# SOME INVESTIGATIONS ON OPTIMAL OPERATION OF MICROGRIDS

Ph.D. Thesis

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# Some Investigations on Optimal Operation of Microgrids

*Submitted in*
*fulfillment of the requirements for the degree of*
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by

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***Dedicated to my beloved parents, Shri. Anoop Parashar and Smt. Sunita Parashar***

# DECLARATION

I, **Sonam Parashar**, declare that this thesis titled, **"SOME INVESTIGATIONS ON OPTIMAL OPERATION OF MICROGRDS"** and the work presented in it, are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this university.
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- Where I have consulted the published work of others, this is always clearly attributed.
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Date: December 26, 2019

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# CERTIFICATE

This is to certify that the thesis entitled **‘SOME INVESTIGATIONS ON OPTIMAL OPERATION OF MICROGRIDS”** being submitted by **Sonam Parashar (2014REE9533)** is a bonafide research work carried out under my supervision and guidance in fulfillment of the requirement for the award of the degree of Doctor of Philosophy in the Department of Electrical Engineering, Malaviya National Institute of Technology, Jaipur, India. The matter embodied in this thesis is original and has not been submitted to any other University or Institute for the award of any other degree.

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# ABSTRACT

The electric power industries have witnessed many reforms in recent years. Earlier power systems were structured as a centralized vertically integrated utility which comprises of three unidirectional level of operation via generation, transmission and distribution. Conventional power system mainly generates electrical energy from the fossil fuels. With deregulation of power system, the system is now restructured into separate companies, i.e., GENCOs, TRANSCOs and DISCOMs. The concept of smart grid and microgrid is taking shape with broader objectives to improve reliability, efficiency, power quality and safety of power delivery and its usage. The potential promise of the smart grid include environmental benefits, reduction in transmission congestion, peak load shaving, better asset utilization along with increased energy efficiency, reliability, security and power quality, etc. Modern power system is a decentralized bidirectional system with emphasis on maximizing the renewable energy integration to the system. To maximize the renewable penetration in the system, the concept of distributed generation introduced under which the concept of microgrids is a leading idea and growing subsequently. Also, the integration of new technologies as distributed energy resources also comes into the picture with the development of microgrids. The optimal planning and integration of these distributed energy resources along with renewable DGs is necessary for the optimal operation of the microgrid which could reflect many techno-economic, socio and environmental benefits to the system operators, prosumers and consumers as well.

The purpose of this thesis is to investigate different planning and operational strategies for grid connected microgrid with integration of various non-renewable and renewable DGs, energy storage and electric vehicles to maximize the techno-economic benefits of the system operator as well as consumers. An optimal planning and operational framework for interconnection of multi-microgrids is also presented.

Apart from this, a stochastic framework is presented to solve the planning and operational problem of microgrid and interconnected multi-microgrids. Furthermore, the efforts has been also made to improve the existing optimization techniques for the optimal planning and operation of DERs in grid connected microgrid and interconnected multi-microgrid.

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# List of Abbreviations

| | |
|---|---|
| **DER** | Distributed Energy Resources |
| **DG** | Distributed Generation |
| **PCC** | Point of Common Coupling |
| **MT** | Microturbine |
| **FC** | Fuel cell |
| **WT** | Wind Turbine |
| **PV** | Photovoltaic |
| **BES** | Battery Energy Storage |
| **EV** | Electric Vehicle |
| **PHEV** | Plugin Hybrid Electric Vehicle |
| **SOC** | State of Charge |
| **SOH** | State of Health |
| **PSO** | Particle Swarm Optimization |
| **EHO** | Elephant Herding Optimization |
| **MEHO** | Modified Elephant Herding Optimization |
| **TS** | Tournament Selection |
| **TOPSIS** | Technique for Order of Preference by Similarity to Ideal Solution |
| **TC** | Total operating cost |
| **NPV** | Net Present Value |

# List of Symbols

| | |
|---|---|
| $v$ | Forecasted wind speed |
| $v_r$ | Rated wind speed |
| $v_{in}$ | Cut in wind speed |
| $v_{out}$ | Cut out wind speed |
| $\beta$ | Scale factor of MEHO |
| $\Delta t$ | Time step |
| $\eta$ | Effieciency of solar cell array |
| $\eta_c$ | Charging efficiency of BES |
| $\eta_d$ | Discharging efficiency of BES |
| $\mu$ | Mean of the solar irradiation |
| $\mu_p$ | random proximity factor between [0.9-1.1] in MEHO |
| $\mu_{ECF}$ | Mean of the energy consumption factor |
| $\sigma$ | Standard deviation of the solar irradiation |
| $\sigma_{ECF}$ | Standard deviation of the energy consumption factor |
| $A$ | Shape index in weibull distribution function |
| $B$ | Scale indexin weibull distribution function |
| $c_1$ & $c_2$ | Acceleration coefficients |
| $C_i$ | Cost coefficients of BES |
| $C_n$ | Cost coefficients of the non-dispatchable DGs |

| | |
|---|---|
| $e_{m,grid}$ | Total emissions of utility grid |
| $e_{m,i}$ | Total emissions of DG units |
| $ES$ | Size of the BES |
| $FC$ | Fixed cost of BES |
| $G^{i}_{best}$ | Global best position of the $i^{th}$ particle |
| $L$ | Power loss coefficient of solar cell array |
| $l$ | Life time of BES |
| $MC$ | Maintenance cost of the BES |
| $P^{max}$ | Maximum output power |
| $P^{min}$ | Minimum output power |
| $P^{i}_{best}$ | Personal position of the $i^{th}$ particle |
| $P_{BES}$ | Power output of BES |
| $P_{gen}$ | Generated power |
| $P_{grid,t}$ | Hourly exchanging power from utility grid |
| $P_{i,t}, P_{n,t}, P_{j,t}$ | Output power of the dispatchable DGs non-dispatchable DGs and BES at $t^{th}$ hour |
| $P_{load}$ | Load demand |
| $P_{pv}$ | PV output power |
| $P_{w_r}$ | Rated wind power |
| $P_{w}$ | Forecasted wind power |
| $r$ | Rate of interest of BES |
| $r_1$ & $r_2$ | Random numbers between 0 and 1 |
| $S$ | Area of array in $m^2$ |
| $S$ | Total number of BES |

| | |
|---|---|
| $S_k^i$ | Position of the $i^{th}$ particle at $K^{th}$ iteration |
| $SOC^{max}$ | Maximum state of charge |
| $SOC^{min}$ | Minimum state of charge |
| $t$ | Hours index |
| $TCPD$ | Total cost/day of BES |
| $U$ | Total number of DG units |
| $u_i$ | Unit status of the both the renewable and non-renewable DG units |
| $u_n$ | Unit status of BES |
| $v_k^i$ | Velocity of the $i^{th}$ particle at $K^{th}$ iteration |
| $x$ | Random variable representing the solar irradiation |
| $x_{ECF}$ | Random variable representing energy consumption factor |
| $Z_{best,cj,i}$ | Current best position attained by matriarch of all clans |
| $Z_{local,cj}$ | local best position of the elephant of the $cj^{th}$ clan |
| a & b | Cost coefficients of dispatchable DGs |

# Chapter 1

# Introduction

Power system in earlier days was structured as a vertically integrated utility which comprises of three level of operation via generation, transmission and distribution. Conventional power systems mainly generated electrical energy from the fuel which are non-renewable sources of energy like coal, diesel, natural gas etc. Due to increase in demand of electrical energy over limited reserves of fossil fuels and environmental concerns, renewable energy generation under distributed generation is the highly concerned area in modern power industry. The concept of distributed generation is to generate on-site electrical energy i.e. to generate electrical energy near the load. However, large scale integration of distributed generation possess various technical and environmental advantages but also causes many challenges for grid like power quality and stability. To overcome these challenges the concept of microgrid was introduced, microgrid is a paradigm of micro sources such as dispatchable generators, non-dispatchable generators and a storage system operated in a way so that it acts as a control entity and aggregated load for the grid. Microgrid should be operated in such a way so that mismatch of demand and supply would be avoided, power quality and reliability of supply should be maintained to consumers. Moreover, microgrid can be installed at the places where main grid is not able to supply power. Thus, microgrid can be broadly classified in to two categories i.e. standalone microgrid and grid connected microgrid. Though renewable energy sources are clean source of energy but their intermittency causes non-reliable and unstable operation of microgrids. To handle the intermittency of non-dispatchable, coordination of DGs and storage system of optimal capacity must be required for standalone microgrids; whereas for grid connected microgrid battery storage results in maximizing the revenues. Battery storage is categorized as essential and optional storage and integration of these storage technologies results in high operation cost of microgrid as well as makes the system unstable respectively. Moreover, integration of electric vehicles are needed to be focused more as energy storage for sustainable future microgrids. The problems associated with control of power flow in microgrids with integration of these devices are the great concern of research for operation of microgrids which have a scope in sizing, energy management, optimal and economic operation of microgrids.

Microgrid is a conglomeration of various types of small scale power generating sources including renewables and non-renewables, storages and loads. It is also known as medium or low voltage grid which supports the integration of Distributed Energy Resources (DERs) and storages at distribution level of power system to generate power, maintain reliability and ensure quality power supply to the consumers. Moreover, when connected to upstream grid or macro-grid, the small grid environment maintains the reliable operation of the power system with high penetration of DERs. In addition to various technical benefits, e.g., increasing reliability, stability and power quality, microgrids are boom for economic benefits.

Though renewable resources are abundant in nature, microgrid is a promising solution for the integration of renewable energy sources to balance increasing power demand on conventional grid but challenging too in terms of its planning, operation and control due to the intermittent nature of renewable energy sources. Due to the integration of intermittent renewable energy sources, a microgrid may not operate independently and requires some type of energy storage for smooth and reliable operation. Also, it can be connected to main grid for peak shaving and increase economic benefits by buying and selling power from/to main grid. On the basis of such facts microgrids have plug and play operation which means it can be connected or disconnected from upstream grid through Point of Common Coupling (PCC) whenever needed and thus has two modes of operation i.e. grid connected and islanded mode.

Generally, a microgrid consists of number of radial feeders which have given priority for the energy supply as per the type of load connected such as critical loads or non-critical loads. The DERs and storage so called micro sources are installed with a local controller (LC). Each LC controls their respective micro source and the coordinated control of the local controllers is provided by the central controller (MGCC). The MGCC has inbuilt control module. Basically, control module has hierarchical control structure having three different levels of control i.e. primary, secondary and tertiary control. The main role of control structure is voltage and frequency regulation for both operating modes, proper load sharing and DER coordination, microgrid re-synchronization with the main grid, power flow control between the microgrid and the main grid, optimization of microgrid operating cost [1].

Microgrid can operates in two ways: (1) peer to peer (2) plug and play. The peer-to-peer concept insures that no master controller or central storage unit that and the microgrid can continue operating with loss of any component or generator. With one additional source we can insure complete functionality with the loss of any source. Plug-and-play implies that a unit can be placed at any point on the electrical system without re-engineering the controls. The plug-and-play model facilitates placing generators near the heat loads thereby allowing more effective use of waste heat without complex heat distribution systems such as steam and chilled water pipes. [2]

For a microgrid to work autonomously, the key problems are to maintain the active power balance to stabilize system frequency and regulate the reactive power to keep the voltage magnitudes in allowable ranges [3]. Microgrid generally requires to control their voltage and frequency by monitoring and controlling P-f and Q-v droops by maintaining the power flow. Based on the location of the control of voltage and frequency, three types of control scheme are suggested in the literature: (1) unit power flow control (2) feeder power flow control (3) mixed power control. In ‘unit power flow control’ each unit (DG and inverter combination) regulates to provide constant power output and maintain the voltage magnitude and power flow at PCC. If load increases anywhere in microgrid, extra power is supplied by the grid. When the system islands the local power vs frequency droop function insures that the power is balanced within the island. In ‘feeder power flow control’ each DG regulates the voltage magnitude at the PCC and the power that is flowing in the feeder at different points. With this configuration extra load demands are picked up by the DG showing a constant load to the utility grid. In this case, the microgrid becomes a true dispatchable load as seen from the utility side, allowing for demand-side management arrangements. When the system islands, the local feeder flow vs frequency droop function insures the power balance with the loads [2]. In mixed control scheme, some of the DGs regulate their output power while some others regulate the feeder power flow. The same unit could control either power or flow depending on the needs [2].

Energy Management in microgrids is a nonlinear optimization problem which not only requires high computational capabilities of microgrid central controller but also infringes costumer's privacy. The objective of the EMS is to control the power flows in the microgrid in order to: 1) minimize the cost of generation, the cost of energy storage, and the cost of energy purchase from the main grid; 2) minimize the dissatisfaction of the customers in the DSM; and 3) minimize the power losses subject to the DER constraints, the load constraints, the power-flow constraints, and the system operational constraints. The OPF problem is difficult to solve due to the non-convex power-flow constraints [4].

Battery Energy storage is a practically appealing solution to smooth out the power fluctuations in the renewable energy generation, thus improving both the reliability and efficiency of microgrids [5]. Installation of battery storage in microgrid required a great attention for sizing and management. Proper sizing and management of Battery results in economic benefits and smoother operation of microgrid. It supports to control power flow by charging and discharging energy during non-peak and peak hours respectively also it increases the dispatch ability of non dispatchable DGs when integrating with intermittent DGs such as Wind, PV etc and increase revenues by selling power to main grid in grid connected mode. Due to the randomness in renewable resources such as solar and wind, the power generated can deviate from forecasted values. This variation may cause increased operating costs for committing costly reserve units or penalty costs for shedding load. In, addition, it is often desired to charge/discharge and coordinate the energy storage units in an efficient and economical way [6]. Mainly, battery storage in microgrid can be installed for various purposes such as Local load leveling, Peak shaving, Improve power reliability of the grid, Support and regulate the voltage of the grid, Support and regulate the frequency of the grid, Improve power quality, Improve transient stability of the grid, Compensate unbalanced load. [7]. Recent research has discovered that the charging/discharging efficiency of BESs has remarkable dependence on the charging/discharging rate and state-of charge of the ESS [3, 8, 9]. In next sections of this report, literature survey on optimal and economic operation of microgrid is presented which is followed by critical review and research objectives.

**Organization of Thesis**

This thesis is organized in eight chapters addressing the identified research gaps, critical review and proposed research objectives. The brief description of chapters are presented as follows.

Chapter-1; The brief introduction of the problem of optimal operation of microgrid, Energy management of microgrid, Role of BES etc. presented in this chapter.

Chapter-2; This chapter presents the literature survey on the problem discussed in chapter-1. Some research gaps are identified, a critical review followed by the literature survey is also presented. Based on the critical review, some research objectives are framed and proposed.

Chapter-3; The chapter presents the modeling of the DERs, uncertainty of power generation, load, EVs SOC status uncertainty and optimization methods. The modeling of DERs are used in the formulation of the proposed research objectives. The modeling of DERs includes the modeling of the dispatchable DERs such as Microturbine (MT) and Fuel cell (FC) as well as the non-dispatchables such as Wind Turbine (WT) and PV. The uncertainty of power generation from non-dispatchable DERs is modeled which is later used in chapter 4 and 7 for the economic optimal operation of microgrid and interconnected multi-microgrids. In this context an efficient Tournament Selection (TS) based stochastic model is developed to forecast the renewable power generation and load demand of the system. Moreover, initial SOC status uncertainty of EVs is modeled using the montecarlo simulation that can efficiently forecasts the initial SOC status of the EVs at the time of arrival in the parking lot which is further used to co-ordinate the charging/discharging of EVs in a parking lot of an office microgrid in chapter 6. Furthermore, a new optimization method called the Elephant Herding Optimization (EHO) is explored and some modifications are suggested in the EHO to improve the performance of the algorithm for the economic optimal operation of microgrid which is further named as Modified Elephant Herding Optimization (MEHO) algorithm

Chapter-4; The chapter presents the stochastic scheduling or stochastic operational management of the microgrid. The TS based stochastic method and MEHO method presented in chapter-3 is implemented to solve the daily scheduling problem of the microgrid. The presented methods are implemented on a single bus grid connected microgrid installed with dispatchable, non-dispatchable DGs and BES. The renewable power generation and load of the system is forecasted using TS method and the total operating cost of the microgrid is compared between two cases (1) deterministic scheduling and (2) stochastic scheduling

Chapter-5; presents the multi-objective sizing and operation of BES in grid connected microgrid. The efforts have been made to formulate and combine the two different objective functions for sizing and operation of BES; For sizing, total operating cost of the microgrid and total emissions reduction by integrating BES, for operation, total operating cost total and wear cost of the BES . A combination of PSO-TOPSIS presented in chapter-3 is implemented to solve the formulated problem.

Chapter-6; In this chapter, a new charging /discharging model of PHEVs in an office microgrid is presented considering various uncertainties associated with driving distance of PHEVs and renewable generation. The objective is to minimize the total cost of operation of microgrid as well as to reduce the load variance for achieving maximum benefit both for the microgrid operator as well as vehicle owners. To deal with the associated uncertainties montecarlo simulation is used which is presented in chapter-3. The problem is formulated and solved using PSO as presented in chapter-3.

Chapter-7; In this chapter, a new optimization framework is developed for optimal accommodation and operational management of interconnected multi-microgrids in distribution systems to maximize the annual profit of distribution network operators and stakeholders. Efforts are made to transform a 33-bus distribution system in to self-sustained network of microgrids. The work is comprises of the two stages (1) planning and (2) operation stages. Firstly, the renewable DGs are accommodated in the system then an operation model is developed and multi-objective optimization problem is formulated for co-ordinated operation of interconnected multi- microgrids and DNO in a distribution system to reduce the total operating cost of the DNO as well as to increase the benefits of the stakeholders. To solve the formulated problem, PSO-TOPSIS is implemented. The proposed strategic framework is investigated under different scenarios .

Chapter-8; The chapter summarizes the major contributions, conclusions drawn and future scope of the work reported in this thesis

# Chapter 2

# Literature Survey

This section presents a summary of the reported work in literature about optimal operation of microgrid under various modes and scenarios with and without the integration of battery storage and electric vehicle. The literature survey is categorized as: (1) Optimal operation of microgrid [10-67] (2) Optimal operation of microgrid with battery storage integration [68-137] (3) Optimal operation of microgrid with integration of electric vehicle [138-171] (4) Optimal operation of interconnected microgrids [172-180].

## 2.1 Optimal Operation of Microgrid

It has been noticed in literature, optimal operation problem of microgrid is attempted as scheduling problem and optimal power flow problem under various constraints within the framework of energy management. The scheduling problem is further solved as a day ahead unit commitment and/or economic dispatch problem under rolling time horizon. The formulation could be a mixed integer linear programming (MILP) or mixed integer nonlinear programming (MINLP) which strictly depends on the type of microgrid, power sharing scheme and type of assets (dispatchable or non dispatchable). Microgrid is optimized for fuel cost minimization. Carlos et al. [10] presented different power sharing schemes for minimizing the fuel consumption rate for variety of power resources and concluded that power-sharing scheme aimed at maximizing the financial benefits of microgrid. A multi stage fuel minimization problem in VSC based microgrid considering stability, voltage and frequency constraints is solved [11].

An economic emission load dispatch EELD problem is formulated to obtain different optimal output sets of DER mix among micro turbines and diesel generators of various sizes in CHP based microgrids [12]. Seon-Ju Ahn et al. introduced new droop constraints based on the two different power sharing principles for stable islanded operation of microgrid. A power dispatch problem of economic operation of microgrid is considered where total generation cost is minimized for multiple control areas in grid connected microgrid considering non dispatchable sources as negative load [13]. A quality of usage (QOU) based scheduling is presented by Yingsong Huang and Shiwen Mao, a QOU blocked probability is a criteria defined to block excessive demand of consumer [14] [15]. A least cost unit commitment and associated dispatch for the scheduling problem of renewable based microgrid is presented with a new probability based concept called probability of self-sufficiency (PSS) which indicates the probability that the microgrid is capable of meeting local demand in a self-sufficient manner [16]. Stochastic scheduling for CHP microgrid and responsive loads is presented in [17–19]. A microgrid scheduling problem with multiple islanding constraints is considered by Amin Khodaei [20] in which a T-T (total hours of scheduling and no. of consecutive hours of microgrid islanding) islanding criteria is developed to scrutinize the microgrid capability for operating in islanding mode for multiple hours. A resiliency oriented microgrid scheduling is presented where the scheduling problem is considered as normal operation problem and resilient operation problem, the objective is to minimize the microgrid load curtailment when supply of power from the main grid is interrupted for long time [21]. Xiong Wu et al. [22] presented a hierarchical scheduling problem of microgrid considering uncertainties in which the problem is divided in to two level problem i.e. upper level and lower level. The lower level ensures the minimal deviation of demand and supply while the upper level minimizes the total cost of generation of microgrid. The presented scheme reduces the effect of uncertainty in the economic operation of microgrid. In [23]a network reconfiguration based daily scheduling of microgrid is proposed in which cost of energy losses are minimized using network reconfiguration technique and then daily scheduling is optimized to minimize the operating cost of microgrid. In [24] a new concept called provisional microgrids is introduced. Provisional microgrids are the microgrids which have similar characteristics of microgrid but doesn't have islanded capability and dependent on one or more electrically connected microgrids; an uncertainty-constrained optimal scheduling model is developed considering prevailing uncertainties associated with loads, non-dispatchable generation, market price forecasts, islanding incidents and the available unused capacity from coupled microgrids. In [18, 19] stochastic scheduling of microgrid is investigated. Frequency consideration is taken in to account under the scheduling framework of microgrid in [25, 26]. Economic operation problem of microgrid is considered in [27–34]. Operating cost is minimized under different information availability (decision for shifting the loads, decision for buying/selling the energy to/from grid by each user in different time slots decision of amount of electricity buying/selling the energy to/from grid by each user) for a grid connected residential microgrid containing multiple households or users in [31]. In [35–38]optimal power flow problem is solved for microgrid. A total cost including production cost (active and reactive power production cost) of distributed generators (wind and diesel generator), cost of power grid losses and the cost of power (active and reactive powers) provided by primary substation using optimal power flow algorithm and active management schemes such as the coordinated voltage regulation of on load tap-changers (OLTCs) and the power factor control of WTs and diesel generators in a 30-bus 11-kV radial distribution system is minimized. The OPF problem is modified including active management scheme [35]. A non-convex optimal power flow problem is solved either to minimize the power distribution losses or to minimize the cost of power drawn from substation and supplied by DGs while effecting voltage regulation [38]. Duong Tung Nguyen and Long Bao Le [39] presented a risk constrained profit maximization problem for microgrid aggregator in which uncertainties are converted into risk constraints. In [40, 41] energy management of microgrid is presented.

## 2.2 Optimal Operation of Microgrid with Integration of Battery Energy Storage

In [42–57] optimal sizing problem of battery storage is solved from different perspectives of operation of microgrid. In [42] sizing problem of battery storage is considered on the basis of cost benefit analysis and an optimal size of battery is determine for a wind farm. Changsong Chen et al. [44] presented an economical allocation of battery storage on the basis of net present value. A unit commitment problem with spinning reserve with various uncertainties associated with renewable generation is considered in a microgrid to determine the optimal size of the battery [45]. Shaghayegh Bahramirad et al. [46] presented a reliability constrained battery sizing problem in which power outage probability of the units are considered. A cost based sizing problem of battery is formulated in which microgrid operating cost is minimized [47, 56]. Load shedding for frequency regulation in microgrid is considered to determine the optimal sizing problem of microgrid [51, 55]. A probabilistic unit commitment problem of microgrid is solved to determine the size of battery storage. Optimal operation of microgrid with battery storage integration is presented in [58–105]. Jen-Hao et al. [59] presented optimal charging/discharging scheduling of battery storage system for distributed systems interconnected with sizeable PV generation systems to minimize line loss of the distribution system. In [60] a flexible battery management system is presented for active reactive optimal power flow problem (A-R-OPF) in which lengths (hours) of charge and discharge periods of BSSs for each day is optimized. Yoash Levron et al. [62] considered battery storage capacity and internal losses constraints in optimal operation of microgrid where battery storage is used to balance the power (demand and supply). In [64], useful life of lead acid batteries is increased in optimal operation of standalone microgrid considering lifetime characteristics of battery (life loss cost of battery storage is considered).

