumers are studied to check the influence on the utility's load and its impact on the distribution network. The collected resource data of solar energy is analyzed to determine the potential of solar grid-based VPP in the selected study area. The load profile of 11 kV distribution feeders is analyzed including the reliability parameters. The existing evaluation shows that increased penetration of solar-based DERs causes negative effects on the utility network such as voltage fluctuations, reduced power quality, and utility revenue loss. Further, the pilot study on the part of the utility network is done to know the implication of VPP on the distribution network. The combined dispatch problem of DER, DR, and storage is proposed for peak shaving in the industrial and residential feeder. The DER-CAM model is implemented for optimal scheduling of DERs within the VPP framework. The VPP was found to be beneficial for the selected area with a 31.45% saving in annualized energy cost. The major conclusions drawn from this chapter are as follows:

1. The present distribution network needs significant up-gradation in the form of VPP for large scale penetration of DERs.
2. The generation from solar-based DERs reduces both energy and demand charges for the consumers.
3. The utility still facing numerous outages due to increased load and congestion.
4. The individual consumer load and generation profiles can be aggregated for better control during scheduling.

7.2 Improvement in Reliability and Flexibility of Grid using VPP.

In chapter 4, the VPP implications on reliability and flexibility of 90 bus 11 kV Industrial feeder are analyzed. The loading and reliability data of that feeder is collected, which includes the demand profile and failure rates of various components of the feeder. The complete feeder is modelled in ETAP for load flow calculations. After that, the MCS is utilized for computing the reliability indices for determining the influence of VPP on the network. The reliability indices such as EENS are declined by 68% with the VPP application. Further, the techno-economic analysis has been done with MILP for optimal scheduling of the VPP. The annualized energy and load curtailment cost is significantly declined with the VPP influence. The autonomous operation of VPP is also analyzed section-wise for the particular outage.

The grid flexibility with the VPP is also determined in this chapter during an outage and it is found that the VPP could act as the alternative supply source for supplying the demand. The major conclusions of this chapter are as follows:

1. The present grid incurred significant loss for not supplying the demand during the outage period.
2. The MCS is an effective and accurate way to compute the reliability indices than simple analytical methods.
3. The combined application of recloser and DER significantly improves the reliability indices like SAIFI, SAIDI, and EENS.
4. The flexibility of the distribution network is also increased with the VPP as it acts as an alternative source for supplying the high priority load.
5. The proposed model is validated on IEEE 34 bus test system and improved the system reliability significantly.
6. MILP optimization is a cost-effective algorithm for the optimal scheduling of VPP.

7.3 Peak Load Shaving Using VPP

In chapter 5, the VPP application in peak load reduction for utility feeder is discussed. The demand profile of residential and industrial feeder is evaluated. It is found that the demand for the feeders is exceeding the current carrying capacity of the feeders, which results in increased losses and line breakdowns. The concept of VPP is utilized for peak shaving in these feeders by combined scheduling of DERs and DR. The generation from the DERs installed on these feeders are aggregated for effective control. Both feeders are also interlinked with each other through RMU, so the load or generation can be shifted during DER excess generation period. The DER CAM model is utilized for the optimal dispatch for the objective of reducing peak demand. The results show that the peak demand is declined by 45% and 53% of its original value for the industrial and residential feeder respectively. The adverse effect such as reverse power flow is also noticed with high penetration of DERs during the low demand period. The major conclusions of this chapter are as follows:

1. In the current scenario, the demand for feeders is escalating and surpassing the current carrying capacity of the line conductor.
2. The generation from the DERs are coinciding with the industrial demand profile, and effective in reducing the peak demand.
3. The demand for the industrial feeder is declined to a quite low value during weekends as the industrial load is out of operation.
4. The solar tariff is an effective way of limiting the reverse power flow with a marginal increase in energy cost.
5. The DER CAM model is more cost-effective and sophisticated than other simulation tools.
6. The implementation of the VPP concept leads to deferral in the utility network augmentation.