## 2.3 Optimal Operation of Microgrid with Integration of Electric Vehicles

An optimal charging/discharging of electric vehicles is investigated in microgrid optimal operation in [106–144]. An economic dispatch problem of microgrid with integration of electric vehicle is presented in [108]. A charging net revenue of electric vehicle charging station is maximized by doing one day ahead scheduling in [115]. A multi objective problem to minimize microgrid line loss and operating cost as well as increasing the value of energy stored in EV and fuel cell is presented in [116]. Eric Sortomme and Mohamed A. El-Sharkawi in [117] presented a vehicle to grid algorithm to optimize energy and ancillary services (load regulation and spinning reserve) in order to offer financial benefit to EV owners and system benefits to utilities. The algorithm is used by aggregator or third party. The objective is to maximize the profits of aggregator while providing additional system flexibility, peak shaving to utility grid and low cost of EV charging to user. Energy to vehicle, bulk energy selling spinning reserve, regulation up capacity, regulation down capacity are considered as income for aggregator. In [110], effect of price uncertainty and battery degradation cost on EV scheduling is analyzed. The objective function is formulated as a cost minimization function. Soroush Shafiee et al. [120] investigates the impacts of Plug in hybrid Electric vehicle (PHEVs) on power distribution system. A sensitivity analysis is performed to demonstrate the effects of PHEV operation modes on the network load profile. PHEV impacts investigation verified that, the voltage deviation is not a sophisticated issue in the distribution systems, while peak load and loss increment are both the big concern to the widespread use of PHEVs in distribution systems due to coincidence of daily peak load and charging time of PHEVs. Derakhshandeh et al. [121] presented an electricity and heat generation scheduling method coordinated with PEV charging in an Industrial microgrid considering photovoltaic (PV) generation systems coupled with PV storages. The method is based on dynamic optimal power flow (DOPF) over a 24-hour period and includes security-constrained optimal power flow (SCOPF), industrial MG's factories constraints, PV storage constraints and PEVs dynamic charging constraints. The objective function of the proposed DOPF is to minimize the overall cost during the schedule period i.e. 24 hours, overall cost is a sum of cost and revenue and the cost imposed on industrial microgrid is costs of electricity production by CHP systems, heat production by the boilers, the total operation cost of PV generation systems and electricity purchased from upstream network. Gouveia, J. Moreira et al. [123] presented three types of coordinated wind PEV energy dispatching approaches in context to vehicle to grid i.e. valley searching, interruptible and variable rate energy dispatching aiming to promote user demand response through optimizing the utilization efficiency of wind power generation as well as meeting the dynamic power demands. In valley searching, charging and discharging of EV not interrupted and it searches valley of wind power and load curve during day and night time and fills it through the charging and discharging. In interruptible charging and discharging dispatch, a cut level concept is used which is proposed in earlier works defined as the level to which power generation or power consumption needs to be adjusted to identify the time slots. An optimal energy management for a residential microgrid including vehicle to grid system is proposed. The objective function is to minimize the economic costs associated with the exchanged energy between the grid and the microgrid [128]. A price incentive model is utilized to generate strategy to coordinate the charging of EVs and BSS to minimize the total cost of EVs and maximize the profit of BSS in grid-connected mode. In islanded mode, based on the power balance between renewable electric sources and loads, the fuzzy control method is applied to produce the service price of EV according to its state of charge. Combined with the interruptible load scheduling, the energy management and dispatch of EVs and BSS are optimized to minimize the operational cost and maximize the benefit of islanded microgrid. The main optimization problems are formulated as a cost minimizing problem and a profit maximizing one, which are implemented in a Modeling Language for Mathematical Programming. Optimal integration of PHEV in microgrids is proposed in [126] where objective function is to minimize the total cost which includes the total scheduling cost and total infrastructure cost. The objective function is optimize under two modes. In first mode main grid is treated as unidirectional and in second mode bidirectional power flow is considered. The microgrid considered is an office microgrid consisting employee vehicle and office vehicle. In order to minimize the infrastructure cost optimal number of parking is exploited. The optimal solution for DNO is obtained. In [125] Electric vehicle charging in an office microgrid with PV and CHP unit is considered. Different charging strategies and charging power ratings for workplace charging are examined for their grid impact and their impact on the self-consumption of the locally generated electricity. The grid impact can be significantly reduced by using strategies that require limited future knowledge of the EV mobility behavior and limited communication infrastructure. These strategies allow a high number of EVs to be charged at an office building, even with a limited number of charging spots, due to the large standstill times.

## 2.4 Optimal Operation of Interconnected Microgrids

Mohammad Fathi and Hassan Bevrani [139] presented load demand management with the aim of operational cost minimization in distributed smart grids. It was shown that this objective could be achieved by a collaboration between MGs using a communication infrastructure and defining a set of parameters known as purchase prices. The problem is formulated as a power dispatching problem between distributed power sources with the objective of grid operational cost minimization. They presented Energy consumption scheduling to achieve low-power generation cost and a low peak-to-average ratio. A multi objective problem is formulated in stochastic framework to capture the uncertain demand over. The paper addressed the energy consumption scheduling in a distribution network with connected microgrids consisting of a local area with a determined demand and neighboring areas with an uncertain demand. Nima Nikmehr and Sajad Najafi Ravadanegh formulated economic operation of multiple microgrids (MMGs). A stochastic and probabilistic modeling is presented for small scale energy resources and load demand at each microgrid. The power interchange between MGs is considered. Results show that it is possible to regulate the power demand and power transaction between each MGs and the main grid. Moreover, it is indicated that the power sharing between MGs with main grid can reduce the total operation cost of the future distribution network. Objective function includes generated power, purchased and sold power, and O&M costs [143]. Zhaoyu Wang et al. [136] presented a normal operation and self-healing of network microgrids. In normal operation objective is to schedule dispatchable DGs energy storages and controllable load to minimize the operation cost and maximize the supply adequacy of each microgrid. In emergency mode, objective is to minimize the active and reactive power transfer to $n^{th}$ microgrid. When a generation deficiency or fault occurs in a microgrid, the mode switches to the self-healing mode and the local generation capacities of other MGs used to support the emergency portion of the system. Reactive power transfer is also considered in this paper .The proposed method applied on a system with six microgrids. However, uncertainties associated with non-dispatchables, market prices and load are not considered also networked microgrids are not connected to main grid.

## 2.5 Critical Review

### 2.5.1 Uncertainties Handling and Problem formulation

It has been concluded from literature that uncertainties are the one of the major issue in optimal and economic operation of microgrid. It makes system to violate demand-supply constraint and requires large spinning reserve which may increases the operating cost of microgrid. Various uncertainties associated with renewable DERs, load, electrical energy prices and electric vehicles etc. are needed to be handled properly. Most of the work presented in literature consider deterministic model for problem formulation while stochastic model is more realistic which captures the randomness of these uncertainties.

### 2.5.2 Integration of Battery Energy Storage

To mitigate the adverse effects of uncertainties in the operation of microgrid and to increase the economic benefits of microgrid, battery storage is required to integrate with DERs in microgrid. This storage have high installation cost thus needs to be sized properly and coordinated with DERs by controlling its charging and discharging cycle. The charging discharging cycle of battery also effects its useful life, so it is necessary to schedule battery storage optimally.

### 2.5.3 Integration of Electric Vehicles

Taking the environmental concern in present and future, increasing number of electric vehicles in transportation sector laying down the extra burden on electrical distribution systems which needs to be managed properly as electric vehicles act as load when in charging mode and as a source when discharging. The charging and discharging scheduling of electric vehicle is necessary for the optimal operation of the microgrid as well as for the benefits of vehicle owner.

### 2.5.4 Interconnected Microgrids

In literature, less work is reported for the coordinated operation of microgrids. However, the power sharing among the microgrids in a distribution system is necessary to mitigate mismatch of demand-supply and for economic benefits. Thus optimal operational strategies are required to be developed for interconnected operation of microgrids.

### 2.5.5 Multiobjective Problem Formulation

The planning and operational problem of microgrids consists of multiple objectives which have to be taken into consideration. However, single objective problem is well attempted in the literature but multi-objective planning and operation are an important aspect to consider various techno-economic and environmental standards to increase the profits of the microgrid operator, stakeholders and consumers.

### 2.5.6 Optimization Techniques

Optimization techniques play crucial role in solving any kind of real life complex problem. In literature, planning and operational problem of DERs in microgrids and interconnected multi-microgrids are the complex problem imposing of large number of constraints. To solve this type of problem numerous optimization techniques are suggested but the outcome of these techniques seems to be indicative that require modification in the existing techniques and development and exploration of new optimization techniques.

## 2.6 Research Objectives

On the basis of the critical review discussed in above section, following research objectives are proposed and attempted in this thesis.

1. To carryout literature survey on strategies, constraints and optimization techniques used for optimal and economic operation of microgrid.

2. To formulate optimal operation problem of microgrid considering various uncertainties for optimizing operating cost and to develop suitable method to solve the problem.

3. To formulate siting/sizing problem of BES for optimal operation of micro grid for maximizing net economic benefit of microgrid and to develop suitable method to solve the problem.

4. To formulate optimal operation problem of microgrid coordinating EVs for optimizing operating cost of the microgrid, increasing the benefit of the consumers and to develop suitable method to solve the problem.

5. To formulate optimal operation problem for interconnected microgrids for optimizing total operating cost and benefits of the stakeholders in the system and to develop suitable method to solve the problem.

6. To improve existing optimization techniques to efficiently achieve the above objectives.

# Chapter 3

# Modeling of Distributed Energy Resources and Optimization Methods

Frequent Development of microgrids and renewable DGs penetration in microgrids leads the power industry to innovate and improve the power generating sources, energy storages, EVs etc. and operational schemes of power system so that it will become supportive to gain techno-socio, economic and environmental benefits. Recent trend is to generate power from small and quick generating units to develop more efficient and economical energy storages for microgrids as well as for EVs. Moreover, to manage power generation from renewable energy resources and to supply system load demand in microgrids is a challenging one for system operator due to uncertain output of renewable DGs. The randomness in the output of renewable DGs and system load demand may creates the difficulty to take optimal scheduling decisions of microgrids thus requires some stochastic modeling of random variables associated with renewable DGs output and system load demand for the optimal scheduling of microgrid. By addressing all the discussed issues, this chapter presents the modeling of the renewable and non-renewable DGs, Battery Energy Storages (BES) and EVs which is later used in further chapters of the thesis. Moreover, optimization methods such as Particle Swarm Optimization (PSO), Elephant Herding Optimization (EHO) and a multi-objective decision making technique called Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) are also presented. Some modifications to improve the EHO are suggested based on which, a new optimization method known as Modified Elephant Herding Optimization (MEHO) is proposed and presented. The optimization techniques presented and proposed in this chapter is used in the work presented in the later chapters of the thesis.

## 3.1 Modeling of Non-Renewable Distributed Generations

This section presents the modeling of microturbine, fuel cell, BES and EVs. In this thesis, microturbines and fuel cells are used as dispatchable generators in microgrid test systems due to several advantages such as clean source of energy, high reliability, low maintenance etc. However BESs and EVs are used as generating source as well as load. The generated energy from the BESs and EVs is also dispatchable.

### 3.1.1 Microturbine and fuel cell

Microturbines are the small scale combustion based turbines. These are quick start units and available with the capacity to generate a few kilowatts to few megawatts of power. Generally, natural gas is used as combustion material to start microturbine but the other fuels like hydrogen, propane, biogas and diesel can also be used whereas fuel cell is a new electrical energy generating technology, which generates pollution free energy by hydrogen and oxygen through an electro-chemical process. The residue after chemical process is only heat and water. In literature fuel cost function of the microturbine and fuel cell is suggested as a linear function and is given by Eq.3.1 [45] [145] and Eq.3.2 [47]

$$C(P) = a + bP \tag{3.1}$$

$$C(P) = c \times P \tag{3.2}$$

where, $a$, $b$ and $c$ are the fuel cost coefficients and $P$ is the output power or generated power by the microturbine or fuel cell.

### 3.1.2 Battery Energy Storage

Nowadays, different type of energy storages are available in the market for the microgrid application such as electro-chemical battery, super-capacitors, flywheel, compressed air energy storage, magnetic energy storage etc. In this work, Lithium ion battery energy storage is considered to be installed with the microgrid. These BESs are quite popular for microgrid due to their low self-discharge rate and best energy to weight ratio. While planning the scheduling of the BES for the optimal operation of microgrid, it is important to know the SOC status available for the considered scheduling time step. In this work hourly scheduling of BES is considered so the SOC status at each scheduling hour can be calculated by Eq. 3.3 and Eq. 3.4 [45] [47] [126].

$$\text{For charging}: SOC_{t+1} = SOC_t + (\Delta t \times P_{BES,t+1})\eta_c \tag{3.3}$$

where, $SOC_{t+1}$ and $SOC_t$ are the state of charge of BES at $(t+1)^{th}$ and $t^{th}$ time respectively. $P_{BES,t+1}$ is the charging power of BES at time $t$. $\Delta t$ is the time step and $\eta_c$ is the charging efficiency of BES.

$$\text{For discharging}: SOC_{t+1} = SOC_t - \frac{(\Delta t \times P_{BES,t+1})}{\eta_d} \tag{3.4}$$

where, $SOC_{t+1}$ and $SOC_t$ are the state of charge of BES at $(t+1)^{th}$ and $t^{th}$ time respectively. $P_{BES,t+1}$ is the discharging power of BES at time $t$. $\Delta t$ is the time step and $\eta_d$ is the discharging efficiency of BES.

#### Modeling of the Wear Cost of Li-BES

BES life can be estimated as the calendar life and cycle life. In this work, Li-BES wear cost is modeled using cycle life of li-BES. The cycle life of any BES depends on the DOD of the BES. Fig.3.1 shows the relationship between the DOD and life cycle counts of the Li-BES [146, 147]. The curve is best fitted by the mathematical expression given by Eq.3.5 [147]

$$LCC(d) = 694DOD(d)^{-0.795} \tag{3.5}$$

Thus, the average BES wear cost per energy unit can be expressed by 3.6 and 3.7 [148, 149]

$$C_{AW} = \frac{\text{Total installation cost of BES}}{\text{Total transferrable energy during the life cycle}} \tag{3.6}$$

$$C_{AW} = \frac{C_{BI} \times \Delta_t}{2 \times LCC(d) \times DOD(t) \times ES \times \eta_c \times \eta_d} \tag{3.7}$$

The total BES wear cost can be given by 3.8 [148]

$$C_{AW} = \frac{C_{BI} \times P_{BES} \times \Delta_t}{2 \times LCC(d) \times DOD(t) \times ES \times \eta_c \times \eta_d} \tag{3.8}$$

### 3.1.3 Electric Vehicles

Conventional transportation is a major source for the green house gas emissions. Thus, taking the environmental concerns and with continuously ongoing development in the

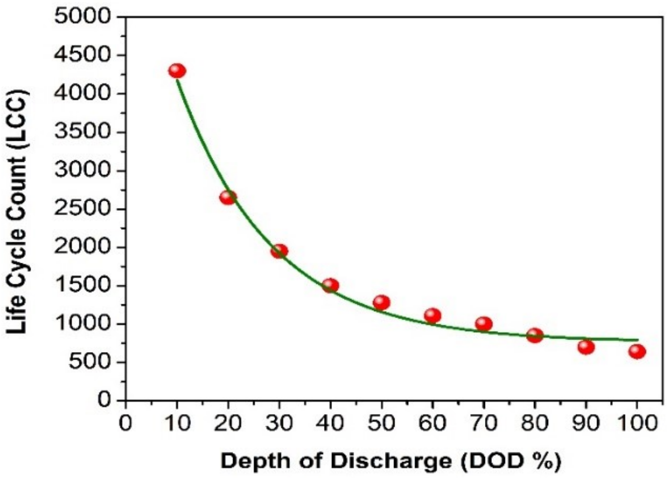


Fig. 3.1: Relationship between life Cycle and DOD of Li-BES

area of energy storage technologies electric vehicle fleet rises in the transportation sector. This changing trend in transportation sector laying down the burden on electrical distribution system as EVs acts as negative and positive load demand on the distribution system means it can generate as well as consume the electrical energy. EVs are considered as the mobile energy storage in electrical distribution system and are classified as per the trend of electricity used as their energy source. These includes Hybrid Electric Vehicles (HEVs), Plug-in-Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicles (BEVs). In this work, PHEVs are considered. These type of EVs can be plugged out and plugged in for charging and discharging the electrical energy in charging facility thus enables the Grid to Vehicle (G2V) and Vehicle to Grid (V2G) charging/discharging schemes. The availability of the charging and discharging of the electrical energy from these mobile energy storages are time constrained and quite uncertain. One of the main uncertainty associated with these EVs is the estimate of the initial SOC of the BES while the vehicle arrived in the charging facility. This estimation is required for the optimal operational planning of microgrid integrated with EVs for the techno-economic benefits of microgrid operator and consumers as well. In this work, the uncertain SOC status of BES of each and every vehicle is modeled. The initial SOC status of every PHEVs is a function of daily energy consumption factor of the respective PHEVs. The Energy consumption factor of PHEVs is considered as an uncertain parameter which depends on the daily driving distance of the PHEVs. This factor generally follows the normal distribution [126]. The montecarlo simulation along with normal distribution model is used to forecast the Energy Consumption Factor (ECF) of each PHEV.

$$f(x_{ECF}) = \frac{1}{\sqrt{2\pi\sigma_{ECF}^2}} e^{\frac{-(x_{ECF}-\mu_{ECF})^2}{2\sigma_{ECF}^2}} \tag{3.9}$$

where, $x_{ECF}$ is a variable representing energy consumption factor, $\mu_{ECF}$ and $\sigma_{ECF}$ are the mean and standard deviation of the energy consumption factor respectively.

#### Monte Carlo Simulation

Monte Carlo simulation is a method of repeating random experiments to model the risk or uncertainty. The method gives the distribution of the possible outcomes followed by some probability distribution function. Following steps are suggested in this work to model the uncertainty associated with energy consumption of PHEVs using montecarlo simulation:

1. Generate a normally distributed random number between minimum and maximum limits of ECF for each PHEV.
2. Obtain a normal cumulative distribution function (cdf) of the generated random number.
3. Repeat the experiment for *e* times. In this work *e* is a no. of Monte carlo simulations and is set to 1000.
4. Obtain the mean of the cdfs of the random numbers obtained from repeated Monte carlo simulations.
5. Calculate the inverse cdf of the mean cdf which represents the forecasted ECF.

After forecasting the energy consumption factor for each PHEVs, the initial SOC of BESs for each PHEV can be obtained from

$$SOC_{PHEV,i}^{initial} = SOC_{PHEV,i}^{max} - (SOC_{PHEV,i}^{max} \times ECF_{PHEV,i}) \tag{3.10}$$

## 3.2 Stochastic Modeling of Renewable DGs and Load Demand

### 3.2.1 Solar Power Generation

Generally, Normal or Gaussian distribution function to model solar irradiation in the literature. So, the solar irradiation is modeled as Normal distribution function and is shown by

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-\mu)^2}{2\sigma^2}} \tag{3.11}$$

where, $x$ is a variable representing the solar irradiation, $\mu$ and $\sigma$ are the mean and standard deviation of solar irradiation respectively. Then the hourly PV power is calculated using equation

$$P_{pv,t} = \eta SxL \tag{3.12}$$

where, $P_{pv,t}$ is the hourly PV power output $\eta(\%)$ is the efficiency of solar cell array, $S$ is the area of array in $m^2$, $L$ is the power loss coefficient.
A set of PV power generation called PV power Scenarios $(P_{pv} \in N_{pv})$ for each $N_{pv}$ samples is obtained having $(\rho_{pv} \in N_{pv})$ probabilities.

### 3.2.2 Wind Power Generation

Wind speed is uncertain and varies with different geographical conditions. It is a variable following certain type of probabilistic density function (PDF). Generally, wind speed follows Weibull distribution function. In this work, an hourly stochastic wind power generation is modeled using Weibull distribution function which is a well fitted PDF for wind speed and is given below

$$f(v) = \frac{B}{A}(\frac{v}{A})^{B-1} e^{-(\frac{v}{A})^{B-1}} \tag{3.13}$$

where, $A$ and $B$ are the shape index and scale index respectively. $v$ is the variable representing wind speed.
Weibull PDF is fitted to an hourly annual historical data [150] to obtain shape and scale index parameters. The $N_w$ no. of random samples using Eq.3.13 for each hour are drawn for wind speed. The hourly wind power generation for each sample is calculated using

piece wise function given below

$$P_{w,t} = \begin{cases} 0 & v_t < v_{in}, v_t > v_{out} \\ P_{w_r,t} \times [\frac{v_t - v_{in}}{v_r - v_{in}}] & v_{in} \leq v_t \leq v_r \\ P_{w_r,t} & v_r \leq v_t \leq v_{out} \end{cases} \tag{3.14}$$

Where, $P_{w,t}$ and $P_{w_r,t}$ are the forecasted and rated wind power at time $t$ respectively. $v_{in}, v_{out}, v_r$ and $v_t$ are the cut in, cut out, rated and forecasted wind speed.
A set of wind power generation called wind power scenarios $(P_w \in N_w)$ for each sample is obtained having $(\rho_w \in N_w)$ probabilities.

### 3.2.3 Load Demand

For the simplicity, the system load demand is also modeled as a Normal PDF discussed in previous section. An hourly load $P_{d,t}$ is modeled having $N_d$ samples drawn from Eq..3.11 with corresponding probabilities $(\rho_d \in N_d)$.

### 3.2.4 Combined Stochastic Modeling of the System

As discussed in the previous sections, for each hour, wind power, solar power and load demand have forecasted scenarios or set of values namely $P_{pv,t}, P_{w,t}, P_{d,t}$ respectively with corresponding probabilities $\rho_{pv}, \rho_w, \rho_d$. Thus, the modeled system will have $N_{pv} \times N_w \times N_d$ of possible scenarios states with probability of $\rho_{pv} \times \rho_w \times \rho_d$ for each hour. In this work equal number of samples are considered for wind, PV and load i.e. $N_{pv} = N_w = N_d = 365$.

### 3.2.5 Tournament Selection based Scenarios Sampling

In this work, tournament selection method is used for the scenarios sampling. Tournament selection method is a probabilistic method and chooses the most probabilistic scenario state from the pool of the competitor scenarios states. This method is more accurate method as compared to the other scenario sampling methods available in the literature [151–153]. The method calculates the combined probability of the randomly selected independent events and chooses the most probabilistic individual scenario states as an outcome. From the previous sections, hourly scenarios and possible states of whole system are obtained for 24 hours. Each hour has number of scenarios and $N_{pv} \times N_w \times N_d$ possible states with corresponding probabilities. The tournament selection method randomly selects the hourly possible states $[P_{pv}, P_w, P_d]$ and calculates their corresponding combine probability $\rho_{pv} \times \rho_w \times \rho_d$. In this work 1000 tournaments are considered to be played between the players of the data set of variables to select the best player from each set of variables for declaring the best scenario of each hour. The scenario state having highest probability is chosen as the forecast of the wind power, solar power and load demand.

## 3.3 Optimization Methods

### 3.3.1 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is an evolutionary swarm based computational technique introduced by James Kennedy and Russel Eberhart in 1995 [154]. The technique is inspired by swarm behavior of various insects, schooling of fish, flock of birds etc. The computational steps mainly comprises of two parameters i.e. velocity and position of particles. The technique assumed that the particles in a swarm moves with a certain velocity and changes their position according to their respective new calculated velocity at each iteration step. The velocity of the particle is composed of particle's own intelligence as well as the intelligence from the other superior particles in the swarm. These components are known as cognitive and social behavior of the particle respectively. The velocity and the position updating equation are given by Eq.3.15 and Eq.3.16 respectively.

$$v_{k+1}^{i} = w \times v_{k}^{i} + r_1 c_1 \frac{(P_{best}^{i} - S_{k}^{i})}{\delta_t} + r_2 c_2 \frac{(G_{best}^{i} - S_{k}^{i})}{\delta_t} \tag{3.15}$$

$$S_{k+1}^{i} = S_{k}^{i} + v_{k+1}^{i} \tag{3.16}$$

where, $v_k^i$ is the velocity of the $i^{th}$ particle at $K^{th}$ iteration, $v_{k+1}^i$ is the velocity of the $i^{th}$ particle at $(K+1)^{th}$ iteration, $c_1$ & $c_2$ are the acceleration coefficients, $r_1$ & $r_2$ are the random numbers between 0 and 1, $P_{best}^i$ and $G_{best}^i$ are the personal and global best positions of the $i^{th}$ particle, $S_k^i$ is the position of the $i^{th}$ particle at $K^{th}$ iteration and $S_{k+1}^i$ is the position of the $i^{th}$ particle at $(K+1)^{th}$ iteration.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $P_{DG}^{1}$ | $P_{DG}^{2}$ | ------- | $P_{DG}^{N}$ | $P_{BES}^{1}$ | $P_{BES}^{2}$ | ----- | $P_{BES}^{M}$ | $P_{grid}$ |

Fig. 3.2: Structure of individual for optimal operation of microgrid

### 3.3.2 Elephant Herding Optimization

The EHO algorithm is a recently developed nature-inspired method proposed by Wang et al. in 2015 [155]. The algorithm is inspired from the herding behavior of elephants. The elephant researchers discovered that female elephants (FEs) secure their babies from hungry predators by communicating through the ground with seismic waves generated from the foot stomping and low-frequency rambling of elephants. The discovery shows that elephants may be able to sense these vibrations through their feet and interpret them as warning signals of a distant danger.