7.4 Generalised Model of VPP for DER High Penetration

In chapter 6, the VPP model is designed for both grid-connected and autonomous operation. The individual mathematical modelling of the VPP components such as solar PV, battery, load, and grid are described. The multi-objective model is designed for minimizing the VPP cost, peak load, and EENS. The workflow of the research methodology and the modified PSO algorithm are explained in detail. The different VPP scenarios are taken for the techno-economic analysis for finding optimal dispatch configuration. From the results, it is found that the addition of storage into VPP can reduce the EENS by 62.30% and make it the optimal configuration of the VPP for both grid-connected and autonomous operation. The detailed individual VPP dispatches with different resources and operating modes are analyzed. It is concluded that with the utilization of DR and battery, a significant portion of load can be supplied in the event of an outage. The proposed model optimization results are also validated with other optimization techniques and found cost-efficient in comparison to others. The major conclusions of this chapter are as follows:

1. The aggregation of DER generation from the solar PV install at different location of feeder can result in effective control and utilization.
2. The VPP integration in the grid assists utility in minimizing energy and demand costs by dispatching the partial load through the DERs.

3. During the outage, the VPP can be used as an alternative resource to supply emergency demand.
4. The VPP autonomous operation enhances the reliability of the feeder by declining the EENS during an outage.
5. The low priority demand can be curtailed or shifted to maintain the balance between supply and demand.
6. The charge and discharge rate of the battery is also influence the VPP scheduling.
7. Apart from the VPP applications in the utility, it also assists the consumer in reducing the energy and demand charges.
8. In comparison to other optimization techniques, the PSO is more simple and cost-efficient.

The thesis evaluates the potential of the VPP in the distribution network of the power utility. The existing network is unable to handle the large penetration of grid integrated DERs in a secure and efficient manner. With the VPP concept, the critical aspect such as reliability is enhanced, in the event of an outage, the reliability indices are improved and load curtailment cost is declined by 61%. Moreover, the peak load on the feeders is also declined by scheduling the DERs generation and storage devices, which defer network augmentation and reduce energy cost by 44%. Apart from analyzing the VPP by DER-CAM model, the research determines the VPP implications by the multi-objective model based on the PSO technique, which is found to be efficient than other algorithms available.

7.5 Future Scope of the Research

The concept of VPP in itself is new in the power sector, especially for the developing countries. The present study focused on the solar grid-based VPP that optimally schedules the electrical dispatch for various utility applications. The possible extensions of this research topic in different aspects are as follows:

- There is huge potential for other types of DERs in the VPP framework such as wind, gas turbines, and biomass.

- The storage medium like fuel cell could also be used in place of the battery storage while scheduling.
- The commercial aspect of the VPP can also be further analyzed with the influence of various energy markets.
- The uncertainty in solar output with the cloud movement and its influence on the electrical dispatch is also a potential area of study.
- The impact of the bi-directional flow of energy on the distribution transformer is needed to be studied.
- The other optimization techniques can also be tested for VPP scheduling.
- The protection system is needed to be studied in detail as the VPP is operated in islanding and grid-connected mode.
- The utility instead of investing in central power plants can invest in the installation of their small-scale DERs at different locations of the feeder for the reserve requirement and a long-term revenue stream.

List of Publication

Corresponding Author of the following Publications:

Journal Publication

1. Techno-economic analysis of solar grid-based virtual power plant in Indian power sector: A case study. International Transactions on Electrical Energy Systems (Wiley) 2019; e12177. https://doi.org/10.1002/2050-7038.12177.(Published) SCI Indexed.
2. Optimization of Solar Grid Based Virtual Power Plant Using DER CAM Model. (Under Review).
3. Potential of Smart Grid Distributed Generation in Commercial Buildings. UGC Care Journal (Published).
4. Designing of Multi-Objective Optimal Virtual Power Plant Model for Reliability Enhancement in Radial Network.(Under Review).
5. Designing of Multi-objective Optimal Virtual Power Plant Model for Reliability Enhancement in Radial Network: A Case Study of Indian Power Sector. (Under Review).

Book Chapter

1. Techno-Economic Analysis of Hybrid Optimization Model: A Case Study. Energy Harvesting Technologies for Powering WPAN and IoT Devices for Industry 4.0 Up-Gradation.(Published) Scopus.