In nature, elephant is also considered as a social animal and the herd consists of several clans of FEs and their calves. Each clan moves under the influence of a matriarch or a leader elephant. The FEs use to live with their family groups, whereas the male elephants (MEs) separated when they grow up and live in contact with their family group using low-frequency vibrations, as shown in Figure.3.3.

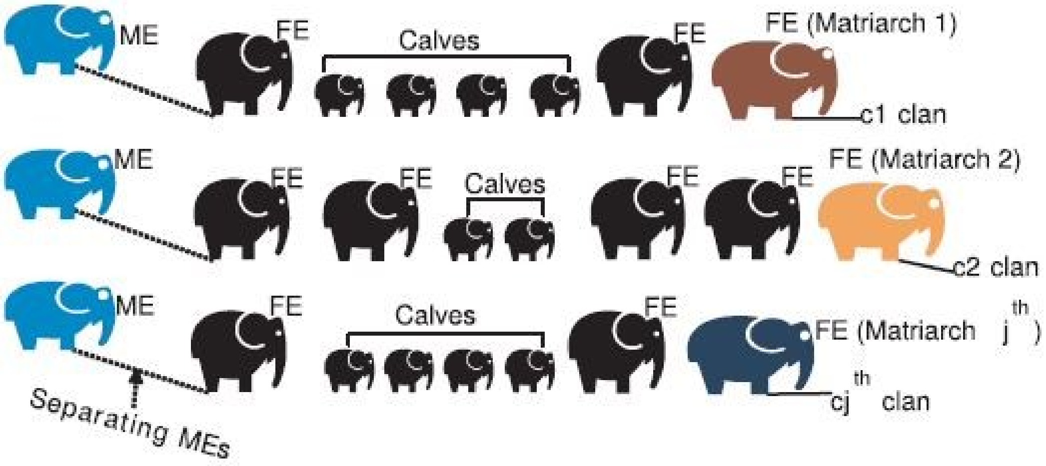


Fig. 3.3: Herding behavior of elephants

The number of elephants in each clan may assume to be equal. The group of matriarch hold the best solution in the herd of elephants while the worse solution is decoded from the position of the group of MEs.

The herding behavior of elephants is mathematically modeled and divided into various steps as suggested in [155]

1. Position update: In this step, position of each elephant in different clans except the matriarch and ME that holds the best and worse solution in each clan, is updated

as

$$Z_{new,cj,i} = Z_{cj,i} + \alpha \times (Z_{best,cj,i} - Z_{cj,i}) \times r \tag{3.17}$$

where,$Z_{new,cj,i}$ is the new updated position of the $i^{th}$ elephant in $cj^{th}$ clan, $Z_{cj,i}$ is the old position of the $i^{th}$ elephant in $cj^{th}$ clan. $Z_{best,cj,i}$ is the best position of the $i^{th}$ elephant in $cj^{th}$ clan. $\alpha$ and $\beta$ is the scale factor set between 0 and 1 in MEHO. $r$ is the random number between 0 and 1.

2. Position update of the fittest elephant of each clan: The position of the fittest elephant, i.e., matriarch, is updated as

$$Z_{new,cj,i} = \beta \times Z_{center,cj} \tag{3.18}$$

$$Z_{center,cj} = \textstyle\sum_{i=1}^{n} \frac{Z_{cj,i,d}}{n_z}$$

where $\beta$ is a scale factor generally in the range of 0 to 1.

3. Separating the worst elephant individual: Now, the worst elephants individual or MEs will be separated from their family groups. This is implemented by modifying the worst solution as

$$Z_{worst,cj,i} = Z_{min} + (Z_{max} - Z_{min} + 1) \times rand \tag{3.19}$$

### 3.3.3 Modified Elephant Herding Optimization

In this section, the limitations of the basic EHO are discussed and some modifications are suggested to improve the optimization technique as follows:

- Observation I: In standard EHO, the position of the fittest elephant leading the clan is updated by following the mean position or average information received by all elephants of that clan only, as expressed in Eq. 3.18. The expression works satisfactory for the benchmark functions. But, when it is applied to real-life problems, the results are not satisfactory. It may be due to the fact that in Eq.3.18, the position of the matriarch is updated by following the mean response of the respective clan. Moreover, $\beta$ in Eq.3.18, randomly chosen between [0, 1], may further affect the position of the solution. This may result in poor fit solution, which deteriorates the mean of the clan. As a cumulative effect, the herd may not be able to reach the global best solution.

- Suggested Improvement I: In order to overcome the above limitation, it is suggested to update the position of matriarch elephants around the current best position as

  $$Z_{new,cj,i} = Z_{best,cj,i} + (\beta \times Z_{center,cj}) \tag{3.20}$$

  Where, $Z_{best,cj,i}$ is the current best position attained so far by the leader elephants of all clans. This improves the mean of each clan and, thereby, the ability to find the global best solution.

- Observation II: According to a separating operator used in the basic method, the male or worst elephants have to leave the group when they grow up. Therefore, the newly generated baby elephants will attain the randomly chosen positions so as to maintain the constant number of elephants in each clan, as expressed in 3.19. However, it is observed that the elephants keep their babies near the stronger females in order to protect them from hungry predators.

- Suggested Improvement II: In order to overcome the above limitation, it is suggested that the newly generated babies should be allocated the position near to a stronger female. Therefore, the newly generated babies will occupy the position near to the leader of the respective clan. The modified equation is expressed as

  $$Z_{worst,cj,i} = Z_{fittest,cj,i} \tag{3.21}$$

such that $Z_{fittest,cj,i} = \mu_p \times Z_{local,cj}$ where,$\mu$ is a random proximity factor between [0.9-1.1] and $Z_{local,cj}$ is the local best position of the elephant of the $cj^{th}$ clan

### 3.3.4 Technique for Order of Preference by Similarity to Ideal Solution

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a multi-criteria decision analysis method based on euclidean geometry in which optimal solution is selected based on its optimal euclidean distance from Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) [156–158]. The TOPSIS approach comprises of the following mathematical steps:

1. Normalized Decision Matrix: This matrix is used to change all dimensional quan-

tities into non dimensional quantities and can be given by 3.22

$$N_{ij} = \frac{f_{ij}}{\sum_{i=1}^{K_i} f_{ij}^2} \tag{3.22}$$

2. Weighted Normalized Decision Matrix:This matrix is used to assign the weightage to the objectives if required otherwise it can be skipped if all objectives are of same weightage.

$$W_{ij} = wt_{ij} \times N_{ij} \tag{3.23}$$

3. Calculation of PIS and NIS: PIS and NIS are the vectors containing the best and worse solutions of the objectives respectively.

$$\begin{aligned} PIS &= [W_1^+, W_2^+, W_3^+ .....W_{K_i}^+] \\ NIS &= [W_1^-, W_2^-, W_3^- .....W_{K_i}^-] \end{aligned} \tag{3.24}$$

4. Calculation of Euclidean distance: Euclidean distance of each alternative solution from PIS and NIS can be calculated using Eq. 3.25

$$\begin{aligned} D_i^+ &= \sqrt{\sum_{j=1}^{K_i} (W_{ij} - W_j^+)^2} \\ D_i^+ &= \sqrt{\sum_{j=1}^{K_i} (W_{ij} - W_j^+)^2} \end{aligned} \tag{3.25}$$

5. Calculation of Relative closeness index: The solution corresponding to the highest valued RCI corresponding represents the best compromising solution.

$$RCI = \frac{D_i^-}{D_i^- + D_i^+} \tag{3.26}$$

## 3.4 Summary

In this chapter modeling of microturbine, fuel cell, wind turbine DG, solar DG, system load demand, Lithium-ion BES (Li-BES) and PHEVs are presented. A new TS based method is proposed to model uncertain renewable power and system load demand. Apart from this, the chapter enlightens the optimization methods such as PSO, EHO and Proposed MEHO along with a multi-objective decision technique called TOPSIS are presented. All the modeling and optimization methods proposed and discussed in this chapter are further used in this thesis.

# Chapter 4

# Optimal Operation of Grid Connected Microgrid

Operational management of microgrid is an important issue to achieve various techno-economic challenges in operation of microgrid. It is widely focused on scheduling of the available generating sources following the load demand of the system over a finite time horizon. The increasing non-dispatchable DGs penetration creates an uncertain operational environment for microgrid operational management. It is a very challenging task for a microgrid system operator to take various planning and operational decisions under the uncertainty or lack of information about the power generation and consumer load demand. The uncertain generation and load may create some serious technical and economical disasters in operational management of microgrid such as mismatch of demand and generation, mismatch of frequency, economic losses, etc. Thus, it is necessary to model the uncertainty of the intermittent renewable generation and load for the smooth operation of microgrids and to achieve various techno-economic and environmental benefits. This chapter presents a deterministic and stochastic optimal scheduling of grid connected microgrid. Firstly, the proposed MEHO discussed in section 3.3.3 is established by implementing it on deterministic optimization problem of micrgrid. Secondly, an efficient stochastic model is developed for the stochastic scheduling of the grid connected microgrid. The model is used to capture the uncertainties of load demand and renewable resources. The chapter also presents the comparison of the total operating cost of the grid connected microgrid obtained by performing the deterministic as well as the stochastic scheduling using MEHO .

## 4.1 Deterministic Scheduling of Grid Connected Microgrid using MEHO

Deterministic scheduling of microgrid is based on the deterministic values of the control variables that means all the power output of the DGs, BESs and exchanging power from grid are deterministic in nature. In order to validate the application of the proposed optimization method MEHO, discussed in section 3.3.3, in optimal scheduling of the microgrids, The method is implemented to perform the deterministic scheduling of the microgrid and the results are compared with the results already available in literature of other optimization methods.

### 4.1.1 Problem Formulation

In this section, the deterministic optimal scheduling problem of microgrid is formulated. In order to know the optimal dispatches or schedules of each DERS and utility grid in the grid connected AC microgrid, it is required to optimize the daily total operating cost (TC) of the microgrid. TC can be defined as the total expenses incurred by the microgrid operator to supply the load demand. It is comprises of the total fuel cost of the dispatchable DGs, cost of charging/discharging the power from BES, cost of exchanging power from utility grid, startup and shutdown cost of dispatchable DGs, operation and maintenance cost of DGs and total operating cost of BES. In this context, a mathematical expression consisting of the various decision variables such as total power output of the dispatchable and non-dispatchable DGs, total charging/discharging power of BES, total exchange power to/from utility grid along with cost coefficients is presented. The variables such as selling power to utility grid and charging power of BES is considered as the negative generation and hence the values of these variables are negative in the formulated mathematical expression. The deterministic scheduling problem of microgrid is formulated for following two different operational cases:

1. Case A (Islanded mode): In this mode of operation, microgrid is not able to exchange the power with utility grid and has to supply the load by its own generation of power. The problem is investigated at three different level of SOC such as minimum SOC, maximum SOC and 50% of maximum SOC.
2. Case B (Grid connected mode): In this mode of operation, microgrid can exchange

power with utility grid. Moreover, microgrid can sell or buy the power to/from utility grid to gain the maximum economic benefits. The problem is investigated at three different level of SOC such as minimum SOC, maximum SOC and 50% of maximum SOC.

#### Objective Function

The objective of the deterministic scheduling is to minimize the total operating cost of the grid connected microgrid over a finite time horizon $T$.
For grid connected mode:

$$\begin{gathered} TC = min \sum_{t=1}^{T} (Cost_{units}) + OM + TCPD \\ \text{where, } Cost_{units} = C_{DG} + C_{Grid} + C_{BES} + SUC_{DG} + SDC_{DG} \end{gathered} \tag{4.1}$$

For islanded mode:

$$\begin{gathered} TC = min \sum_{t=1}^{T} (Cost_{units}) + OM + TCPD \\ \text{where, } Cost_{units} = C_{DG} + C_{BES} + SUC_{DG} + SDC_{DG} \end{gathered} \tag{4.2}$$

where,

$$\begin{aligned} C_{DG} = \Big[ & Bid_{MT \times P_{MT,t}} \times u_{MT,t} + Bid_{FC \times P_{FC,t}} \times u_{FC,t} \\ & + Bid_{PV \times P_{PV,t}} \times u_{PV,t} + Bid_{WT \times P_{WT,t}} \times u_{WT,t} \Big] \end{aligned} \tag{4.3}$$

$$C_{Grid} = \begin{cases} Bid_{Grid,t} \times P_{Grid,t} & P_{Grid,t} > 0 \\ (1 - tax)(Bid_{Grid,t} \times P_{Grid,t}) & P_{Grid,t} < 0 \\ 0 & P_{Grid,t} = 0 \end{cases} \tag{4.4}$$

#### Constraints

1. Power balancing constraints: The constraint ensures that at each hour, total generation of the system including generation from dispatchable DGs, non-dispatchable

DGs and BES should be equal to the system load demand.

$$\begin{aligned} P_{gen,t} &= P_{load,t} \\ \text{or } P_{gen,t} - P_{load,t} &= 0 \\ \text{where, } P_{gen,t} &= P_{i,t} + P_{n,t} + P_{j,t} + P_{grid,t} \end{aligned} \tag{4.5}$$

2. SOC constraints of BES: At each hour, SOC of the BES should remain in predefined limits for the satisfactory operation and longevity of BES.

$$SOC_t^{min} \leq SOC_t \leq SOC_t^{max} \tag{4.6}$$

3. Power limiting constraint: The power output of each DG, BES and utility grid should be in predefined limit

$$\begin{aligned} P_{MT,t}^{min} &\leq P_{MT,t} \leq P_{MT,t}^{max} \\ P_{FC,t}^{min} &\leq P_{FC,t} \leq P_{FC,t}^{max} \\ P_{BES,t}^{min} &\leq P_{BES,t} \leq P_{BES,t}^{max} \\ P_{grid,t}^{min} &\leq P_{grid,t} \leq P_{grid,t}^{max} \end{aligned} \tag{4.7}$$

### 4.1.2 Simulation Results

A grid connected microgrid [47], consisting of a MT,FC, WT, PV and a BES is considered in this work. It is assumed that 500 kWh Li-BES is installed with the microgrid. The hourly operating reserve is assumed as 5 % of hourly load. The rate of interest of Li-BES is considered as 6%, cost of BES is about 465(€ct/kWh), maintenance cost of BES is 15(€ct/kWh), life-time of BES is taken as 3 years, $\eta_c$ and $\eta_d$ is assumed to be 90%. DOD of BES is considered as 90%. Table.4.1 shows the power limits and bids of MT, FC, PV, WT, BESS and Grid. The forecasted load,wind power and solar power is shown in Fig.4.1. Hourly bid of grid is shown in Fig.4.2.

The proposed MEHO is tested on considered test system for two operational cases (1) Case A: Islanded mode (2) Case B: Grid connected mode. The pop size is taken as 30 and the maximum number of iteration is set to 100. To validate the obtained results, 100 independent trials of algorithm are simulated, the results are also compared with the other existing methods in the literature.

Table 4.1: Power Limits and Bids of MT, FC, PV, WT, BES and grid

| Type | $P_{min}$(kW) | $P_{max}$(kW) | Bid (€ct/kWh) | OM Bid(€ct/kWh) | Startup & Shutdown Cost (€ct) |
|---|---|---|---|---|---|
| MT | 6 | 30 | 0.457 | 0.0446 | 0.96 |
| FC | 3 | 30 | 0.294 | 0.08618 | 1.65 |
| PV | 0 | 25 | 2.584 | 0.2082 | 0 |
| WT | 0 | 15 | 1.073 | 0.525 | 0 |
| BESS | 30 | 30 | 0.38 | - | 0 |
| Grid | 30 | 30 | - | - | - |

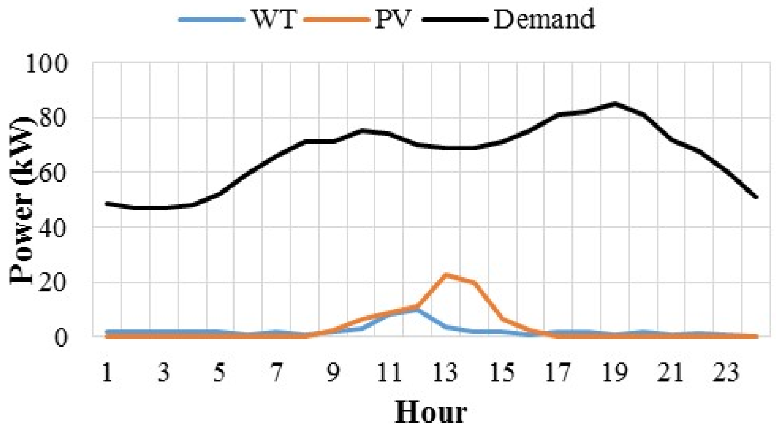


Fig. 4.1: PV Power, Wind Power and load demand

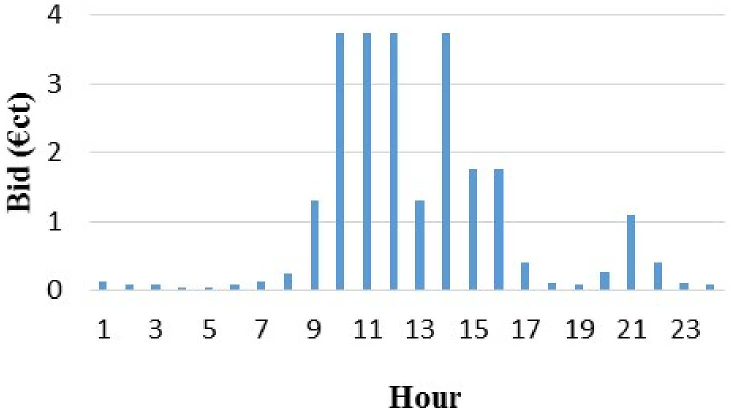


Fig. 4.2: Hourly grid bid

**Case A: Islanded Mode**

In this case, it is assumed that microgrid is operating in islanded mode, i.e., there is no exchange of power between grid and microgrid and, hence, there will be less economic benefit to microgrid. BES is connected in microgrid and it is assumed to be fully charged initially. The total cost of operation obtained in this mode is 869.5849 (€ct/day). Fig.4.3 shows the coordinated dispatch of DERs and BES for this case.

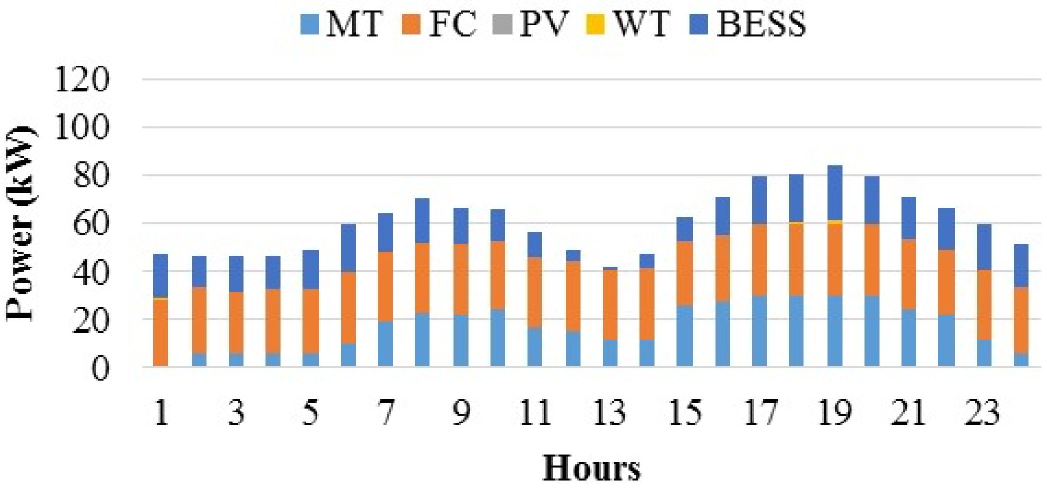


Fig. 4.3: Coordinated Dispatch for Case A

It can be analyzed from the Fig.4.3 as it is in islanded mode there is no exchange of power to the utility grid and hence less reduction in TC. Also, the BES is assumed to be fully charged. So, BES is always discharging in its SOC and power limits shown in Table. 4.1 until it is fully discharged. The reason for frequent discharging of BES is either the cost of discharging power of BES is lower than the MT or the total load demand at $t^{th}$ hour is greater than the available output power of the dispatchable and non dispatchable DGs. It is assumed that the non-dispatchble DGs are always in on state and supplying its full output power. So, these DGs dispatches for all 24 hours.

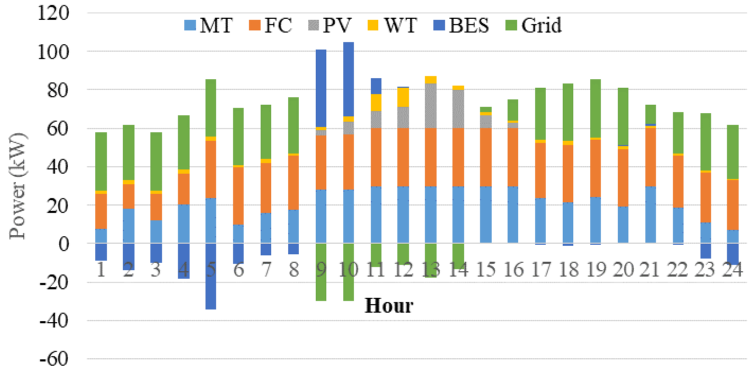
### Case B: Grid Connected Mode

In this case, microgrid with installed BES is considered to be in grid connected mode. So, there is an exchange of power between grid and microgrid. In this case, three initial SOC levelof BES are considered i.e. 1.) Minimum SOC level 2.) 50% of maximum SOC level 3.) Maximum SOC level. The total cost of operation of microgrid obtained in this mode for different SOC levels are shown in Table.4.2

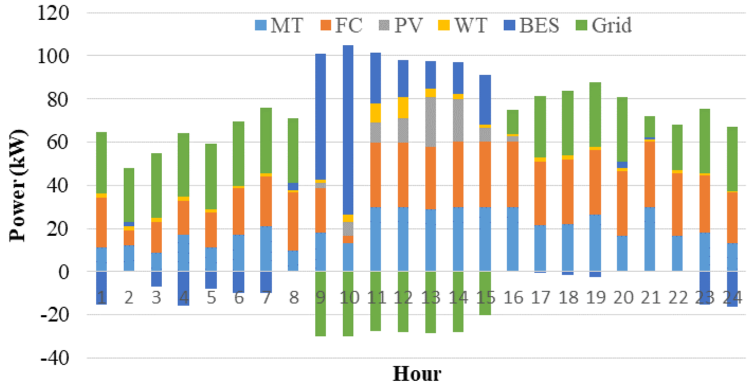
Table 4.2: Cost Comparison at different SOC levels for Case B

| SOC Levels | TC(€ct/day) |
|---|---|
| Minimum SOC level | 446.62 |
| 50% of maximum SOC level | 627.1578 |
| Maximum SOC level | 415.4322 |

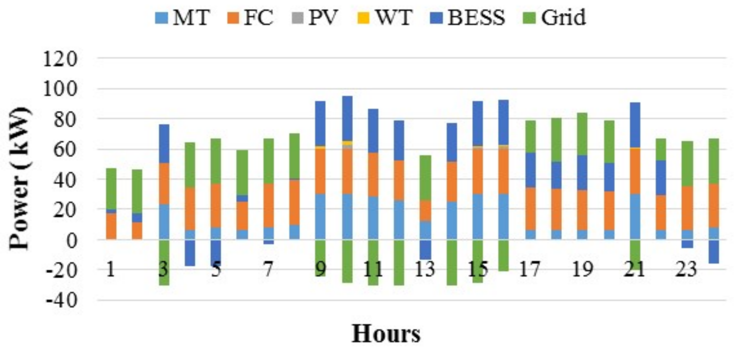
It can be clearly seen from the Fig.4.4 that the presence of the negative grid exchang-



(a) Minimum SOC level



(b) Fifty percent of maximum SOC level



(c) Maximum SOC level

Fig. 4.4: Coordinated Dispatch for Case B at different SOC levels

ing power or the selling power to the grid. In Fig.4.4(c), the microgrid is selling power to the grid between 09:00-16:00 hours mostly, the grid prices at these hours are high as shown in Fig. 4.2, ensures the profit to the microgrid operator hence reduces the TC. Likewise, in previous case, non-dispatchable DGs are considered to be always in on state. Hence, supplying power for all 24 hours at their maximum generation. MT and

FC dispatches the power as per the load demand and the lower cost coefficient. In this case BES is assumed to be fully charged. So, it is charging and discharging the power as per the available SOC, load demand, charging/discharging cost coefficient and the hourly grid price. BES mostly charging in hours between 01:00-07:00 hours and 17:00-24:00 hours when grid price is low and discharging power between 09:00-16:00, when grid prices are high. Thus, the co-ordinated charging and discharging of BES results in increased profit and reduce TC of the microgrid.

Table.4.3 shows the comparative analysis of results obtained for two modes of operation of microgrid by using proposed MEHO, IBA [47] and EHO [155] methodology. The daily total cost of operation of microgrid obtained from MEHO for case A and B are compared with EHO and IBA. Case A is not assumed in [47] so, it is not compared with IBA. It is found that the results obtained for Case A and Case B are best for the proposed MEHO.

Table 4.3: Comparative analysis of total operating cost of the microgrid using various optimization methods

| Sr. No. | Solution Methodology | Total Cost of Operation (€ct /day) | |
|---|---|---|---|
| | | Case A | Case B |
| 1 | IBA [47] | - | 424.0082 |
| 2 | EHO [155] | 885.1251 | 509.4951 |
| 3 | Proposed MEHO | 869.5849 | 415.2582 |

Table.4.3 shows the performance comparison of EHO and MEHO after 100 rial runs. It has been analysed from the table that the best, worse and mean fitness of proposed MEHO is better than the EHO.

Fig.4.5 shows the convergence characteristic of EHO and proposed MEHO.

Table 4.4: Performance Comparison of EHO and MEHO for scheduling of microgrid after 100 trial runs

| - | Best fitness | Worse fitness | Mean fitness | Standard deviation | CPU Time(sec) |
|---|---|---|---|---|---|
| EHO | 509.495 | 621.827 | 563.926 | 25.31 | 2.7 |
| MEHO | 415.258 | 523.563 | 431.282 | 28.367 | 3.8 |

It has been clearly seen from the Table.4.3 that the cost obtained by the proposed approach for case A is more than the cost obtained for case B because in case A, microgrid is considered in islanded mode and there is no exchange of power between microgrid and grid. This causes less economic benefit to the microgrid due to no exchange of

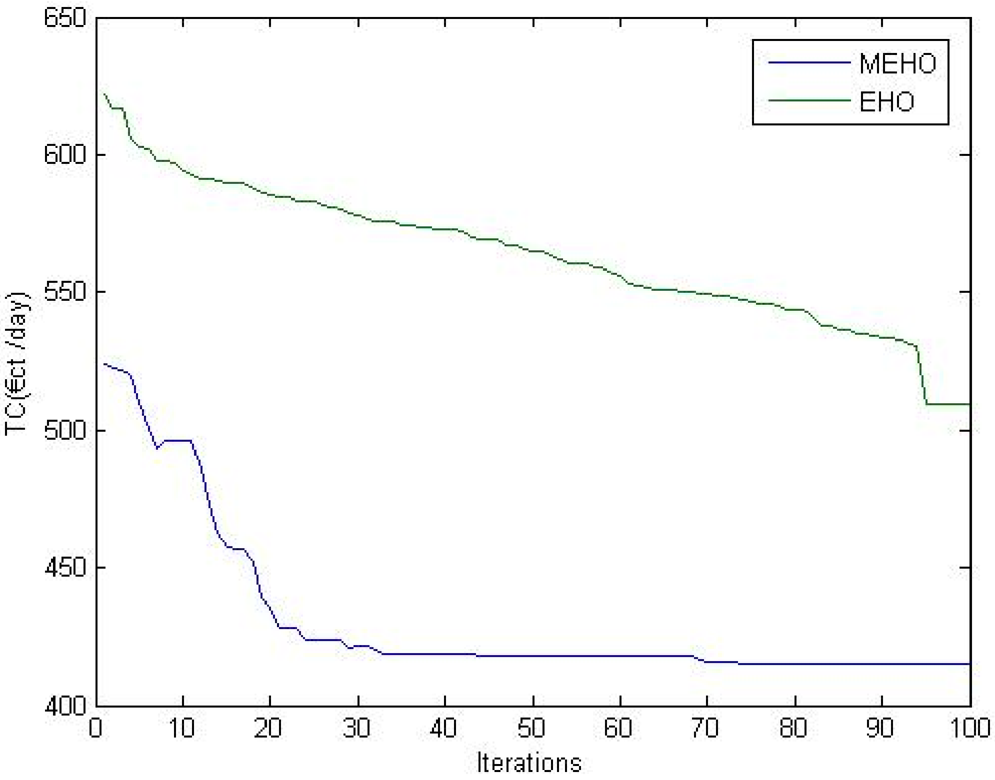


Fig. 4.5: Convergence characteristics of MEHO and EHO

power to/from the grid, while in case B, microgrid is in grid connected mode, so there is more economic benefit to the microgrid which results in reduction of total cost of the microgrid. It has been concluded from the comparative analysis of results that the proposed MEHO is able to efficiently solve the scheduling problem of microgrid.

## 4.2 Comparative Study of Deterministic and Stochastic Scheduling of Grid Connected Microgrid using MEHO

Stochastic scheduling of microgrid is based on the random values of the control variables such as output of DERs, grid prices of exchanging power to/from grid, load demand of the system etc. The randomness in the values of these variables creates the need for the stochastic scheduling of microgrid. In this section, a comparative study of deterministic and stochastic scheduling is presented to investigate the impact of uncertainty of random variables on total operating cost of the microgrid. A proposed TS based stochastic model presented in section 3.2 is used to model the random variables which are further used to formulate the problem. Both deterministic and stochastic scheduling of microgrid is performed and the total operating cost of microgrid is compared for both type of scheduling process.

### 4.2.1 Problem Formulation

In this section, the scheduling problem of microgrid is formulated. In order to know the optimal dispatches or schedules of each DERS and utility grid in the grid connected AC microgrid and to supply the load demand at minimum cost, it is required to optimize the daily total operating cost (TC) of the microgrid. TC can be defined as the total expenses incurred by the microgrid operator to supply the load demand. It is comprises of the total fuel cost of the dispatchable DGs, cost of charging/discharging the power from BES, cost of exchanging power from utility grid and startup and shutdown cost of dispatchable DGs. In this context, a mathematical expression consisting of the various decision variables such as total power output of the dispatchable and non-dispatchable DGs, total charging/discharging power of BES, total exchange power to/from utility grid along with cost coefficients is presented. The variables representing the selling power to the utility grid and charging power of BES is considered as the negative generation and hence the values of these variables are negative in the formulated mathematical expression. The purchasing power from the grid and the discharging of BES is considered as the positive variables. In this work, two types of schedulings are investigated, i.e, stochastic and deterministic scheduling.

#### Objective Function

The objective of the scheduling of microgrid is to minimize the total cost of the microgrid. Therefore, the objective function for a time horizon $T$ is defined as

$$\begin{aligned} minimize(TC) = \sum_{t=1}^{T} \Big[ \sum_{i} [a_i + (b_i \times P_{i,t})] + \sum_{n} C_n \times P_{n,t} + \sum_{j} C_j \times P_{j,t} \\ + \sum_{i} SUC_{i,t} + SDC_{i,t} \Big] + (C_{grid,t} \times P_{grid,t}) \end{aligned} \tag{4.8}$$

where, $TC$ is the total cost of the microgrid in \$, a & b are the cost coefficients of dispatchable DGs, $C_n \& C_i$ are the cost coefficients of the non-dispatchable DGs and BES respectively in \$/kW. $C_{grid,t}$ is the hourly grid price in \$/kW. $P_{i,t}, P_{n,t}, P_{j,t} \& P_{grid,t}$ are the output power of the dispatchable DGs non- dispatchable DGs and BES at $t^{th}$

hour and hourly exchange of power from utility grid respectively. $SUC_{i,t}\&SDC_{i,t}$ are the start-up cost and shut-down cost of the dispatchable DGs at $t^{th}$ hour respectively.

**Constraints**

1. Power balancing constraints

$$\begin{aligned} P_{gen,t} &= P_{load,t} \\ \text{where, } P_{gen,t} &= P_{i,t} + P_{n,t} + P_{j,t} + P_{grid,t} \end{aligned} \tag{4.9}$$

2. SOC constraints of BES.

$$SOC_{j,t}^{min} \leq SOC_{j,t} \leq SOC_{j,t}^{max} \tag{4.10}$$

3. Power limiting constraint

$$\begin{aligned} P_{i,t}^{min} \leq P_{i,t} \leq P_{i,t}^{max} \\ P_{j,t}^{min} \leq P_{j,t} \leq P_{j,t}^{max} \\ P_{grid,t}^{min} \leq P_{grid,t} \leq P_{grid,t}^{max} \end{aligned} \tag{4.11}$$

### 4.2.2 Simulation Results

In this work, A single bus grid connected AC microgrid is considered, installed with MT, FC, WT, PV and a Li-BES [45]. The energy rating of BES is 1000 kWh, $\eta_c$ and $\eta_d$ are taken as 0.9. The depth of discharge of BES is assumed as 90%. Initially, BES is assumed to be fully charged. The various cost coefficients and power limits of the considered DERs are shown in Table.4.5.

Table 4.5: Power Limits and Bids of MT, FC, PV, WT, BES and grid

| Type | $P_{min}$(kW) | $P_{max}$(kW) | Bid ($ /kWh) | a($/kWh) | b ($/kWh) | Startup & Shutdown Cost ($) |
|---|---|---|---|---|---|---|
| MT | 100 | 3000 | - | 30 | 0.13 | 150 |
| FC | 100 | 1000 | - | 80 | 0.50 | 30 |
| WT | - | - | 0.082 | - | - | - |
| PV | - | - | 0.122 | - | - | - |
| BESS | -500 | 500 | 0.07 | - | - | - |
| Grid | -1000 | 1000 | - | - | - | - |

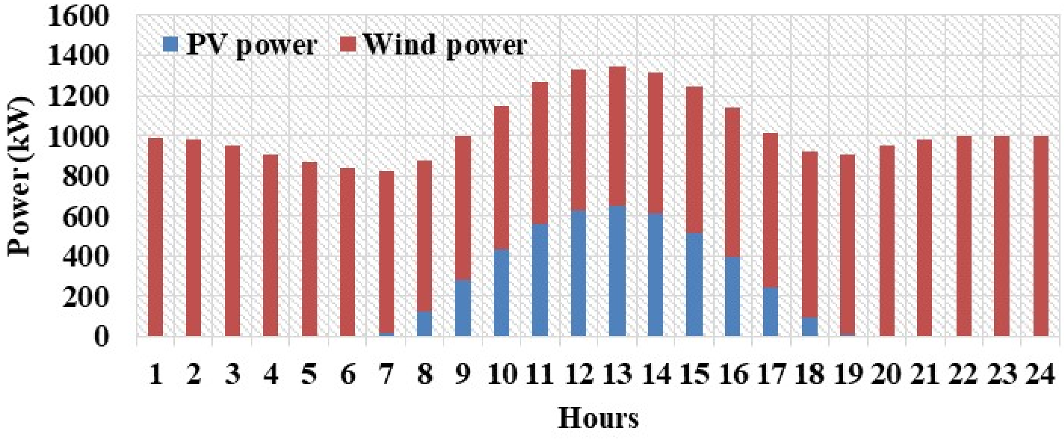


Fig. 4.6: Deterministic PV and Wind Power

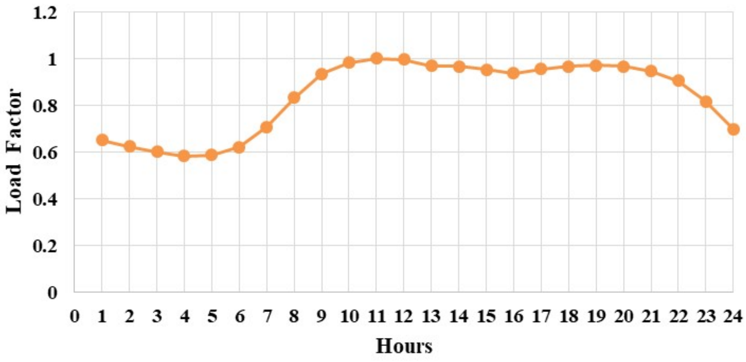


Fig. 4.7: Load factor of the system

The parameters of the WT are: $P_{wr} = 1000kW$, $v_{in} = 3m/s$, $v_{out} = 30m/s$, and $v_r = 12m/s$. The parameters of the PV source are: $\eta = 15.7\%, L = 0.75$ and $S = 7000m^2$.The system has a peak load of 4000 kW. The Time of Use (TOU) grid prices for selling and purchasing the power to/from the utility grid are considered as 0.055$/kWh (if $loadfactor <= 0.5$), 0.072 $/Kwh (if $0.5 < loadfactor <= 0.75$) and 0.122 $/kWh (if $loadfactor > 0.75$). It is assumed that non-dispatchable DGs are always in on state and generating the forecasted power. Fig.4.6 shows the deterministic output power of the wind and PV. Fig. 4.7 shows the deterministic load factor of the load demand for the considered system.

A modified elephant herding optimization algorithm which is discussed in section 3.3 is implemented to solve the formulated problem for two types of scheduling i.e. deterministic scheduling and stochastic scheduling. The parameters of MEHO, $\alpha$ and

$\beta$ are set to 0.8 and 0.1 respectively. The population of elephants in a clan is taken as 60, and the maximum number of iterations is considered as termination criteria which is set to 30. The wind power, PV power and load demand of the system are forecasted using the proposed stochastic approach discussed in section 3.2 and are shown in Fig. 4.8 and Fig. 4.9, respectively. Fig. 4.10 shows the comparison of the total cost of the microgrid obtained after minimizing the formulated objective function in section 4.2.1. It can be observed from the Fig. 4.10 that there is vast difference in TC for stochastic and deterministic scheduling of microgrid. As the power generated from renewable is intermittent in nature and load demand is also unpredictable, the stochastic model provides more realistic results as compared to deterministic model. Also, the stochastic scheduling manifested the significant effects on daily scheduling of the microgrid as reduction in TC by 15.65 % in stochastic scheduling over deterministic scheduling is noticed which is worthy of attention for operational planning of the microgrid.

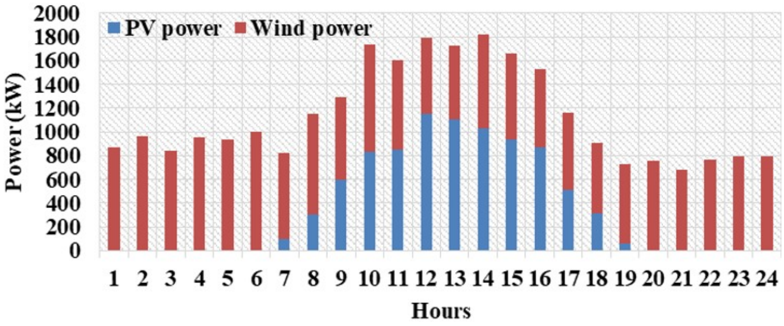


Fig. 4.8: Stochastic PV and Wind Power

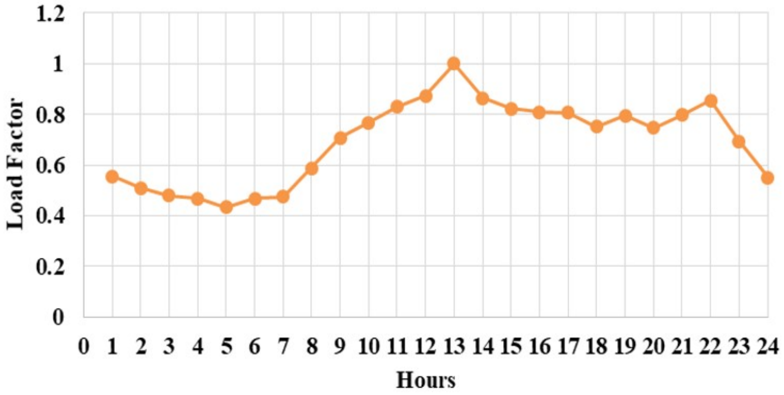


Fig. 4.9: Stochastic load factor of the system

Figs.4.11(a) and 4.11(b) shows the scheduling of DERs, BES and utility grid for deterministic and stochastic scheduling of microgrid respectively. As per the TOU grid pricing discussed above and the load factor shown in Figs.4.7 and 4.9, the grid

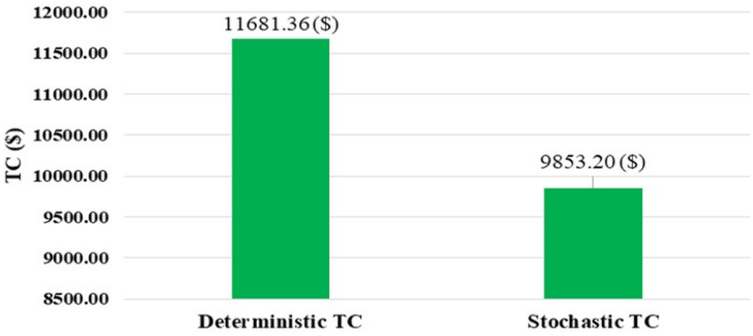
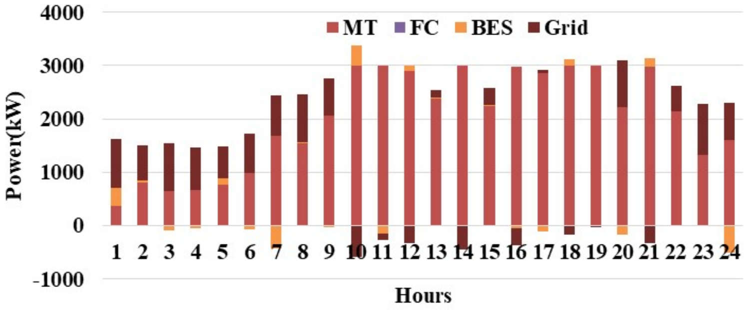
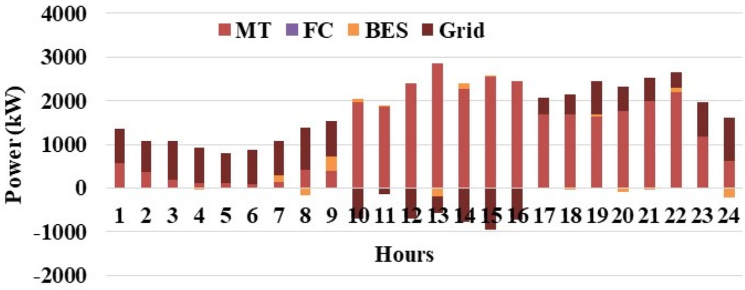


Fig. 4.10: Comparison of deterministic and forecasted TC

prices are 0.072$/kWh between 01:00-07:00 hours and 0.122$/kWh between 08:00-24:00 hours in case of deterministic scheduling. In stochastic scheduling the grid prices are 0.055$/kWh between 01:00-07:00 and 23:00-24:00 hours, 0.072$/kWh during 08:00-10:00 and 0.122$/kWh 11:00-22:00 hours. The MT and FC dispatches the power as per their cost coefficients and startup and shutdown cost, the cheapest DG will dispatch first. However, BES will dispatch the power as per the SOC available and the cost coefficient. The BES will act as load and generator when the grid prices are low and high respectively. The microgrid is selling the power to the utility grid when the grid prices are high and purchasing the power, when the grid prices are low. The non-dispatchable DGs are considered always in on state and the dispatches the power as shown in Figs.4.6 and 4.8 for both type of scheduling.



(a) Deterministic scheduling of DERs and utility grid



(b) Stochastic scheduling of DERs and utility grid

Fig. 4.11: Scheduling of Microgrid

## 4.3 Summary

In this chapter, the scheduling problem of microgrid is solved by the MEHO algorithm. The quantitative results show that the total cost obtained using proposed methodology for the assumed cases is less than the other swarm based intelligent techniques existing in the literature. Also, a new stochastic model to predict the uncertain renewable resources and system load demand is developed and discussed. The proposed MEHO is explored to solve the formulated deterministic and stochastic scheduling problem of microgrid. The study reveals a significant impact of stochastic scheduling over the deterministic scheduling which results in noteworthy reduction in total cost of the microgrid. It may be concluded that the proposed optimization method has potential to solve the complex scheduling problem of microgrid. Moreover, the proposed stochastic model can forecast more realistic renewable generation and load demand which may be very useful for better decision making for optimal operational management strategies of microgrid.

## Chapter 5

# Planning and Operation of Battery Energy Storage in Grid Connected Microgrids

The salient features of BES as discussed in chapter 1 could bring economic benefits to the microgrid owner when it is operated optimally, i.e., coordinated charging/discharging schedule of BES power with the utility grid. Apart from this, BES may also be beneficial in decreasing the carbon emissions from utility grid and different generating units installed in microgrid such as FC, MT and small scale diesel turbine etc. This could be possible by discharging available power optimally at different instants of time. Thus, to optimally operate the microgrid, sizing of BES plays an important role in the microgrid. Moreover, frequent operation of the BES in microgrid may effect the SOH and thus, reduces its useful life. Thus, it is necessary to investigate the optimal operation of BES taking cycle age in to consideration. In this chapter, a multi-objective framework for the sizing of BES for grid connected microgrid is presented. Also, the multi-objective optimal operation of Li-BES considering lifetime characteristics is also investigated.

## 5.1 Optimal Planning of Battery Energy Storage in Grid Connected Microgrid

The motivation behind the multi-objective planning of the BES in this work is the techno-economical and environmental concern. The global warming rises the concern for the world to take steps to control it. The carbon credit and carbon offset protocols allow many countries who are the leaders in producing carbon emissions to take controllable measures by using green technologies. In this way, there is an opportunity to these leader countries for trading of carbon credits which not only beneficial from the point of economic profits but also for the environmental benefit. In this context, this work proposes a multi-objective framework for the sizing of BES in which the aim of the microgrid operator is to minimize the daily TC and emissions to gain both techno-economic and environmental benefits.

### 5.1.1 Problem Formulation

In this section, multi-objective BES sizing is mathematically formulated. The two different objectives such as total cost of the microgrid and total emissions from the DGs, BES and utility grid is mathematically expressed. The TC comprises of the fuel cost of the DG units, startup and shutdown cost of the dispatchable DGs charging/discharging cost of the BES, cost of exchanging power from the utility grid and total cost per day of battery while the total emission constitutes with total emissions from non-renewable DG units, BES and utility grid. Following three different cases are considered for which the problem is investigated:

1. Case A: In this case BES sizing problem is investigated when only TC is minimized.

2. Case B: In this case BES sizing problem is investigated when only emissions are minimized.

3. Case C: In this case BES sizing problem is investigated when both TC and emissions are minimized simultaneously.

#### Objective Function

The optimal sizing of BES aims to reduce the total cost of the microgrid, the total emissions from the generating units installed in microgrid and from utility grid for a finite time horizon $T$.

$$\begin{aligned} minf_1 = \sum_{t=1}^{T}\Bigg[\sum_{i=1}^{U}\Big(u_{i,t}(P_{i,t}\times C_i)+SUC_{i,t}+SDC_{i,t}\Big)+ \\ \sum_{n=1}^{S}\Big(u_{n,t}(P_{n,t}\times C_n)\Big)+(P_{grid,t}\times C_{grid,t})\Bigg]+TCPD \end{aligned} \tag{5.1}$$

where, $U$ is the total number of DG units, $S$ is the total number of BES. $u_{i,t}$ and $u_{n,t}$ are the unit status of the both the renewable and non-renewable DG units and BES at $t^{th}$ respectively. $P_{i,t}$,$P_{n,t}$ and $P_{grid,t}$ are the output power of DG units, BES and exchanging power from the utility grid respectively at $t^{th}$ hour $C_i$, $C_n$ and $C_{grid,t}$ are the cost coefficients of power from DGs, BES and grid respectively.

$$minf_2 = \sum_{t=1}^{T}\Bigg[\sum_{i=1}^{U}(P_{i,t}\times e_{m,i})+\sum_{n=1}^{S}(P_{i,t}(P_{n,t}\times e_{n,i})\Bigg]+(P_{grid,t}\times e_{m,grid}) \tag{5.2}$$

where, $e_{m,i}$ and $e_{m,grid}$ are the total emissions of DG units and utility grid.

$$F = optimal[f_1, f_2] \tag{5.3}$$

$$TCPD = \frac{1}{365}\Bigg[\Bigg(\frac{r(1+r)^l}{(1+r)^l-1}FC\times ES\Bigg)+ES\times MC\Bigg] \tag{5.4}$$

where, $TCPD$ is the total cost/day of BES, $r$ is the rate of interest of BES, $l$ is the life time of BES, $FC$ is the fixed cost of BES, $ES$ is the size of the BES and $MC$ is the maintenance cost of the BES.