Conference Publications

1. Hybrid Optimization Model for Smart Grid Distributed Generation Using HOMER. IEEE 3rd International Conference on Recent Developments in Control, Automation & Power Engineering,(RDCAPE'19), Noida (Published)
2. Impact of Solar Grid-Based Virtual Power Plant on Grid Flexibility. 3rd International Conference on Intelligent Circuits and Systems (ICICS 2020) (Accepted).

3. Feasibility Analysis of Smart Grid Distributed Generation Using RETScreen: A Case study of Industrial Building. 3rd International Conference on Intelligent Circuits and Systems (ICICS 2020) (Accepted).

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ABBREVETIONS & NOTATIONS

DER	Distributed Energy Resource
DR	Demand Response
DER-CAM	Distributed Energy Resource Customer Adoption Model
VPP	Virtual Power Plant
MINLP	Mixed Integer Non-Linear Programming
PSPCL	Punjab State Power Corporation Limited
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
HOMER	Hybrid Optimization Model For multiple Energy Resources
SCADA	Supervisory Control and Data Acquisition
RMU	Ring Main Unit
TOD	Time of Day
MILP	Mixed Integer Linear Programming
TOD	Time of Day
ETAP	Electrical Transient Analyzer Program
DG	Distributed Generation
PSO	Particle Swarm Optimization
DER	Distributed Energy Resource
LS	Load Shifting
DSM	Demand Side Management
SAIFI	System Average Interruption Frequency Index

SAIDI	System Average Interruption Duration Index
CAIFI	Customer Average Interruption Duration Index
ASAI	Average Service Availability Index
MTTR	Mean Time To Repair
MCS	Monte Carlo Simulation
η	Efficiency of a solar panel (14.9%)
S_t	Solar irradiation (1200 W/m^2)
t	Time-step
N	Number of solar panels connected either in series or parallel
A	Area occupied by solar panels
PV_t	Estimated output of solar PV
$Load_t$	Total demand on the feeder
$FlexL_t$	Schedulable demand
$IntrrL_t$	Non Schedulable demand
$EmgL_t$	Emergency demand
s	season (winter, summer including paddy season)
U_{Loadt}^{Imp}	Energy imported from the grid (kWh)
C_{EENS}	Cost of not supplying demand ($/kWh)
$EENS$	Expected Energy Not Supplied (kWh)
$Ttod$	Energy usage charges [$/kWh]
$Max\mathbf{S}$	Maximum rating of solar PV [kW]
SPE	Theoretical peak solar conversion efficiency [%]
$\mathbf{SRE}_{\mathbf{m.h}}$	Solar radiation conversion efficiency of generation

	technology c, in month m, and hour h [%]
$\boldsymbol{OMC}$	Fixed annual O&M costs of solar PV [$/kW]
$\boldsymbol{Max\ H}$	Maximum annual operation hours for technology [hour]
NS	Number of units of solar PV installed
OS	Number of units of solar PV operating
$\boldsymbol{Cap}$	Rated output of solar PV [kW]
$\boldsymbol{SI_{m,d,h}}$	Solar insolation during specified time period of month, day and hour [kW / m^2]
$\boldsymbol{VCC}$	Variable capital cost of solar PV in [$/kW]
$\boldsymbol{SA}$	available area for solar technologies [m^2]
$\boldsymbol{FCC}$	Fixed capital cost of solar PV[$]
η	Efficiency of a solar panel (14.9%)
$\boldsymbol{S_t}$	Solar irradiation (800 W/m^2)
$\boldsymbol{Pur}$	Consumer purchase binary decision of solar PV [0 or 1]
$\boldsymbol{An_i}$	Annuity factor for investments in technologies i
$\boldsymbol{TF_m}$	Tariff for fixed charges for using utility infrastructure in month m [$]
$\boldsymbol{TP_{s,p}}$	Maximum demand charges under the PSPCL tariff for season s and period p [$/kW]
$\boldsymbol{p}$	Tariff period (on-peak, mid-peak, off-peak)
$\boldsymbol{\lambda}$	Failure rate/ Yr
$\boldsymbol{Pur}$	Consumer purchase binary decision of solar PV [0 or 1]
$\boldsymbol{An_i}$	Annuity factor for investments in technologies i
$\boldsymbol{TF_m}$	Tariff for fixed charges for using utility infrastructure in month m [$]

$TP_{s,p}$	Maximum demand charges under the PSPCL tariff for season s and period p [$/kW]
$\mathrm{P}_{\mathrm{t}}^{\mathrm{bat}}$	Operational price of battery in dispatch
$\mathrm{m}_{\mathrm{t}}^{\mathrm{bat}}$	maintenance coefficient of battery
$\mathrm{E}_{\mathrm{t}}^{\mathrm{bat}}$	Discharging or recharging of the battery
$\mathrm{d}_{\mathrm{t}}^{\mathrm{bat}}$	Depreciation coefficient of the battery
C_t^{VPP}	Total Cost of VPP
C_t^{PV}	Total Cost of PV
C_t^{Batt}	Total Cost of Batteries
C_t^{Grid}	Total cost of Grid
C_t^{EENS}	Total cost of EENS
$C_{Imp,t}^{Pspcl}$	Purchasing cost of electricity
$C_{Exp,t}^{Pspcl}$	Selling cost of electricity
C_{EENS}	Cost of not supplying demand ($/kWh)
$\mathrm{DisR}_{\mathrm{t}}^{\mathrm{bat}}$	Discharging rate of the battery
$\mathrm{ChrR}_{\mathrm{t}}^{\mathrm{bat}}$	Charging rate of the battery
$\mathrm{TotCap}_{\mathrm{t}}^{\mathrm{bat}}$	Total capacity of the battery
$\mathrm{Cap}_{\mathrm{t}}^{\mathrm{bat}}$	Initial capacity of the battery
$\mathrm{DisR}_{\mathrm{t}}^{\mathrm{bat}}$	Discharging rate of the battery
$\mathrm{pol}_{\mathrm{t}}^{\mathrm{bat}}$	Pollution coefficient of the treatment cost
$C_{Imp,t}^{VPP}$	Cost of VPP of utility imports
$C_{Exp,t}^{VPP}$	Cost of VPP of utility exports

APPENDICES

A.1 Electrical cost of Industrial feeder

Total ELECTRICITY costs ($)	**878496.88**
TOD ELECTRICITY costs by month ($)	
january	90376.18
february	71107.58
march	65703.32
april	56607.20
may	63261.55
june	74765.88
july	64032.70
august	67790.86
september	91159.92
october	55766.98
november	106273.37
december	71651.34

A.2 Electrical cost of Industrial feeder with TOD tariff

ELECTRICITY costs by TOD ($)			
on = on-peak; mid = mid-peak; off = off-peak			
	on	mid	off
january	0.00	70343.06	20033.12
february	0.00	55571.29	15536.30
march	0.00	51463.60	14239.72
april	0.00	45713.86	10893.34
may	22119.61	25366.52	15775.42
june	32175.49	22753.77	19836.62
july	29559.60	18872.69	15600.41
august	28717.96	23455.58	15617.32

september	42354.73	30236.89	18568.29
october	18957.25	24182.75	12626.98
november	0.00	80767.01	25506.36
december	0.00	50445.56	21205.78

A.3 Feeders Load Data

Feeders Maximum Demand Monthly

Industrial Feeder		Residential Feeder	
Month/Yr	Load (A)	Month/Yr	Load (A)
Mar-11	240	Mar-11	85
Apr-11	250	Apr-11	100
May-11	240	May-11	120
Jun-11	240	Jun-11	130
Jul-11	240	Jul-11	140
Aug-11	240	Aug-11	140
Sep-11	250	Sep-11	130
Oct-11	290	Oct-11	123
Nov-11	180	Nov-11	110
Dec-11	182	Dec-11	95
Jan-12	197	Jan-12	100
Feb-12	190	Feb-12	101
Mar-12	190	Mar-12	100
Apr-12	190	Apr-12	126
May-12	200	May-12	175
Jun-12	200	Jun-12	175
Jul-12	210	Jul-12	220

Typical Daily Load Profile

Time’ (Hrs)	Load(A) Residential feeder	Load(A) Industrial feeder	Load(A) Residential feeder 1	Load(A) Industrial feeder 1
1	25	20	60	15
2	25	20	60	15
3	25	20	60	15
4	25	20	60	15
5	30	25	70	20
6	30	25	70	20
7	45	30	100	35
8	45	30	100	35
9	35	75	100	85
10	35	75	95	85
11	30	120	105	120
12	30	120	105	120
13	30	100	95	90
14	25	125	100	125
15	25	125	100	125
16	27	15	110	115
17	40	15	110	115