**Constraints**

1. Power balancing constraint

$$P_{gen,t} - P_{load,t} = 0 \tag{5.5}$$

2. Power limiting constraints of DG units, BES and grid

$$\begin{aligned} P_{i,t}^{min} \le P_{i,t} \le P_{i,t}^{max} \\ P_{n,t}^{min} \le P_{n,t} \le P_{n,t}^{max} \\ P_{grid,t}^{min} \le P_{grid,t} \le P_{grid,t}^{max} \end{aligned} \tag{5.6}$$

3. SOC constraints of the battery

$$SOC_{n,t}^{min} \le SOC_{n,t} \le SOC_{n,t}^{max} \tag{5.7}$$

## 5.2 Methodology

In this work the combination of PSO and TOPSIS discussed in section 3.3.1 and section 3.3.4 is implemented to solve the formulated problem. PSO is an swarm intelligence based optimization technique whereas TOPSIS is decision making method. The combination of these techniques use to solve the multi-objectives problems in which PSO optimizes the problem whereas TOPSIS helps in selecting the optimal set of the multi-objective solution among the multiple sets of the multi-objective solutions. The objectives are evaluated by assigning equal weightage, the acceleration coefficients in PSO are set to 2, the maximum and minimum value of inertia weight is taken as 0.9 and 0.4 respectively, the PSO is implemented with the swarm size of 50 and maximum number of iteration is set to 30. Fig.5.1 shows the flowchart of the optimization technique implemented.

### 5.2.1 Simulation Results

A grid connected microgrid consisting of MT, FC, PV, WT and BES is considered as a test system in this work [47]. The fixed cost, maintenance cost and the life time of Li-BES is assumed as 465 €ct/kWh, 15 €ct/kWh and 3 years respectively. Also the charging and discharging efficiency of the Li-BES is considered as 0.9. The initial SOC of Li-BES is assumed to be equal to its full capacity and the minimum SOC limit of Li-BES is considered as 10% of its full energy rating. The maximum range for sizing of BES is considered as 1700 kWh and each size is taken with the increase in step size of 100 kWh.

It is assumed that the unit status of the WT and PV is always equal to one. The daily load demand and the generated power from wind and PV is shown in Fig.5.2. Fig.5.3 shows the market price which varies hourly. Table.5.1 shows the power limits, bids and emissions of different DGs, BES and utility grid. The multi-objective sizing of BES is solved for the considered test system and a detail analysis is performed and discussed.

The total cost and emission for the considered test system is obtained after minimizing both the objectives individually for each size of the BES is shown in Figs.5.4(a) and 5.4(b), respectively. It can be clearly seen from the results that the obtained optimal size of BES is 300 kWh with TC 923.06 €ct, in case when only TC is minimized; However, if emission is merely minimized, the optimal size of BES is 800 kWh with total emis-

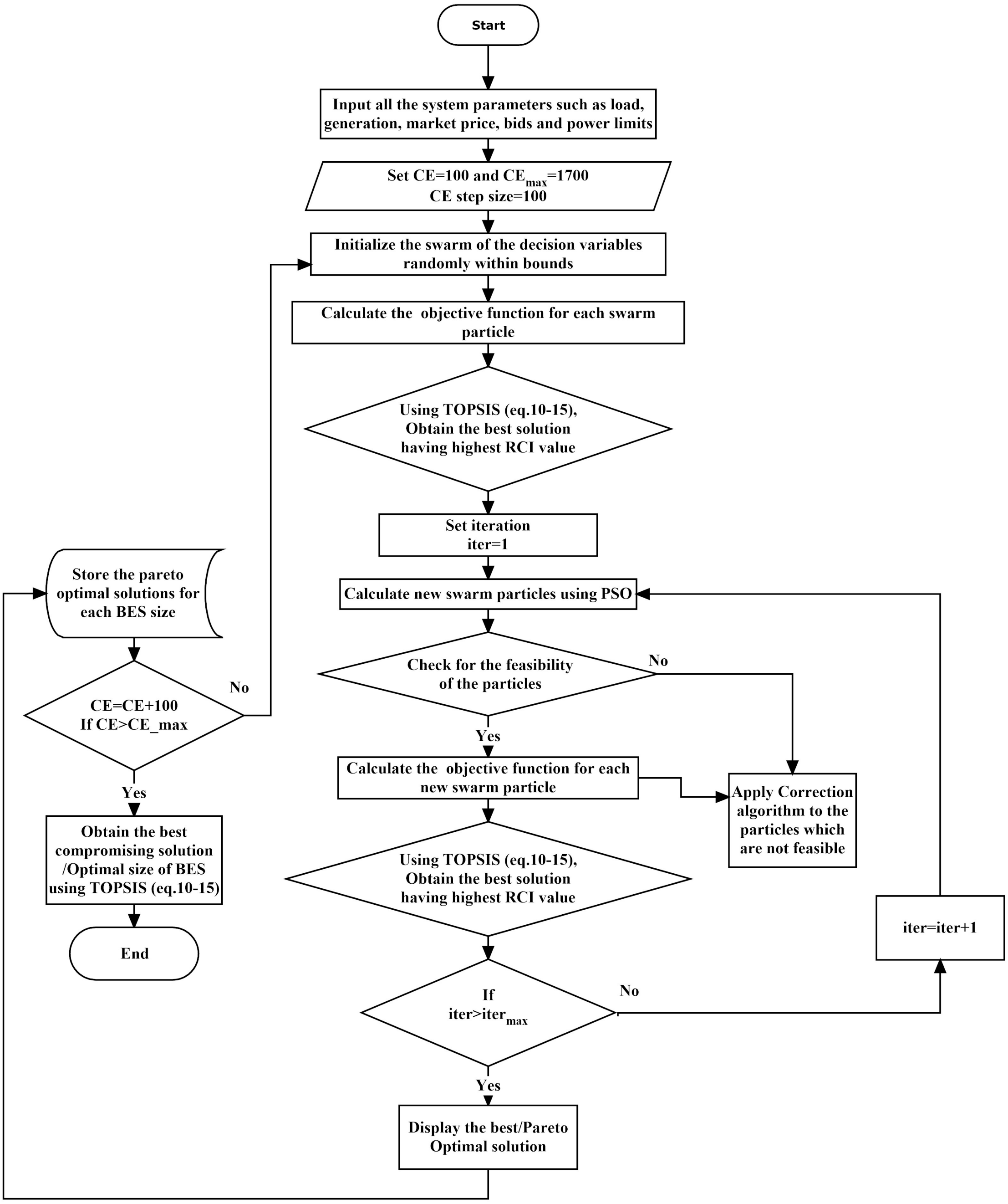


Fig. 5.1: Flow chart of the PSO-TOPSIS implemented for sizing of the BES

sions of 621.78 kg/MWh. The curve showing a relation between the size of BES and the optimal solutions after minimizing the total cost and emissions of the microgrid simultaneously is shown in Fig.5.4(c). The optimal size of BES for the multi-objective problem is 700 kWh, which is obtained as the best compromising solution having highest RCI index value in all the optimal solutions obtained after solving the formulated objectives simultaneously. The total cost obtained for the optimal size of BES is 1123.13 €ct and the emission is 776.09 kg/MWh. It has been also, observed from the Fig.5.4(c) that

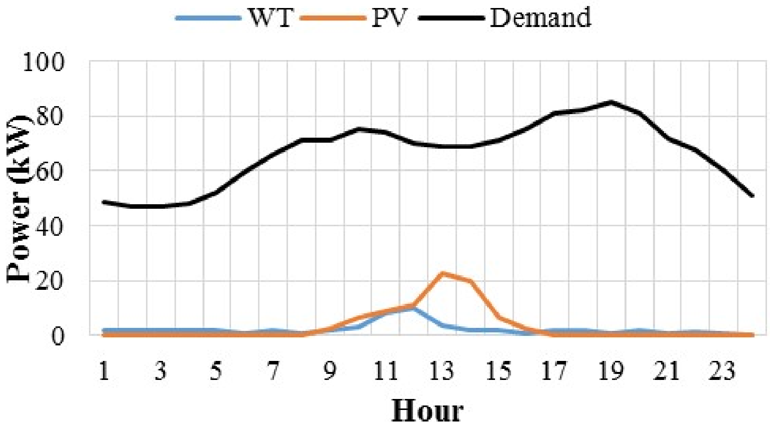


Fig. 5.2: Forecasted PV Power, Wind Power and load demand

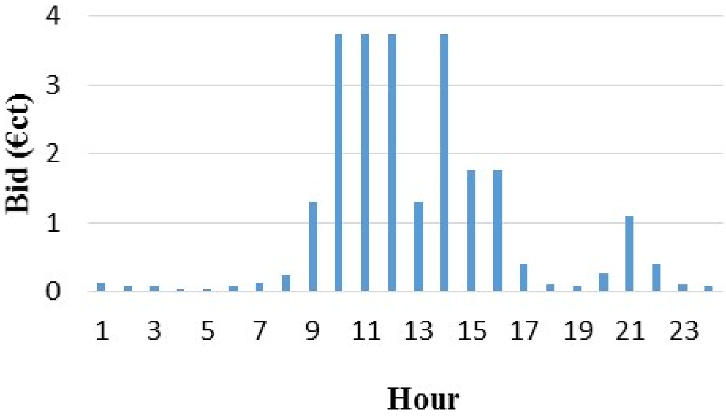
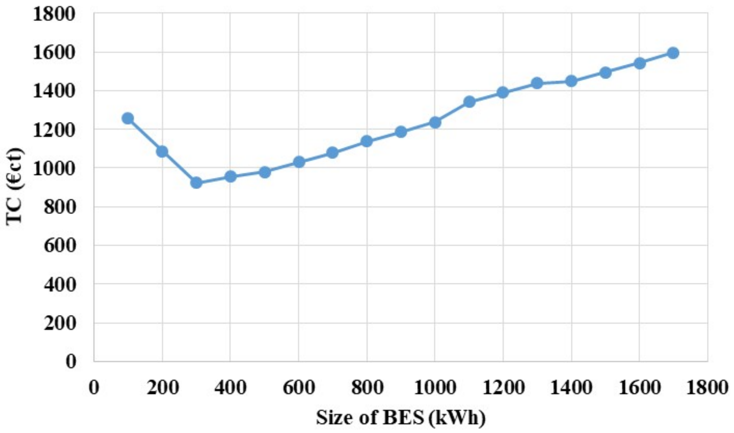


Fig. 5.3: Hourly Grid Bid

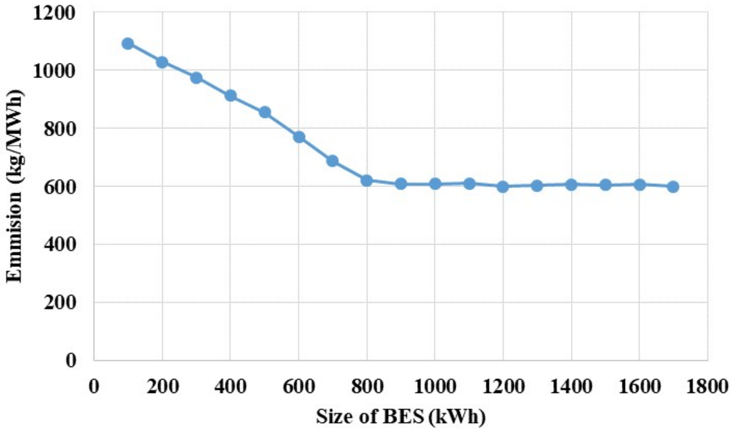
Table 5.1: Power limits, bids and emissions

| Type | $P_{min}$ (kW) | $P_{max}$ (kW) | Bid (€ct/kWh) | OM Bid (€ct/kWh) | Startup & Shutdown Cost (€ct) | CO2 (kg/MWh) | SO2 (kg/MWh) | NOx (kg/MWh) |
|---|---|---|---|---|---|---|---|---|
| MT | 6 | 30 | 0.457 | 0.0446 | 0.96 | 720 | 0.036 | 0.1 |
| FC | 3 | 30 | 0.294 | 0.08618 | 1.65 | 460 | 0.03 | 0.0075 |
| PV | 0 | 25 | 2.584 | 0.2082 | 0 | 0 | 0 | 0 |
| WT | 0 | 15 | 1.073 | 0.525 | 0 | 0 | 0 | 0 |
| BES | 30 | 30 | 0.38 | - | 0 | 10 | 0.02 | 0.01 |
| Grid | 30 | 30 | - | - | - | 1072 | 0.6 | 7.0 |

after 700 Kwh, TC is increasing continuously while the total emission remains approximately the same for further BES sizes. This is due to the fact that TC is increasing with TCPD, which is continuously increasing with the increase in size of BES by 51.77 €ct at each step size while the emissions are dependent on the output of the generating

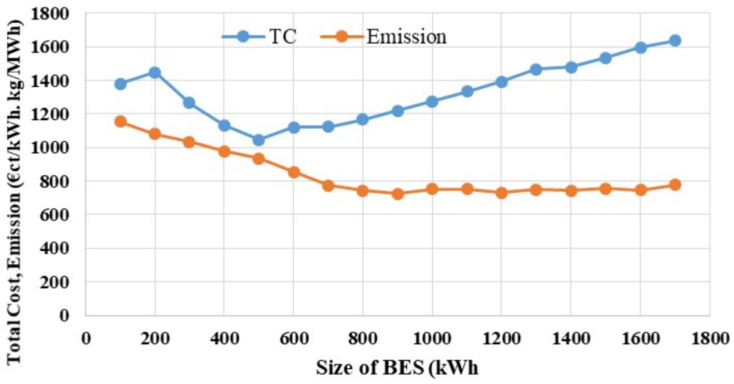


(a) Optimal solutions at each BES size for case A



(b) Optimal solutions at each BES size for case B

sources, BES and the utility grid. Thereby, a trade-off between the two objectives is noticed.



(c) Optimal solutions at each BES size for case C

Fig. 5.4: Optimal solutions at each BES size

Fig.5.5 shows the scheduling of the microgrid for the obtained optimal size of the BES. It can be observed from the figure that a trade off lies between the charging/discharging of BES and exchanging power to/from grid. Microgrid sells the power to the grid when the grid prices are high to ensure the maximum profit and reduced TC whereas the BES discharges power at the time of higher grid prices and vice versa. Scheduling of microgrid for case C reveals that the selling of power to utility grid is taking place between 09:00-16:00 hours and 20:00-21:00 hours, one can clearly see from the Fig.5.3 that at these hours grid prices are high. So, the microgrid operator is getting the profit and reduced TC. BES is assume to be fully charged in this case. So, it is charging/discharging as per its available SOC status, power limit and cost coefficient. The non-renewable DG such as MT and FC are dispatched as per their power limits, fuel cost and startupand shutdown cost.

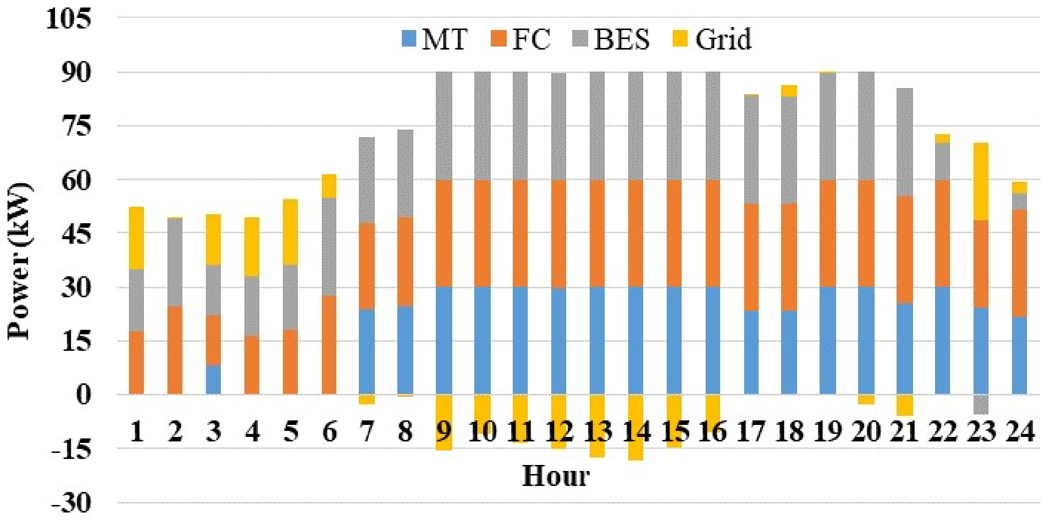


Fig. 5.5: Scheduling of microgrid for the optimal size of BES in case C

## 5.3 Optimal Operation of Battery Energy Storage in Grid Connected Microgrid

In this section the multi-objective operational management of the grid connected AC microgrid considering lifetime characteristics of Li-BES is presented. A multi-objective operational management problem of microgrid is formulated to minimize the total operating cost of the microgrid as well as the total wear cost of the BES simultaneously to get the optimal scheduling of microgrid along with maximized Li-BES life while maintaining its good State of Health (SOH). To solve the formulated complex multi-objective problem a PSO-TOPSIS is implemented. The motivation behind this multi-objective framework is to optimize the frequent charging/discharging of Li-BES in optimal operation of microgrid along with minimization of TC. The aim is to investigate the scheduling of microgrid while BES to maintain the good SOH and increased cycle age life of the Li-BES.

### 5.3.1 Problem Formulation

The mathematical formulation of the multi-objective operational problem of BES consists of two different objectives such as minimization of the daily TC of the microgrid as well as total wear cost of the BES. TC includes the fuel cost of the DGs, startup and shutdown cost of the non-renewable DGs, charging/discharging cost of BES and cost of exchanging power from the utility grid whereas the total wear cost discussed in section3.1.2 constitutes the depth of discharge and no.of life cycle count during each charging/discharging transition of BES, charging/discharging efficiency of BES, size of the BES and total investment cost of the BES. Following three different cases are considered for which the problem is investigated:

1. Case 1: In this case, operational problem of microgrid is investigated when only TC is minimized.

2. Case 2: In this case, operational problem of microgrid is investigated when only total wear cost of Li-BES is minimized.

3. Case 3: In this case, operational problem of microgrid is investigated when both TC and Total wear cost of Li-BES is optimized.

#### Objective Function

The objective is to minimize the total operating cost of microgrid and total Li-BES wear cost installed in microgrid for a finite time horizon $T$ is given by

$$\begin{aligned} min f_1 = \sum_{t=1}^{T} \Bigg[ \sum_{i=1}^{U} \Bigg( u_{i,t}(P_{i,t} \times C_i) + SUC_{i,t} + SDC_{i,t} \Bigg) + \\ \sum_{n=1}^{S} \Bigg( u_{n,t}(P_{n,t} \times C_n) \Bigg) + (P_{grid,t} \times C_{grid,t}) \Bigg] \end{aligned} \tag{5.8}$$

where, $U$ is the total number of DG units, $S$ is the total number of BES. $u_{i,t}$ and $u_{n,t}$ are the unit status of the both the renewable and non-renewable DGs units and BES at $t^{th}$ respectively. $P_{i,t}$,$P_{n,t}$ and $P_{grid,t}$ are the output power of DG units, BES and exchanging power from the utility grid respectively at $t^{th}$ hour $C_i$, $C_n$ and $C_{grid,t}$ are the cost coefficients of power from DGs, BES and grid respectively.

$$min f_2 = \sum_{t=1}^{T} (u_{BES,t} \times C_{W,t}) \tag{5.9}$$

where, $u_{BES,t}$ and $C_{W,t}$ are the cycle transition status and wear cost of the BES at $t^{th}$ hour.

$$F = optimal[f_1, f_2] \tag{5.10}$$

#### Constraints

1. Power balancing constraint

$$P_{gen,t} - P_{load,t} = 0 \tag{5.11}$$

2. Power limiting constraints of DG units, BES and grid

$$\begin{aligned} P_{i,t}^{min} \leq P_{i,t} \leq P_{i,t}^{max} \\ P_{n,t}^{min} \leq P_{n,t} \leq P_{n,t}^{max} \\ P_{grid,t}^{min} \leq P_{grid,t} \leq P_{grid,t}^{max} \end{aligned} \tag{5.12}$$

3. SOC constraints of the battery

$$SOC_{n,t}^{min} \leq SOC_{n,t} \leq SOC_{n,t}^{max} \tag{5.13}$$

### 5.3.2 Simulation Results

A grid connected microgrid installed with a WT, PV, MT, FC and a Li-BES is considered as a test system in this work. Fig.5.2 shows the load demand of the system and renewable power generation. Table.5.1 shows the power limits and bids of the DGs, BES and grid. Hourly grid prices are shown in Fig.5.3. A Li-BES has a capacity of 300 Kwh with fixed cost of 465 €ct/kWh. The charging and discharging efficiency are set to 90% and the minimum state of charge considered as 10% of the full capacity of Li-BES. The Li-BES assumed to be fully charged initially The formulated problem is solved using PSO-TOPSIS for three different cases: 1) When only total operating cost is minimized 2) When only wear cost of BES is minimized 3) When both operating cost and wear cost of BES is minimized simultaneously. The effect of degradation cost on microgrid scheduling is analyzed after solving the formulated problem. Fig.5.6 shows the flow chart of the PSO-TOPSIS implemented to solve the formulated problem in section 5.3.1 Fig.5.7 shows the charging and discharging pattern of Li-BES for the considered three operational cases and the scheduling of microgrid. respectively. Fig.5.8 shows the cost comparison for all the considered operational cases. It can be clearly seen from the results that the scheduling of grid connected microgrid is effected by the wear cost of the Li-BES while one can observe the charging/discharging patterns of the Li-BES for all the considered operational cases are different. The TC obtained for the case 1 is 753.29 €ct, for case 2 wear cost is 701.05 €ct and for case 3 the TC and wear cost obtained is 826.51€ct and 1076.4€ct. Figs.5.7(a), 5.7(b)and 5.7(c) shows the charging/discharging pattern of Li-BES for case 1, case 2 and case 3. The positive values indicates the discharging of BES while the negative means charging of BES. It can

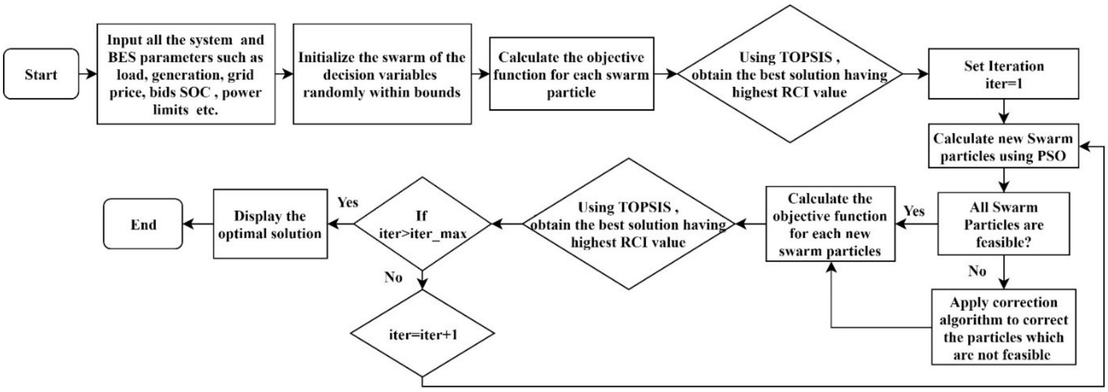
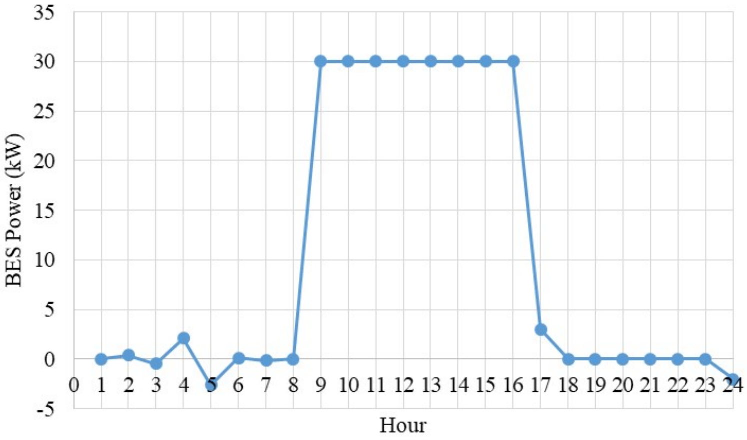