Aug-12	220	Aug-12	200
Sep-12	220	Sep-12	200
Oct-12	220	Oct-12	140
Nov-12	220	Nov-12	120
Dec-12	210	Dec-12	100
Jan-13	220	Jan-13	115
Feb-13	210	Feb-13	115
Mar-13	210	Mar-13	106
Apr-13	200	Apr-13	133
May-13	200	May-13	160
Jun-13	200	Jun-13	183
Jul-13	200	Jul-13	190
Aug-13	210	Aug-13	170
Sep-13	240	Sep-13	160
Oct-13	220	Oct-13	140
Nov-13	190	Nov-13	120
Dec-13	210	Dec-13	120
Jan-14	220	Jan-14	120
Feb-14	220	Feb-14	120
Mar-14	230	Mar-14	110
Apr-14	220	Apr-14	140
May-14	210	May-14	177
Jun-14	220	Jun-14	212
Jul-14	210	Jul-14	210
Aug-14	220	Aug-14	190
Sep-14	240	Sep-14	160
Oct-14	220	Oct-14	150
Nov-14	200	Nov-14	100
Dec-14	210	Dec-14	115
Jan-15	220	Jan-15	124

18	55	50	142	70
19	55	45	140	75
20	45	45	140	75
21	45	35	105	50
22	45	35	90	50
23	30	30	70	40
24	30	30	70	40

Feb-15	220	Feb-15	120
Mar-15	220	Mar-15	120
Apr-15	220	Apr-15	140
May-15	220	May-15	180
Jun-15	220	Jun-15	185
Jul-15	250	Jul-15	200
Aug-15	220	Aug-15	200
Sep-15	220	Sep-15	190
Oct-15	200	Oct-15	150
Nov-15	220	Nov-15	130
Dec-15	190	Dec-15	116
Jan-16	180	Jan-16	110
Feb-16	180	Feb-16	50
Mar-16	210	Mar-16	50
Apr-16	190	Apr-16	75
May-16	210	May-16	110
Jun-16	210	Jun-16	105
Jul-16	210	Jul-16	110
Aug-16	210	Aug-16	110
Sep-16	220	Sep-16	100
Oct-16	200	Oct-16	70
Nov-16	200	Nov-16	60
Dec-16	210	Dec-16	57
Jan-17	220	Jan-17	60
Feb-17	205	Feb-17	55
Mar-17	205	Mar-17	75
Apr-17	210	Apr-17	72
May-17	210	May-17	103
Jun-17	210	Jun-17	110
Jul-17	250	Jul-17	120

Aug-17	260	Aug-17	116
Sep-17	250	Sep-17	90
Oct-17	240	Oct-17	90
Nov-17	240	Nov-17	60
Dec-17	190	Dec-17	65
Jan-18	180	Jan-18	80
Feb-18	180	Feb-18	65
Mar-18	160	Mar-18	65

A.4 Electrical energy purchase from utility

Total annual electricity purchase (kWh)	**9718850.32**
Electricity Purchase by months (kWh)	
january	1056724.02
february	830746.62
march	767260.40
april	656900.64
may	744960.97
june	733307.85
july	622370.10
august	666185.85
september	885264.60
october	652854.68
november	1248469.20
december	853805.40

A.5 Connected Load

Feeder	**Domestic Supply Consumers (No)**	**Domestic Supply Connected Load (kW)**	**Non Residential Supply Consumers (No)**	**Non Residential Supply Connected Load (kW)**	**Small Power Consumers (No)**	**Small Power Connected Load (kW)**	**Medium Supply Consumers (No)**	**Medium Supply Connected Load (kW)**	**Large Supply Consumers (No)**	**Large Supply Connected Load (kW)**
Industrial	29	56	9	714	69	759	72	4979	17	6767
Residential	20k0	2946	425	1579	4	48	2	96	0	0