Fig. 5.6: Flow chart of the PSO-TOPSIS implemented for optimal operation of the BES

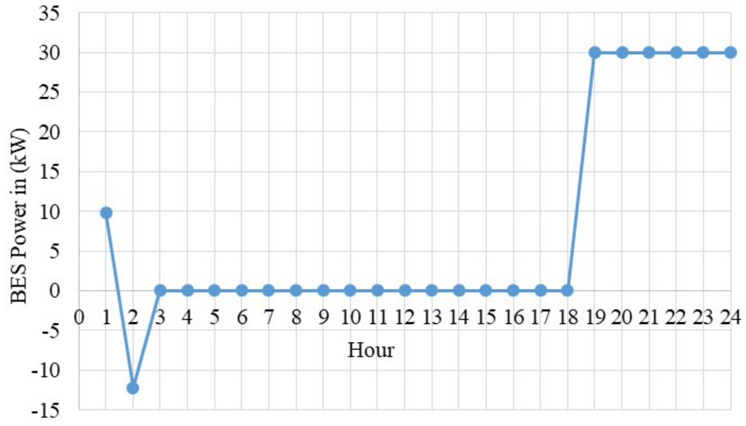


(a) Li-BES charging/discharging power for case 1

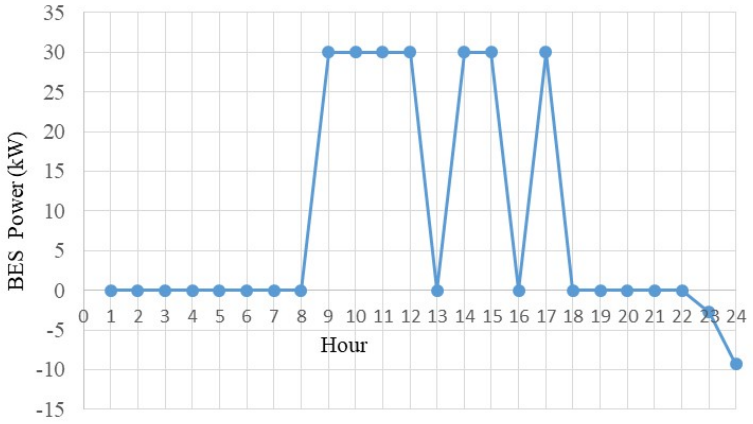
be observed from the Fig.5.7(a) that the Li-BES is discharging at its maximum power between 08:00-17:00 hours, the grid prices during these hours are maximum as shown in Fig.5.3, The objective in this case is to minimize the TC only, thus the discharging pattern will result in increased profit and reduced TC. In case 2, the objective is to minimize the total wear cost of the Li-BES, It can be clearly seen from the Fig.5.7(b) that the BES is maintaining the low charging/discharging transition states. Thus, helps in reducing the total-wear cost of Li-BES.

The objective for case 3 is to optimize the TC and total wear cost of Li-BES simultaneously. From Fig.5.7(c), the charging/discharging pattern is noticed. The pattern reveals that the BES is discharging power during high grid prices between 08:00-12:00 hours, 14:00-15:00 and at 17:00 hours and charging during low grid prices 23:00-24:00 hours. Charging discharging pattern ensures the reduction in TC while. It may also be observed that the transition of the charging/discharging of BES frequently obtained during 08:00-18:00 hours which is a interval of high grid prices. The transition of cycles and discharging of BES are simultaneously responsible for the optimization of the multi-objective problem. Thus, ensures the multi-objective operation of the BES in microgrid.

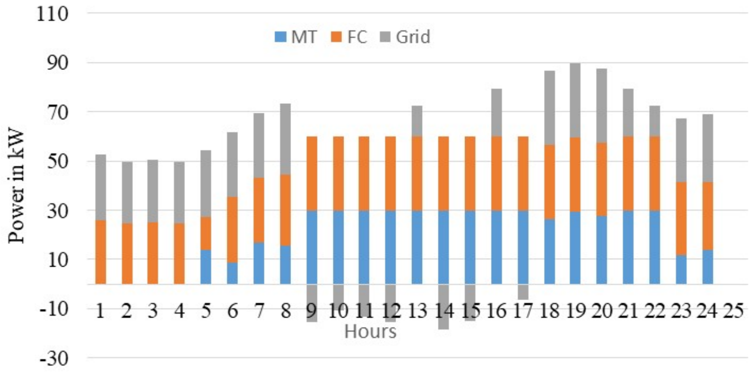
The Fig.5.7(d) shows the scheduling of MT, FC and utility grid. It can be noticed from the figure that the MT and FC are supplying power to fulfill the system load demand as per their fuel cost, startup and shut down cost whereas the negative values of grid showing utility grid is purchasing power between 09:00-17:00 hours which are also the time interval for discharging power of BES as shown in Fig.5.7(c). The higher grid



(b) Li-BES charging/discharging power for case 2



(c) Li-BES charging/discharging power for case 3



(d) Scheduling for case 3

Fig. 5.7: Simulation results for optimal operation of BES in microgrid

prices in this interval makes the purchasing of power by utility grid is a profitable deal to the microgrid operator as well as the discharging of BES in this interval ensures the optimal operation of BES in scheduling of microgrid.

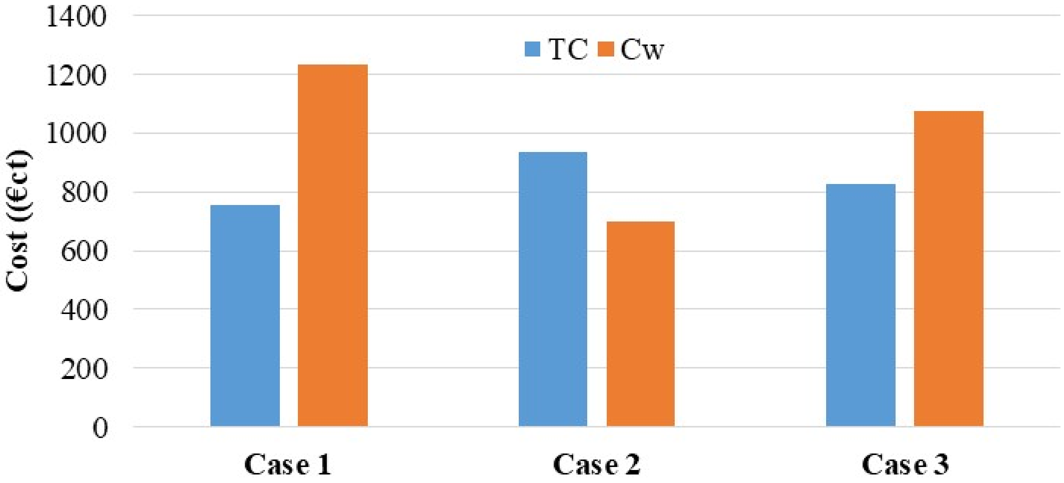


Fig. 5.8: Cost comparison for considered operational cases

Fig.5.8 shows the cost comparison between TC and total wear cost for the considered three cases. The figure reveals that TC is less than the total wear cost of Li-BES in case 1 while in case 2 total wear cost of Li-BES is less than TC, This is due to reason that in case 1, the objective is to minimize the TC only while in case 2, the objective is to minimize total wear cost of Li-BES. Also, the investigation reveals that TC obtained in case 3 is more than the TC obtained in case 1 but less than the TC obtained in case 2. Similarly, total wear cost obtained in case 3 is more than the total wear cost obtained in case 2 but less than the total wear cost obtained in case 3. This is due to the fact that in case 3 both TC and total wear cost is optimized simultaneously.

## 5.4 Summary

A multi-objective problem for optimal sizing of BES in microgrid is formulated and solved. A detailed analysis is performed in which the significant impact of sizing of BES on the operating cost and emission of microgrid is noticed. A combined PSO-TOPSIS multi-objective technique is successfully explored and the results shows a trade-off between the two objectives which validates that the proposed technique is able to solve the formulated problem in an efficient manner. Also, a multi-objective operational problem of microgrid considering cycle age of Li-BES is formulated and solved using PSO-TOPSIS. The study reveals that the useful life of Li-BES can be increased by scheduling the microgrid considering cycle age of Li-BES as a cost function. The different charging patterns of BES effects the total operating cost of the microgrid as well as the useful cycle life of Li-BES.

# Chapter 6

# Optimal Operation of Electric Vehicles in Grid Connected Microgrids

The shifting of EVs from fossil fuels to the electricity laying down the extra burden on electrical distribution systems as EVs acts as load demand on the distribution system when it is in charging mode. EVs can generate as well as consume the electrical energy when in discharging and charging mode respectively. The large penetration of renewable DGs and EVs rises the uncertainties in generation and load as well. This increases the necessity to manage the supply demand scenario in microgrid with gaining of the maximum benefits to the microgrid operator and vehicle owners without compromising technical factors of the supply system and EVs also. In this chapter, a new charging/discharging model of PHEVs in an office microgrid is proposed considering various uncertainties associated with driving distance of PHEVs and renewable power generation. The problem is formulated and solved using PSO. Various uncertainties such as uncertainty in PV power output and ECF of the PHEV is modeled using montecarlo simulation discussed in chapter 3. The proposed model is compared with the existing charging/ discharging strategy commonly used in the literature where vehicles are charged during low grid prices and discharged during high grid prices.

## 6.1 Problem Formulation

This section presents the mathematical formulation for the optimal operation of PHEVs in microgrid. The motivation to formulate the framework for optimal operation of

PHEVs in microgrid is to manage the extra burden of load demand due to EVs penetration in the distribution system, to gain the economic benefits to the microgrid owner, to increase the economic benefits of the vehicle owners and to promote the EV penetration in distribution system. The TC of the microgrid is comprises of the fuel cost of the DG units, startup cost of the DG units and cost of exchanging power to/from the grid.

### 6.1.1 Objective Function

The aim is to minimize the total cost of operation of microgrid for achieving maximum benefits both for the microgrid operator as well as vehicle owners. Thus, the objective function is to minimize the total cost of operation of the microgrid integrating PHEVs for a fixed time horizon $T$ i.e. 24 hours given by

$$\begin{aligned} TC = min\sum_{t=1}^{T}(cost_{units,t} + cost_{grid,t}) + \sum_{n} SUC_{n,t} \\ cost_{units,t} = \sum_{n} P_{unit,n,t} \times C_{unit,n,t} \\ cost_{grid,t} = P_{grid,t} \times C_{grid,t} \end{aligned} \tag{6.1}$$

where, $P_{unit,n,t}$ and $P_{grid,t}$ are the output power of $n^{th}$ type of DG unit and exchange power to/from grid utility at $t^{th}$ hour respectively. $C_{units,n,t}$ and $C_{grid,t}$ are the fuel cost of $n^{th}$ type of DG unit and cost of exchanging power from grid at $t^{th}$ hour respectively.

### 6.1.2 Constraints

1. Power Balance Constraints

$$P_{gen,t} - P_{load,t} \tag{6.2}$$

2. Power Limiting Constraints

$$\begin{aligned} P_{unit,n,t}^{min} \le P_{unit,n,t} \le P_{unit,n,t}^{max} \\ P_{grid,t}^{min} \le P_{grid,t} \le P_{grid,t}^{max} \\ P_{PHEV,i,t}^{min} \le P_{PHEV,i,t} \le P_{PHEV,i,t}^{max} \end{aligned} \tag{6.3}$$

3. SOC Constraints of BES of PHEVs

$$SOC_{PHEV,i,t}^{min} \le SOC_{PHEV,i,t} \le SOC_{PHEV,i,t}^{max} \tag{6.4}$$

## 6.2 Methodology

In this work, PSO discussed in section 3.3.1 is implemented to optimize the formulated problem. The pop size is taken as 50, no. of iterations are 30 and no. of trials are 100. Acceleration coefficients ($C_1$and $C_2$) are set to 2 which is suggested in the basic PSO.

## 6.3 Simulation Results

In this study a grid connected office microgrid is considered as a test system [126], consists of a MT, FC and PV. In this work, two categories of PHEVs are considered, i.e,. office vehicles (OV) and employees's vehicles (EMVs) unlike in addition to [126] . The total no. of PHEVS are 10, out of that 3 are considered as OVs and 7 are EMVs. The available charging /discharging time of the vehicles are different for different categories of PHEVs i.e. OVs are available from 00:00 to 07:00 hours and 18:00 to 24:00 hours whereas EMVs are available between 08:00 to 17:00 hours only. In this work, the charging cost of PHEVs is assumed to be less than the discharging cost to motivate the vehicle owners to participate in the proposed model. The charging and discharging cost assumed as 0.08$/kWh and 0.15$/kWh respectively. Table.6.1 shows the vehicle description and parameters [126]. Figs.6.1 and 6.2 shows the load curve of the microgrid and PV power. Table.6.2 shows the parameters of installed DG units and grid. Table. 6.3 shows the hourly bids of MT, FC and PV. The Time of Use (TOU) grid prices for selling and purchasing the power to/from the utility grid are considered as 0.055$/kWh (if $loadfactor <= 0.5$), 0.072 $/Kwh (if $0.5 < loadfactor <= 0.75$) and 0.120 $/kWh (if $loadfactor > 0.75$).

Table 6.1: Paramters of OV and EMV

| **Parameter** | **OV** | **EMV** |
|---|---|---|
| Battery | Lithium Ion | Lithium Ion |
| Total Energy Capacity | 29.07 kWh | 29.07 kWh |
| Depth of Discharge | 95% | 95% |
| Charging Efficiency | 90% | 90% |
| Discharging Efficiency | 90% | 90% |
| Minimum ECF | 0 | 0 |
| Minimum ECF | 0.4 | 0.25 |

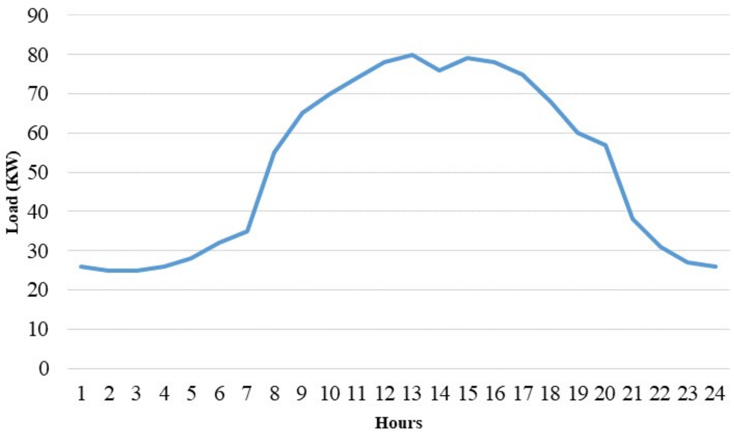


Fig. 6.1: Load curve of the microgrid

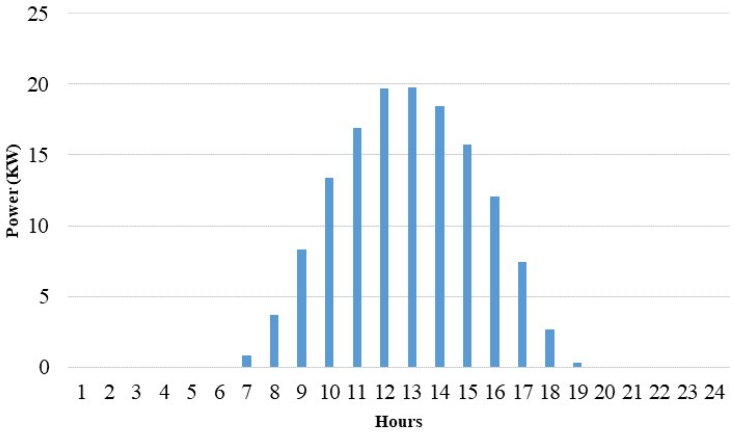


Fig. 6.2: Forecasted PV power

1. Model 1 (Conventional Strategy): In this model, the charging and discharging of PHEVs is based on the hourly grid prices discussed above and hourly bid of MT, FC and PV as shown in Table.6.3. This charging model is frequently suggested in the literature. The charging takes place when grid prices are low and discharging when prices are high to optimize the total cost of the microgrid. The decision is totally based on the hourly grid prices and hourly bids of MT, FC and PV. The total cost of microgrid obtained in this case is 120.66$. Fig.6.5(a) shows the charging and dischaging of PHEVs and Fig.6.5(b) shows the scheduling of MT, FC and grid.

2. Model 2 (Proposed Strategy): In this model, the co-ordinated charging of PHEVs is suggested which not only optimizes the total cost of the microgrid but minimizes the load variance also. The proposed charging and discharging model of PHEVs is

Table 6.2: Power Limits of MT, FC, PV and grid

| Type | Min Power(kW) | Max Power(kW) | Startup cost($) |
|---|---|---|---|
| MT | 8 | 40 | 0.115 |
| FC | 4 | 40 | 0.205 |
| PV | 0 | 20 | 0 |
| Grid | -40 | 40 | 0 |

Table 6.3: Hourly bid of installed DG units($/kWh)

| Hour | MT | FC | PV | Hour | MT | FC | PV |
|---|---|---|---|---|---|---|---|
| 1 | 0.107 | 0.166 | 0 | 13 | 0.115 | 0.17 | 0.086 |
| 2 | 0.107 | 0.166 | 0 | 14 | 0.115 | 0.17 | 0.085 |
| 3 | 0.108 | 0.167 | 0 | 15 | 0.115 | 0.17 | 0.084 |
| 4 | 0.108 | 0.168 | 0 | 16 | 0.117 | 0.171 | 0.083 |
| 5 | 0.109 | 0.167 | 0 | 17 | 0.118 | 0.173 | 0.085 |
| 6 | 0.109 | 0.168 | 0 | 18 | 0.119 | 0.173 | 0.086 |
| 7 | 0.11 | 0.168 | 0 | 19 | 0.118 | 0.174 | 0 |
| 8 | 0.111 | 0.169 | 0.084 | 20 | 0.115 | 0.173 | 0 |
| 9 | 0.112 | 0.17 | 0.085 | 21 | 0.112 | 0.171 | 0 |
| 10 | 0.112 | 0.171 | 0.086 | 22 | 0.11 | 0.17 | 0 |
| 11 | 0.116 | 0.172 | 0.087 | 23 | 0.109 | 0.169 | 0 |
| 12 | 0.117 | 0.171 | 0.088 | 24 | 0.108 | 0.167 | 0 |

designed to reduce the load variance. The model maximizes the benefits of vehicle owners and reduce the total cost of operation of microgrid. The total amount of charging and discharging of PHEVs will be given by Eq. 6.5

$$P_{EV,t}^{charging/discharging} = P_{load,t}^{mean} - P_{load,t} \tag{6.5}$$

The strategy followed by Model 2 is shown schematically in Fig.6.4.

The charging and discharging of PHEVs obtained for 24 in hours in model 2 is shown in Fig.6.5(c), Fig.6.5(d) shows the scheduling of MT FC and grid for model 2. The total cost of microgrid obtained in this model is 103.68$.

It can be observed from the Figs.6.5(a) and 6.5(c) that the positive values shows discharging of PHEV and negative values shows the charging of PHEVs. In case of Model 1 (conventional strategy) all the considered PHEVs are mostly discharges and charges for few hours, i.e., charging/discharging of PHEVs is concentrated in nature.

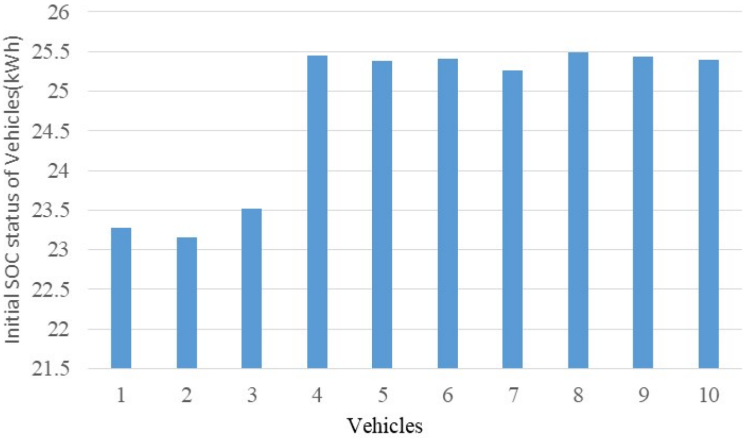


Fig. 6.3: Forecasted initial SOC status of PHEVs

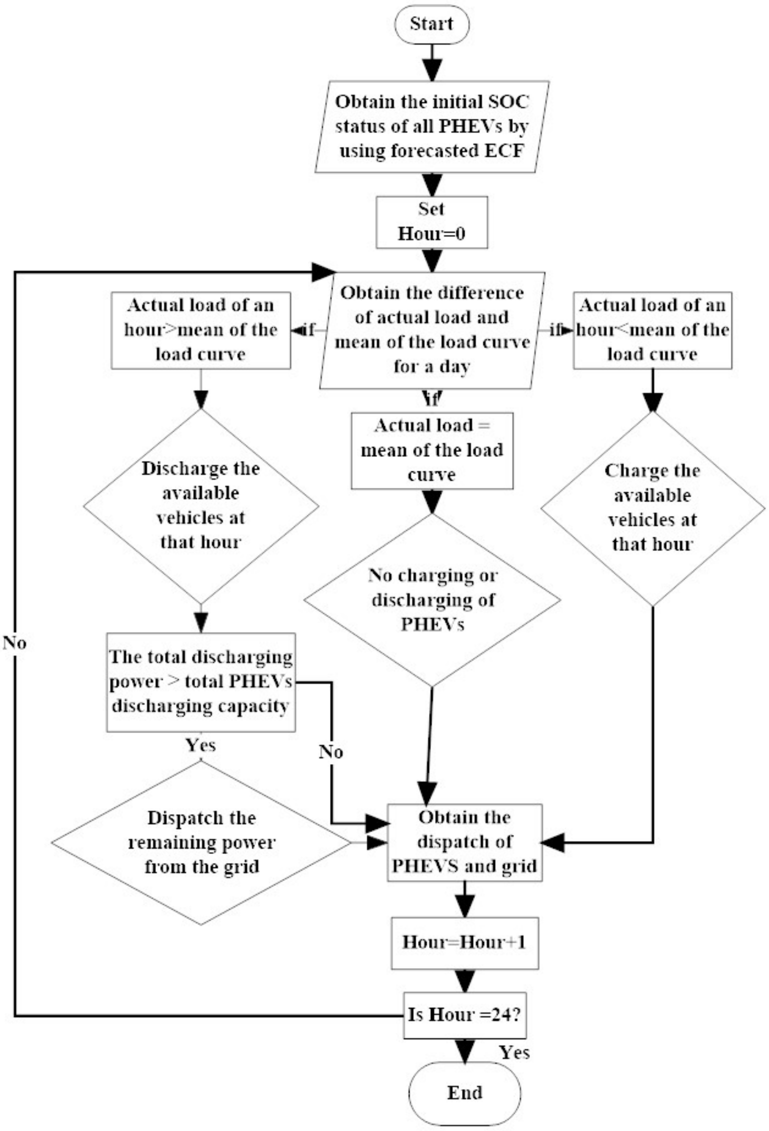
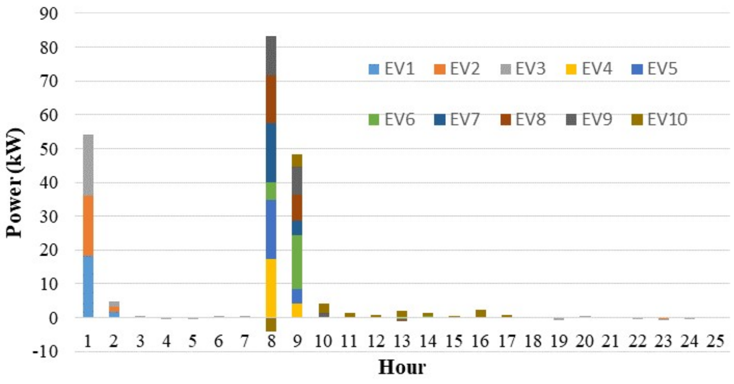
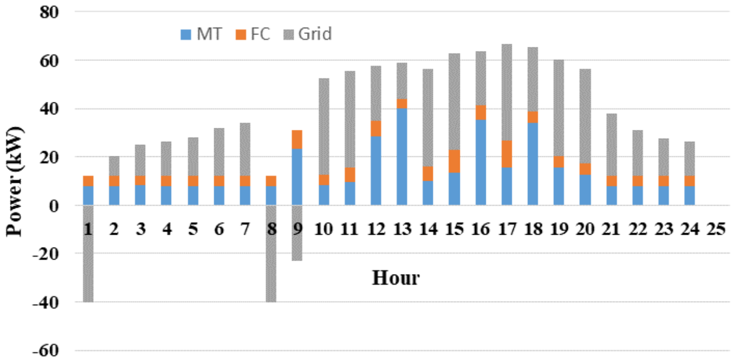


Fig. 6.4: Proposed charging/discharging strategy of PHEVs in Model 2



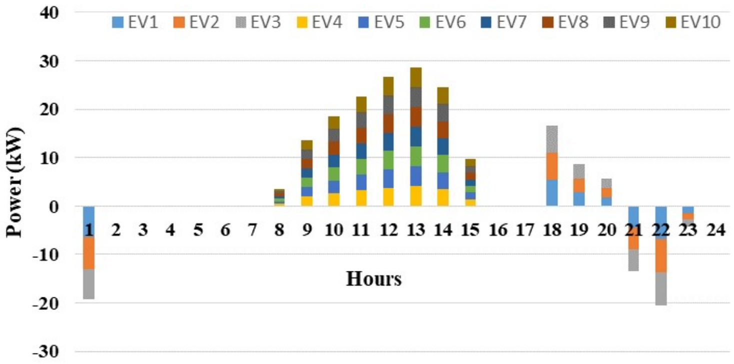
(a) Charging/Discharging of PHEVs in Model 1



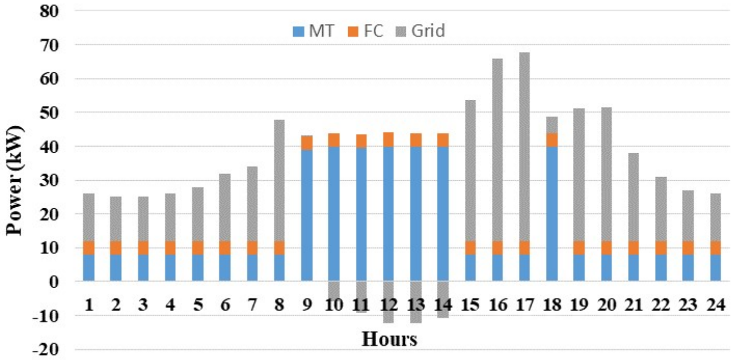
(b) Scheduling of MT, FC and PV in Model 1

But in case of Model 2 charging/discharging of PHEVs is dispersed to many hours of operation and discharging power at high grid prices as per the strategy adopted in Model 2. As a result, Model 2. is better than Model 1 to gain maximum economic benefits to the microgrid owner.

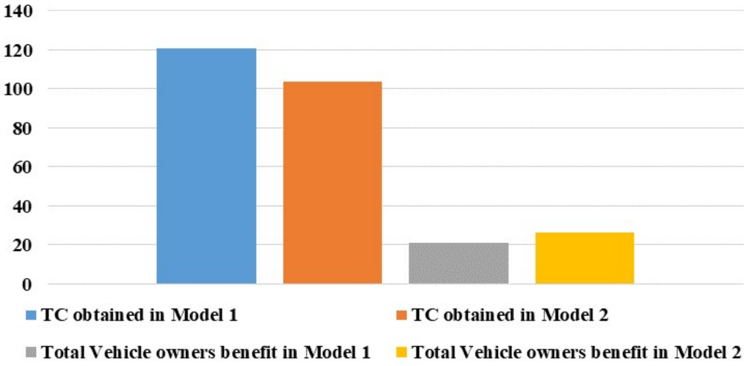
Fig.6.5(e) shows the comparison of results obtained for model 1 and model 2. The total cost of microgrid obtained for model 2 is less than the cost obtained for model 1. Also, the total benefit of vehicle owners obtained in model 2 is 26.20$ which is more than the total benefit that is 20.96$ obtained in model 1.



(c) Charging/Discharging of PHEVs in Model 2



(d) Scheduling of MT, FC and PV in Model 2



(e) Comparison of results

Fig. 6.5: Simulation results for optimal operation of PHEVs in microgrid

## 6.4 Summary

A charging and discharging model for PHEVs in an office microgrid is proposed in this work considering various uncertainties which is modeled using montecarlo simulation discussed in chapter 3. The results shows that the proposed model is very promising as it reduces the total cost of operation of the microgrid and increases the EV owner(s) benefit.

# Chapter 7

# Planning and Operation of Interconnected Multi Microgrids

In this chapter, a new optimization framework is developed for optimal accommodation and operational management of multiple microgrids in distribution systems to maximize the annual profit of distribution network operators and stakeholders. The proposed work is a significant contribution for the future area of concern in smart grid paradigm for revolutionary power system or developing modern distribution systems. A multiobjective optimization problem is formulated for co-ordinated operation of multiple microgrids and DNO in a distribution system. To solve the proposed complex mixed-integer, non-linear and non-convex optimization problem, a bi-level technique for order of preference by similarity to ideal solution particle swarm optimization (PSO-TOPSIS) is proposed. The proposed strategic framework is investigated under different scenarios and simulation results obtained are found to be encouraging.

## 7.1 Proposed Strategic Framework for Multiple Microgrids in Distribution Systems

The depleting conventional energy resources, greenhouse gas emission and inefficacy of traditional vertically integrated power systems have led to the large-scale integration of DER and microgrids in distribution systems. The quick growth of multiple microgrids has considerable impact on distribution systems performance and economics. The high penetration of non-dispatchable DERs may produce many counter-productive results. Alternatively, the optimal sited and sized DERs may provide enormous profits for DNOs, stakeholders and customers such as minimized power/energy loss, emission, investment and operation costs while improving the voltage profile, stability and reliability. Due to the high costs of DER/microgrid investments, many stakeholders are desirable to invest in deregulated power industry. Therefore, compromising benefits of DNOs, stakeholders and customers have to be obtained by deploying DERs and microgrids in distribution systems, which turns out to be a multiobjective optimization problem. In this paper, a multiobjective optimization framework is developed for optimal operational management of multi-microgrids. A multi-criteria decision making technique known as TOPSIS is adopted for multiobjective formulations. The optimization problem of multi-microgrid is divided into two stages: planning and operational management as discussed below.

### 7.1.1 Proposed Multi-microgrid Planning Framework

For any investment, the NPV has to be maximized since NPV indicates the profit that would be generated in future due to the investment done today. Therefore, in planning stage, the optimal integration and electrical boundaries of multiple microgrids are determined to maximize the NPV of the DER/microgrid investment. In order to achieve the optimal planning of multi-microgrids, following strategies have been proposed.

1. Investment Decision Makings: To draw the attention of DNOs and investors to deploy DER/microgrids in existing distribution networks, compromising benefits have to be explored. As a privilege, the selection of DER sites and sizes would be determined by DNOs considering the performance and economics of the system since it is owned by DNOs. Therefore, the DNO will be the mediator between multiple microgrids. In proposed strategy, a microgrid can have energy transaction agreement with DNO not with other microgrids since the energy would travel through the DNO network from one microgrid to another. Moreover, DNO has right to curtail the renewable power generation if system is found to be at the risk or about to violate the system security constraint [159]. Alternatively, the microgrid stakeholders have to maximize the NPV of DER investment according to the given guidelines of DNO.

2. Electric Boundary Selection of Interconnected Microgrids: Generally, the distribu-

tion systems are designed and operated in radial topology comprising of multiple feeders as shown in Fig.7.1. Among these, many feeders are dedicatedly installed to supply power to customers of importance such as schools, some residential areas, hospitals, water supply departments, filling stations etc. Therefore, it may be a strategic planning to define a microgrid boundary according to customer feeders as shown in the Fig.7.1. Also, self adequacy of a microgrid is a very important. To insure the self adequacy of microgrid, DERs are integrated so, i.e. each microgrid is having total local generation more than the total local load demand.

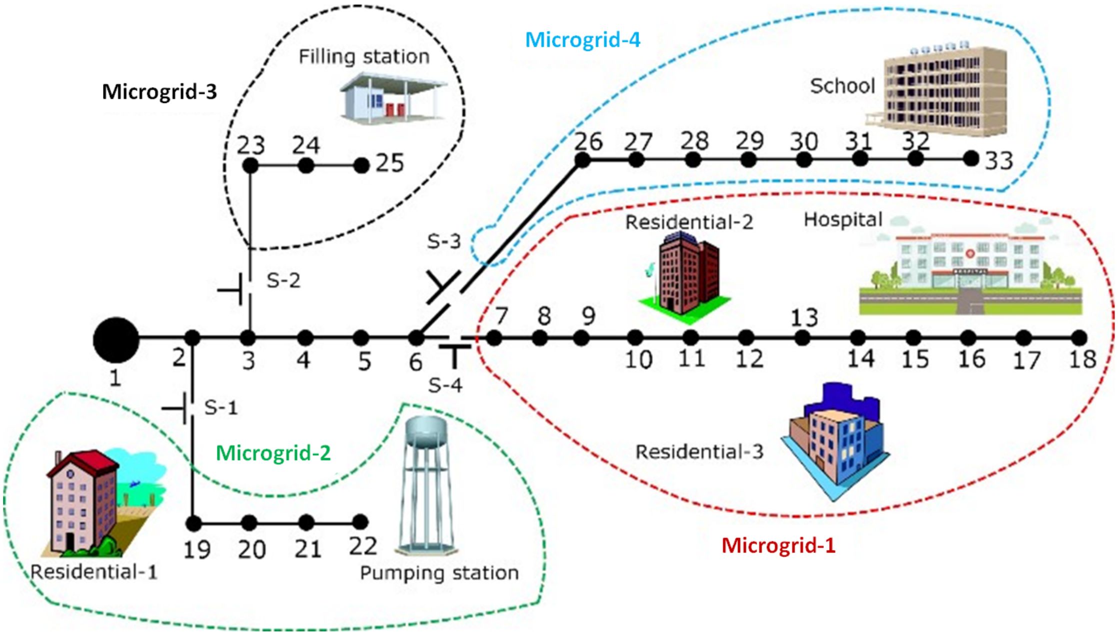


Fig. 7.1: Proposed structure of Multi-microgrids

3. DER Penetration in Microgrids: The high penetration of DERs may generate counterproductive results. Therefore, an optimal hosting capacity has to be obtained to maximize microgrid benefits. In this work, the maximum penetration of DERs in a microgrid is limited by the peak load in that microgrid and minimum one DG is made compulsory to install in each microgrid. Therefore, the rated capacity of installed renewable DG should be less than the peak demand of respective microgrid.

#### Installation of BES in each Multi-microgrid

After DG installation by DNO, the microgrid stakeholders will be allowed to install BES in their respective microgrid for the economic profit. The installed capacity of BES in each microgrid may allow a smooth and profitable operation of mullti-microgrids. In this section a thumb rule is discussed to install a BES of optimal capacity.

$$\begin{aligned} E_{BES} &= max\left[E_{BES}^{chrg}, E_{BES}^{dischrg}\right] \\ \text{where, } E_{BES}^{chrg} &= \sum_{t=1}^{T} E_{BES,t}^{chrg} = \sum_{t=1}^{T} (P_{BES,t}^{chrg} \times \Delta_t)\eta_c \\ E_{BES}^{dischrg} &= \sum_{t=1}^{T} E_{BES,t}^{dischrg} = \sum_{t=1}^{T} \frac{P_{BES,t}^{dischrg} \times \Delta_t}{\eta_d} \end{aligned} \tag{7.1}$$

where, $E_{BES}$ is the total installed capacity of BES, $E_{BES}^{chrg}$ and $E_{BES}^{dischrg}$ are the total charging and discharging energy of BES respectively, $P_{BES,t}^{chrg}$ and $P_{BES,t}^{dischrg}$ are the charging and discharging power of BES at $t^{th}$ hour respectively, $\eta_c$ and $\eta_d$ are the charging and discharging efficiency of the BES.

### 7.1.2 Proposed Operational Management of Multi-microgrids

The strategic optimal planning of multi-microgrids is presented in previous section. However, considering the uncertainty of generation, load and binary decision making of DER, BESs and microgrid dispatches under various operating constraints, operational management of multiple microgrids turns out to be rather more complex optimization problem. The goal of this section is to obtain a compromising solution while maximizing the profits of both microgrid stakeholders and DNO. Therefore, TOPSIS approach is adopted to obtain most compromising solution since maximization of one's profit may decrease others. The operational management of multi-microgrids and DNO is achieved under following strategies framework.

1. The Role and Rights of DNO in Proposed Framework: In practice, each stakeholder is allowed to maximize its profit by following the guidelines of DNO. To achieve this, a common contract between DNO and microgrid owners may include following guidelines:
    - DNO has right to isolate the DER/microgrid from its network if the system is found to be at the risk.
    - The energy transaction between multiple microgrids will be allowed through DNO since it is the network owner.

- It will be the duty of microgrid owners to meet the load demand in their respective electric boundaries as shown in Fig.7.1. They have no rights to collect bills from customers; therefore, DNO will remain the sole owner in proposed model.
- The microgrids/DERs will be paid by DNO as per the energy metered at point of common coupling of their DERs.

2. The Role and Rights of Stakeholders in Proposed Framework

   - The stakeholders can not buy or sell the energy directly from/to grid. They can sale or buy energy through DNO only.
   - The stakeholders can install BES for the smooth operation of microgrid only after the permission by DNO.

## 7.2 Problem Formulation

In this section the objective functions for (i) Multi-microgrid planning and (ii) Operational management of multi-microgrid are formulated.

### 7.2.1 For Proposed Multi-microgrid Planning Framework:

Generally, monetary gain is the primary motive of any investment while minimizing the associated risks. Following the trend, a multi-year optimization framework is developed to maximize the NPV of DER integration while improving the systems performance. The NPV calculation includes the cost of DER investment, annual operation and maintenance cost, grid energy transaction cost. The proposed objective function of DER planning is expressed as.

**Objective Function**

$$\begin{aligned}
NPV &= max(C_{out} - C_{out}^{DG}) \\
\text{where}, C_{out} &= \sum_{y=1}^{N_y} \frac{1}{(1+d_r)^y}\left(\kappa \sum_{t=1}^{T} C_{grid,t} \sum_{i=1}^{N} (1+\lambda)^{y-1} P_{L,t}^i\right) \\
C_{out}^{DG} = C_{PV}^{Inv} \sum_{i \in \Omega MG}^{N} u_{PV}^i P_{PV}^i &+ \sum_{y=1}^{N_y} \frac{1}{(1+d_r)^y}\left(\kappa \sum_{t=1}^{T} C_{grid,t} \sum_{i=1}^{N} (1+\lambda)^{y-1} (P_{L,t}^i - P_{G,t}^i)\right) \\
&+ \sum_{i \in \Omega MG}^{N} u_{PV}^i C_{PV}^{OM} P_{PV}^i
\end{aligned} \tag{7.2}$$

where, NPV is the net present value, $C_{out}$ and $C_{out}^{DG}$ are the cash outflows before DG integration and after DG integration respectively. $C_{grid,t}$ is the hourly grid price, $N_y$ is the total number of planning years, $y$ is the year index, $d_r$ is the discount rate, $\kappa$ is the daily to annual conversion factor, $N$ is the total number of buses in the system, $i$ is the bus index, $\lambda$ is the annual load growth in %, $P_{L,t}^i$ and $P_{G,t}^i$ are the hourly load demand and hourly power generation at bus $i$ respectively. $u_{PV}^i$ binary decision variable for DG installation at bus $i$. $P_{PV}^i$ installation capacity of PV at bus $i$, $C_{PV}^{OM}$ is the operation and maintenance cost of PV and $\Omega MG$ is the set of microgrid.

**Constraints**

The objective function represented in Eq. 7.2 is subjected to the following constraints:

1. Real Power Balance

$$P_{G,t}^i - P_{L,t}^i = V_t^i \sum_{j=1}^{N} V_t^j Y^{ij} cos(\theta^{ij} + \delta_t^j - \delta_t^i) \tag{7.3}$$

2. Reactive Power Balance

$$Q_{G,t}^i - Q_{L,t}^i = V_t^i \sum_{j=1}^{N} V_t^j Y^{ij} cos(\theta^{ij} + \delta_t^j - \delta_t^i) \tag{7.4}$$

3. Node Voltage Limits

$$V^{min} \leq V_t^i \leq V^{max} \qquad \forall i, t \tag{7.5}$$

4. Feeders Thermal Limits

$$I_t^{ij} \leq I^{max,ij} \tag{7.6}$$

5. DG Penetration Limit

$$\sum_{i\in\Omega MG}^{N} u_{PV}^{i} P_{PV}^{i} \leq \sum_{i\in\Omega MG}^{N} P_{L,peak}^{i} \tag{7.7}$$

where, $P_{G,t}^{i}$, $P_{L,t}^{i}$ $Q_{G,t}^{i}$ and $Q_{L,t}^{i}$ are the real and reactive power generation and load demand at bus $i$ respectively.$P_{L,peak}^{i}$ is the peak load demand at bus $i$. $I_{t}^{ij}$ is the feeder current flowing through $i^{th}$ to $j^{th}$ bus, $I^{max,ij}$ is the maximum limit of the feeder current, $V^{min}$ and $V^{max}$are the minimum and maximum voltage limits at $i^{th}$ bus. $V_{t}^{i}$ is the voltage at $i^{th}$ bus.

### 7.2.2 For Proposed Operational Management of Multi-microgrids:

After DER investment, the microgrid has to optimize the DER operations to maximize its profit as per the need of DNO. In this work, following scenarios are investigated to maximize the profit of microgrid owners.

1. Unplanned operation of multi-microgrid system
2. Proposed strategic operation of multi-microgrid system in grid connected mode
3. Proposed strategic operation of multi-microgrid system in Islanded mode.

**Objective Function**

$$F_{1}^{DNO} = min \sum_{t=1}^{T} C_{grid,t} \times P_{grid,t} \tag{7.8}$$

$$F_{2}^{MG} = max \sum_{t=1}^{T} C_{discom,t} \sum_{i\in\Omega_{MG_m}}^{N} u_{i,t} \times P_{i,t} - TCPH \tag{7.9}$$

$$F = optimal[F_{1}^{DNO}, F_{2}^{MG}] \tag{7.10}$$

$$\text{where, } F_{2}^{MG} = [F_{2}^{1}, F_{2}^{2}, F_{2}^{3} .......F_{2}^{m}]$$
$$TCPH = \frac{TCPD}{T}$$

where, $C_{grid,t}$ and $C_{discom,t}$ are the cost of grid energy transaction and cost of energy transaction between microgrid and DNO, $P_{grid,t}$ and $P_{i,t}$ are the grid transaction power and microgrid transaction power at time $t$, TCPH is the per hour total cost of BES and $m$ is the microgrid index.

**Constraints**

The objective function represented in Eq.(7.8)-(7.10) is subjected to the constraints shown in Eq. (7.3)-(7.5) and (7.11)-(7.12)

1. Power limits of BES

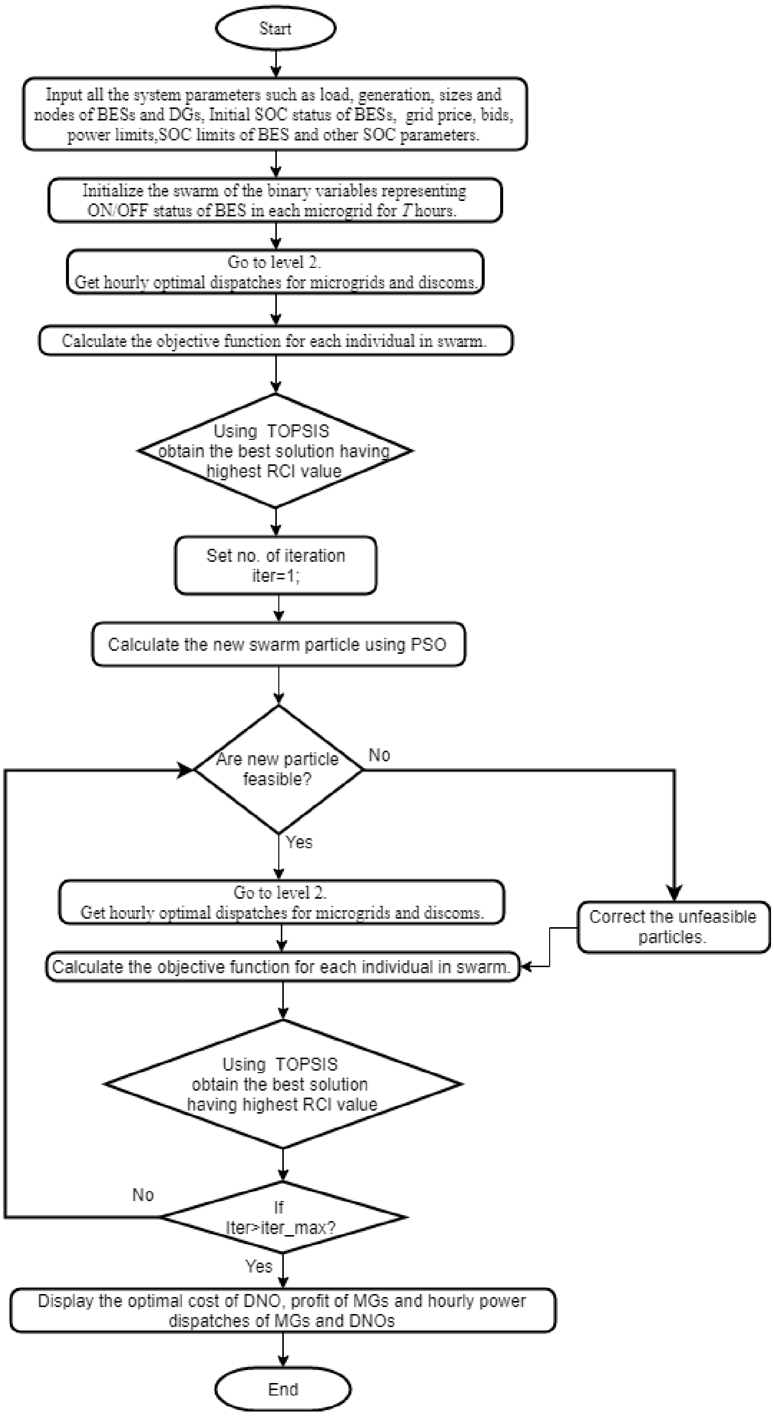
$$P_{BES,t}^{min} \leq P_{BES,t} \leq P_{BES,t}^{max} \tag{7.11}$$

2. SOC limits of BES

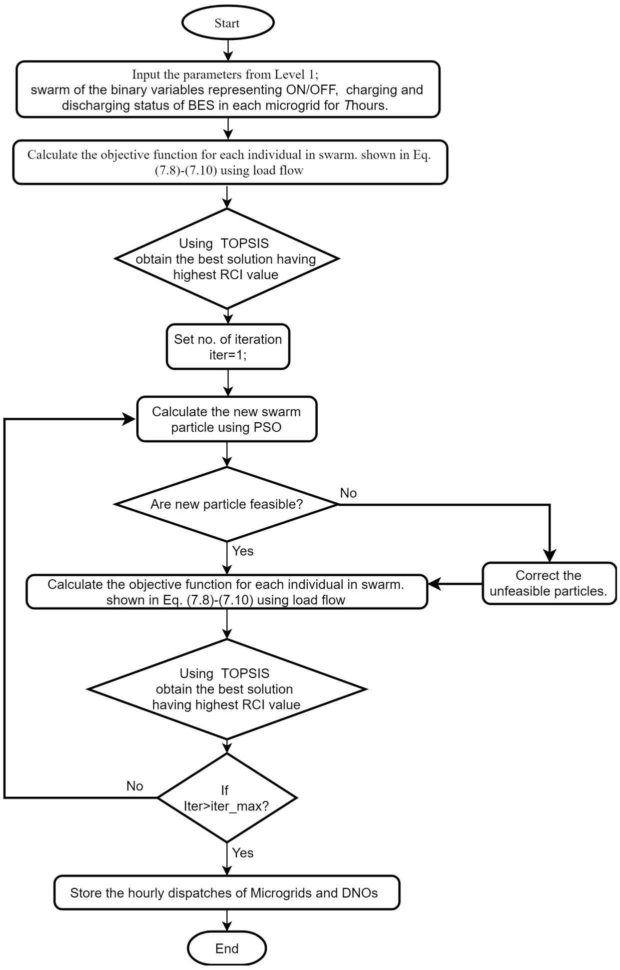
$$SOC_{BES,t}^{min} \leq SOC_{BES,t} \leq SOC_{BES,t}^{max} \tag{7.12}$$

## 7.3 Methodology

In this work, a PSO is used to solve the formulated planning problem of integration of PVs. A bi-level PSO-TOPSIS is used to solve the multi-objective operational problem of DNO and microgrid. The level 1 handles the binary variable such as [-1,0,1] representing the charging state, off state and discharging state of BES while the level 2 take care of the hourly dispatches of the BES as per the decision variables provided by the level 1. The pop size is taken as 30, acceleration coefficients are considered as 2 and the number of iterations is chosen as a termination criteria which is equal to 100 in this work. Fig.7.2 shows the flowchart of the Bi-level PSO-TOPSIS.