A.6 Reliability Data of Industrial feeder

Lambda (Failure rate/ year)	**MTTR**	**Component**
7	4	1
0.0500000000000000	1.50000000000000	2
0.0500000000000000	1.50000000000000	3
0.0500000000000000	1.50000000000000	4
0.0500000000000000	1.50000000000000	5
0.0500000000000000	1.50000000000000	6
0.0500000000000000	1.50000000000000	7
0.0500000000000000	1.50000000000000	8
0.0500000000000000	1.50000000000000	9
0.0500000000000000	1.50000000000000	10
0.0500000000000000	1.50000000000000	11
0.0500000000000000	1.50000000000000	12

0.0500000000000000	1.50000000000000	13
0.0500000000000000	1.50000000000000	14
0.0500000000000000	1.50000000000000	15
0.0500000000000000	1.50000000000000	16
0.0500000000000000	1.50000000000000	17
0.0500000000000000	1.50000000000000	18
0.0500000000000000	1.50000000000000	19
0.0500000000000000	1.50000000000000	20
0.0500000000000000	1.50000000000000	21
0.0500000000000000	1.50000000000000	22
0.0500000000000000	1.50000000000000	23
0.0500000000000000	1.50000000000000	24
0.0500000000000000	1.50000000000000	25
0.0500000000000000	1.50000000000000	26
0.0500000000000000	1.50000000000000	27
0.0500000000000000	1.50000000000000	28
0.0500000000000000	1.50000000000000	29
0.0500000000000000	1.50000000000000	30
0.0500000000000000	1.50000000000000	31
0.0500000000000000	1.50000000000000	32
0.0500000000000000	1.50000000000000	33
0.0500000000000000	1.50000000000000	34
0.0500000000000000	1.50000000000000	35
0.0500000000000000	4	36
0.0500000000000000	4	37
0.0500000000000000	4	38
0.0500000000000000	4	39
0.0500000000000000	4	40
0.0200000000000000	4	41
0.0150000000000000	0.500000000000000	42
0.0150000000000000	0.500000000000000	43
0.0150000000000000	0.500000000000000	44
0.0150000000000000	0.500000000000000	45

0.0150000000000000	0.500000000000000	46
0.0150000000000000	0.500000000000000	47
0.0150000000000000	0.500000000000000	48
0.0150000000000000	0.500000000000000	49
0.0150000000000000	0.500000000000000	50
0.0150000000000000	0.500000000000000	51
0.0150000000000000	0.500000000000000	52
0.0150000000000000	0.500000000000000	53
0.0150000000000000	0.500000000000000	54
0.0150000000000000	0.500000000000000	55
0.0150000000000000	0.500000000000000	56
0.0150000000000000	0.500000000000000	57
0.0150000000000000	0.500000000000000	58
0.0150000000000000	0.500000000000000	59
0.0150000000000000	0.500000000000000	60
0.0150000000000000	0.500000000000000	61
0.0150000000000000	0.500000000000000	62
0.0150000000000000	0.500000000000000	63
0.0150000000000000	0.500000000000000	64
0.0150000000000000	0.500000000000000	65
0.0150000000000000	0.500000000000000	66
0.0150000000000000	0.500000000000000	67
0.0150000000000000	0.500000000000000	68
0.0150000000000000	0.500000000000000	69
0.0150000000000000	0.500000000000000	70
0.0150000000000000	0.500000000000000	71
0.0150000000000000	0.500000000000000	72
0.0150000000000000	0.500000000000000	73
0.0150000000000000	0.500000000000000	74
0.0150000000000000	0.500000000000000	75
0.0150000000000000	0.500000000000000	76
0.0150000000000000	0.500000000000000	77
0.0150000000000000	0.500000000000000	78

0.0150000000000000	0.500000000000000	79
0.0150000000000000	0.500000000000000	80
0.0150000000000000	0.500000000000000	81
0.0150000000000000	0.500000000000000	82
0.0150000000000000	0.500000000000000	83
0.0150000000000000	0.500000000000000	84
0.0150000000000000	0.500000000000000	85
0.0150000000000000	0.500000000000000	86
0.0150000000000000	0.500000000000000	87
0.0150000000000000	0.500000000000000	88
0.0150000000000000	0.500000000000000	89
0.0150000000000000	0.500000000000000	90