Start
Input all the system parameters such as load, generation, sizes and nodes of BESs and DGs, Initial SOC status of BESs, grid price, bids, power limits,SOC limits of BES and other SOC parameters.
Initialize the swarm of the binary variables representing ON/OFF status of BES in each microgrid for T hours.
Go to level 2.
Get hourly optimal dispatches for microgrids and discoms.
Calculate the objective function for each individual in swarm.
Using TOPSIS obtain the best solution having highest RCI value
Set no. of iteration iter=1;
Calculate the new swarm particle using PSO
Are new particle feasible?
No
Yes
Go to level 2.
Get hourly optimal dispatches for microgrids and discoms.
Correct the unfeasible particles.
Calculate the objective function for each individual in swarm.
Using TOPSIS obtain the best solution having highest RCI value
No
If Iter>iter_max?
Yes
Display the optimal cost of DNO, profit of MGs and hourly power dispatches of MGs and DNOs
End

(a) Level 1



(b) level 2

Fig. 7.2: Flowchart of the Bi-level PSO-TOPSIS

## 7.4 Simulation Results

In this work, IEEE 33-bus system is considered for the development of the proposed interconnected multi-microgrid system. The uncertain PV and load demand is forecast using the proposed TS based stochastic technique discussed in section 3.2.5. Figs.7.3 and 7.4 shows the stochastic hourly PV scale factor and load factor respectively. $\eta_c$ and $\eta_d$ are considered as 0.9. The DOD of BES is assumed as 90%. The fixed cost, maintenace cost, rate of interest and life of BES is considered as 60\$/kWh, 20\$/kWh, 6% and 3 years respectively [45]. $T$ is taken as 24 hours. $d_r$ and $\lambda$ are 5% and 3% respectively. $N_y$ is considered as 20 years. $C_{PV}^{OM}$ is taken as 0.01\$/kW

The hourly grid prices are considered as 0.055\$/kWh (if $loadfactor <= 0.5$), 0.072 \$/Kwh (if $0.5 < loadfactor <= 0.75$) and 0.120 \$/kWh (if $loadfactor > 0.75$). However, the prices to sell energy to DNO by multiple-microgrids are 10% cheaper than the hourly grid prices and 10% costlier than the hourly grid prices when DNO is selling power to multiple-microgrids.

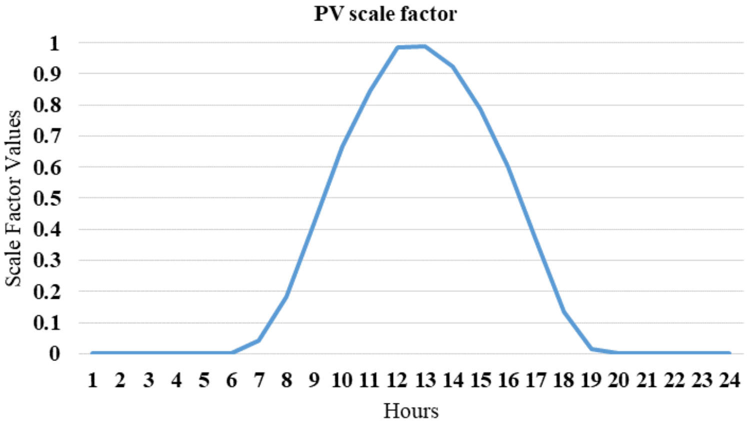


Fig. 7.3: Stochastic PV scale factor

### 7.4.1 Stage-I Strategic Planning of Multiple Microgrid System

At this stage, the PVs are optimally installed on each feeder of the system by DNO to frame microgrids in the system for uninterruptable and reliable supply to the consumers. Also, the BES in each microgrid is installed by the respective stakeholder to cope up with the uncertain generation environment due to intermittent PV and to increase the profit by charging and discharging BES optimally.

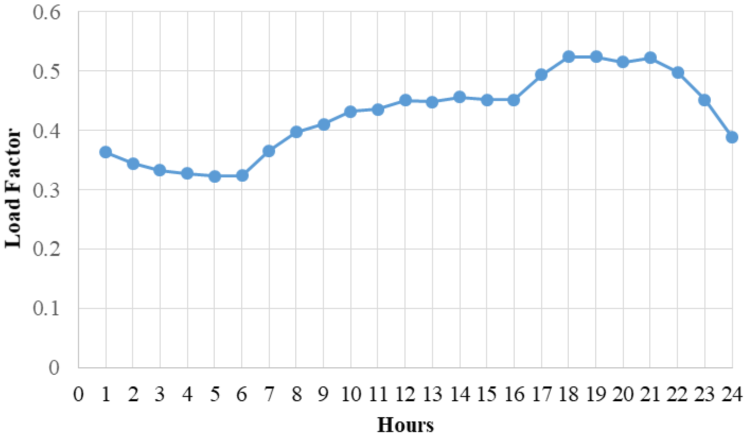


Fig. 7.4: Stochastic Load factor

The PVs are installed with optimal sizes and location on each feeder of the system with *NPV* of 1300621.12$ to frame a multi-microgrid system as shown in Fig.7.5

$$\underbrace{\boxed{N_{14}}\boxed{N_{19}}\boxed{N_{24}}\boxed{N_{31}}\boxed{S_{1368}}\boxed{S_{1454}}\boxed{S_{1390}}\boxed{S_{1447}}}$$

Fig. 7.5: Optimal nodes and corresponding sizes of installed PVs

The BES is installed in each microgrid by each microgrid owner and the sizes of BESs are determined according to a thumb rule explained in section.7.1.1. The optimal sizes of BES installed with each microgrid is shown in Fig.7.6

$$\underbrace{\boxed{E^{MG1}_{10000}}\boxed{E^{MG2}_{10000}}\boxed{E^{MG3}_{12000}}\boxed{E^{MG4}_{10000}}}$$

Fig. 7.6: Optimal sizes of installed BESs in each microgrid

### 7.4.2 Stage-II Multi-objective operation

1. Unplanned operation of multi-microgrid system. In this case, the operation of multi microgrid system is investigated without any strategy and the system is considered to be connected with upstream grid, the PVs are also installed in the system which transforms it into an active entity. It is assumed that the system is getting energized through both the upstream grid and power generation from the PV to fulfill its hourly load demand. In this way, only DNO is responsible for generating all the benefits to itself by selling and purchasing the energy to/from the upstream grid whereas no stakeholder is taking part in planning and operation of the system. The cost of purchasing power from grid by DNO before and after installing the PV in

the system is shown in Fig.7.7 It can be seen from the Fig.7.7 that the cost of purchasing the power from grid is reduced after installing the PVs in the distribution system. Fig.7.8 shows the hourly daily scheduling of BESs after strategic operational management in each microgrid. The negative values indicates the charging of BES while the positive indicates the discharging of BES. Fig.7.9 shows the initial SOC status of BES in strategic grid connected mode. In this work, the initial SOCs for each BES is generated randomly between the limits.

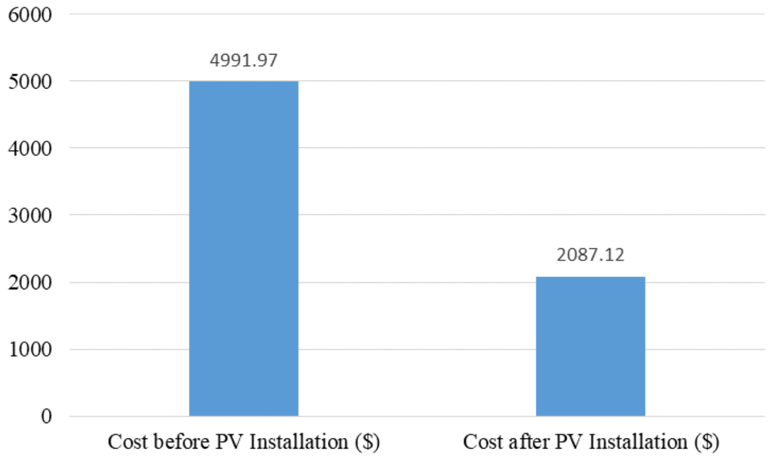


Fig. 7.7: Cost of purchasing power by DNO

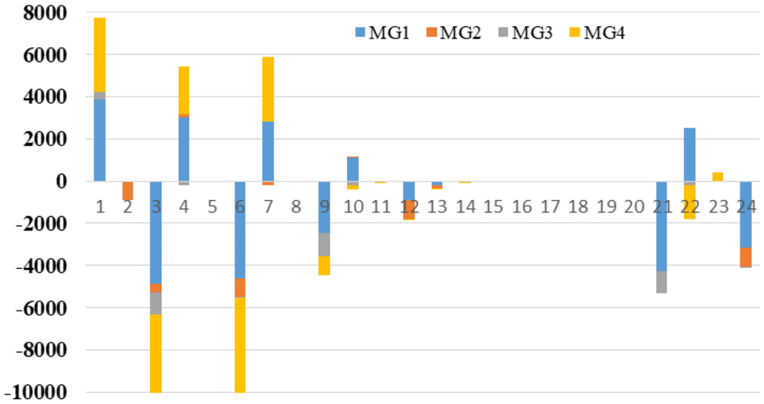


Fig. 7.8: Scheduling of BES in interconnected multi-microgrids

2. Proposed strategic operation of multi-microgrid system in grid connected mode: In this mode of operation of multi microgrid system, the distribution system is optimally installed with the PV and BES which are obtain from the planning stage represented in Figs. 7.5 and 7.6. The system is in grid connected mode so the transaction of grid power to/from upstream grid is allowed when the system having

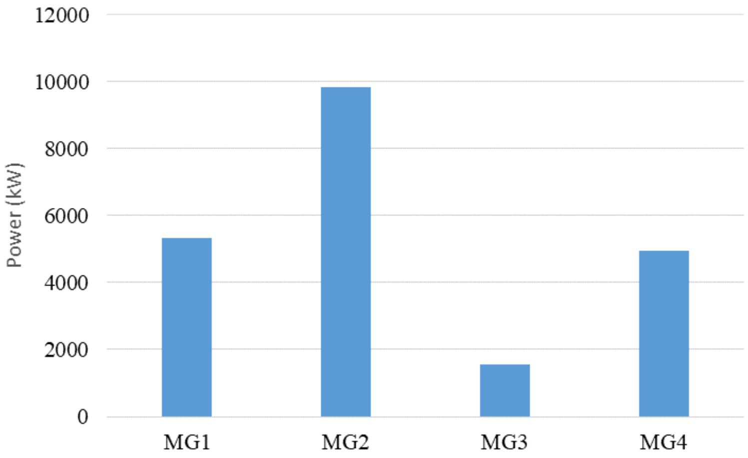


Fig. 7.9: Initial SOC status of BES in each microgrid in grid connected mode

deficit or surplus power. In this case stake holders of various framed microgrids taking part in the operation of the system.

3. Proposed Strategic operation of multi-microgrid system in islanded mode. In this mode, the system is not connected to the upstream grid. It is assumed that the optimally obtained sizes of PV and BES are installed in the system. So, the objective is to fulfill the daily load demand of the system to provide uninterrupted energy supply to the consumers at the minimum operating cost.

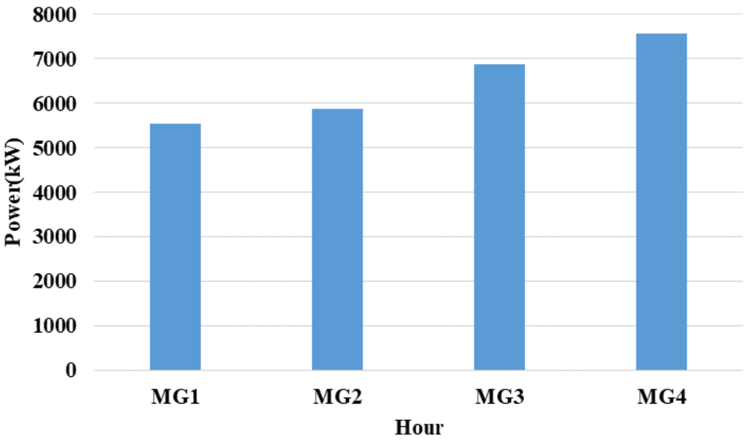


Fig. 7.10: Initial SOC status of BESs in each Microgrid in islanded mode

Fig.7.10 shows the initial SOC status of BES in the islanded mode. The initial SOCs for each BES is generated randomly between the limits.

Fig.7.11 shows the scheduling of BES in islanded mode. The negative and positive values indicates the charging and discharging of BES respectively. Each microgrid schedules the BES to maximize its profit by selling power to DNO and to fulfill

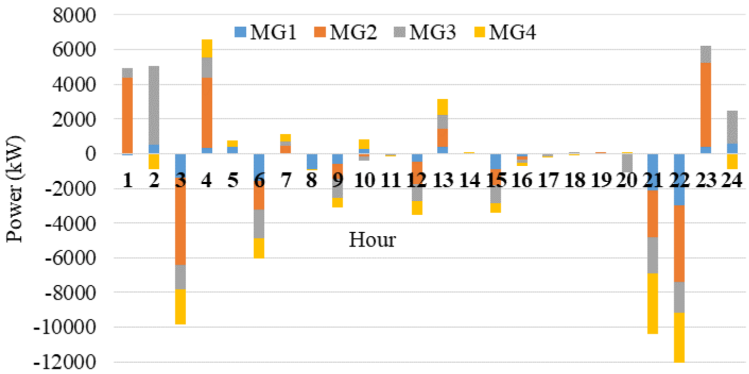


Fig. 7.11: Scheduling of BES in islanded mode

the load demand of its own.

Table 7.1: Net Profit and TC of DNO

| Net Profit/TC ($) | | | | | |
|---|---|---|---|---|---|
| - | MG1 | MG2 | MG3 | MG4 | DNO |
| Islanded Mode | 5103.17383 | 2704.1072 | 21597.3871 | 2954.370687 | 29.8 |
| Grid Connected Mode | -2920.9143 | 3534.2088 | 6565.40693 | -1480.265508 | -16.47945264 |

Table.7.1 shows the Net profit/TC of Microgrid and DNO. Negative values indicates the profits and positive values shows the profits. In case of islanded mode, there is no exchange of power between grid and DNO. So, the profit of stakeholders are less whereas in grid connected mode, the exchange of power between grid and DNO helps in increasing the DNO as well as stakeholders net profit

## 7.5 Summary

This chapter presents the strategical planning and operational management of interconnected multi-microgrids. At planning stage, framework to develop interconnected multi-microgrids in distribution is presented by installing DERs and BESs. A multi-objective operational management of microgrid is solved to obtain compromising benefits of each stakeholder and DNO. To solve the complex multi-objective problem a bi-level PSO-TOPSIS is presented. The results obtained are promising. The net profit of stakeholders are noticed in the strategic grid connected mode while in islanded the net profit of stakeholders are reduced. The cost of purchasing power from grid by DNO is reduced, monetary profit is noticed in case of grid connected mode while in islanded mode the cost is reduce upto a significant level

# Chapter 8

# Conclusions and Future Scope

This chapter summarizes the major contributions, conclusions drawn and future scope of the work reported in this thesis. The investigations are carried out to address the stochastic and deterministic scheduling problem of grid connected microgrid, optimal sizing and operation of BES in grid connected microgrid, optimal operation of PHEVs in grid connected microgrid and the optimal planning and operation of grid connected interconnected microgrids. The efforts has been made to increase the techno-economical, socio and environmental benefits by introducing new strategies, optimization frameworks and optimization techniques for the optimal operation of grid connected AC microgrids.

The scheduling problem of microgrid integrating with BES and EVs is generally a complex optimization problem due to imposition of various equality and inequality constraints and large number of decision variables such as power output of dispatchable and non-dispatchable DGs, charging/discharging of BES and EVs etc. Thus, a powerful optimization tool is required to address such type of complex optimization problem. In this thesis, a newly developed optimization technique ’EHO’ is explored. The algorithm is modified to solve the complex scheduling problem of microgrid and proposed as ’MEHO’. Proposed MEHO is investigated and found better than the existing EHO.

Moreover, the large number of renewable DG penetration in microgrid creates an uncertainty in operation of microgrid. In order to handle the uncertainty an efficient stochastic model is required. In this context, a TS method is proposed. The proposed TS method is used to model the renewable power generation and load demand. It has been concluded from the results that the proposed method requires less historical data and less computation to forecast the random renewable generation and load demand.

In addition to the proposed optimization and stochastic tools or techniques, the efforts are also been made to formulate the multi-objective sizing and operation problem of BES. The aim of the multi-objective formulation is to address the sizing of BES for techno-economic and environmental benefits and the operation of BES for techno-economic benefits while concerning the useful life of BES. The two different multi-objective problem are formulated for optimal sizing and operation of BES in grid connected microgrid. The problem is solved by using a combinatorial optimization technique 'PSO-TOPSIS'. Also, A new problem formulation for optimal operation of interconnected microgrids is presented.

The point-wise contribution from the research work are summarized as under:

1. A more realistic method, tournament selection based stochastic model for optimal operation of grid connected microgrid is proposed in chapter 3.

2. A newly introduced optimization algorithm Elephant Herding Optimization algorithm is explored. Few modifications are suggested in the existing optimization technique and proposed to solve complex real life optimal operation problem of grid connected microgrid in different mode of operations.

3. A multi-objective technique TOPSIS along with PSO is explored to obtain most compromising solution for various multi-objective problems of microgid.

4. A multi-objective sizing of BES in a grid connected microgrid, problem formulation considering techno-economic and environmental benefits is proposed and solved efficiently.

5. The uncertainty associated with initial SOCs of EVs is modeled and an effective operational strategy for grid connected microgrid integrated with EVs parking lot is proposed. The strategical operation is a contribution to the electrification of the transportation and management of the load-demand burden on electrical distribution systems.

6. A strategy to transform existing distribution systems into self-sustained interconnected multi-microgrids is proposed. A stochastic optimal planning and operation framework for interconnected multi-microgrids is proposed.

The chapter-wise conclusions drawn from the research work are summarized as under:

1. It may be concluded from the results of chapter-4 that the proposed TS based stochastic model can forecast more realistic renewable generation and load demand which may be very useful for better decision making for optimal operational management strategies of microgrid.
2. The scheduling problem of microgrid is solved by a recent optimization algorithm EHO. Some modifications are suggested in EHO. The proposed MEHO is found promising as less than that of EHO algorithm and the other swarm based intelligent techniques exists in the literature. Hence the method proposed has better potential to solve the complex scheduling problem of microgrid.
3. It can be concluded from the chapter-5, the multi-objective sizing of BES results in economic benefits to the microgrid operator as well as environmental benefits to the society. The solved problem reveals the significant potential of the BES technology for multiple applications.
4. It can be concluded from chapter-6 that the proposed strategy for optimal integration of EVs results in techno-economic benefits to both microgrid operator and vehicle owners. The strategical operation is a contribution to the electrification of the transportation and management of the load-demand burden on electrical distribution systems. The charging /discharging strategy may help in promoting the EVs.
5. In Chapter-7, the proposed method is suitable to transform the existing distribution systems into interconnected multi-microgrids. The method can be adopted for the transformation of the existing distribution systems in to the future low carbon self-sustained interconnected multi-microgrids.

## 8.1 Future Scope

In this work, short term sizing of BES is investigated. However, long term sizing or multi-year sizing of BES for the optimal operation of microgrid can be investigated in future. In order to investigate the optimal operation of microgrid integrating PHEVs, various uncertainty associated with ECF and renewable generation is considered. However, the effect of fast and slow chargers can also be investigated for optimal integration of PHEVs. Also, the better charging infrastructure and operational strategies of different type of PHEVs considering different charging levels in different types of microgrid structure can be investigated in detail. A detailed analysis can also be performed by considering demand response. Multi-microgrid needs more suitable planning and operational strategies. So, the strategies can also be explored by implementing demand response in multi-microgrid. Moreover, Multi-year planning of BES for the optimal operation of interconnected multi-microgrids can be explored.

# Bibliography

[1] P. Malysz, S. Sirouspour, and A. Emadi, "An optimal energy storage control strategy for grid-connected microgrids," *IEEE Transactions on Smart Grid*, vol. 5, no. 4, pp. 1785–1796, 2014.

[2] C. Wei, Z. M. Fadlullah, N. Kato, and I. Stojmenovic, "On optimally reducing power loss in micro-grids with power storage devices," *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 7, pp. 1361–1370, 2014.

[3] Y. Xu, W. Zhang, G. Hug, S. Kar, and Z. Li, "Cooperative control of distributed energy storage systems in a microgrid," *IEEE Transactions on smart grid*, vol. 6, no. 1, pp. 238–248, 2015.

[4] W. Shi, X. Xie, C.-C. P. Chu, and R. Gadh, "Distributed optimal energy management in microgrids." *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1137–1146, 2015.

[5] K. Rahbar, J. Xu, and R. Zhang, "Real-time energy storage management for renewable integration in microgrid: An off-line optimization approach," *IEEE Transactions on Smart Grid*, vol. 6, no. 1, pp. 124–134, 2015.

[6] S. Talari, M. Yazdaninejad, and M.-R. Haghifam, "Stochastic-based scheduling of the microgrid operation including wind turbines, photovoltaic cells, energy storages and responsive loads," *IET Generation, Transmission & Distribution*, vol. 9, no. 12, pp. 1498–1509, 2015.

[7] A. Urtasun, E. L. Barrios, P. Sanchis, and L. Marroyo, "Frequency-based energy-management strategy for stand-alone systems with distributed battery storage," *IEEE Transactions on Power Electronics*, vol. 30, no. 9, pp. 4794–4808, 2015.

[8] J.-H. Teng, S.-W. Luan, D.-J. Lee, and Y.-Q. Huang, “Optimal charging/discharging scheduling of battery storage systems for distribution systems interconnected with sizeable pv generation systems,” *IEEE Trans. Power Syst*, vol. 28, no. 2, pp. 1425–1433, 2013.

[9] B. Zhao, X. Zhang, J. Chen, C. Wang, and L. Guo, “Operation optimization of standalone microgrids considering lifetime characteristics of battery energy storage system,” *IEEE transactions on sustainable energy*, vol. 4, no. 4, pp. 934–943, 2013.

[10] C. A. Hernandez-Aramburo, T. C. Green, and N. Mugniot, “Fuel consumption minimization of a microgrid,” *IEEE transactions on industry applications*, vol. 41, no. 3, pp. 673–681, 2005.

[11] G. Diaz, C. Gonzalez-Moran, J. Gomez-Aleixandre, and A. Diez, “Scheduling of droop coefficients for frequency and voltage regulation in isolated microgrids,” *IEEE Transactions on Power Systems*, vol. 25, no. 1, pp. 489–496, 2010.

[12] P. Li, S. Zhang, Y. Wang, G. Sun, L. Zhou, and X. Wang, “Research on economic optimal operation of microgrid,” in *Power System Technology (POWERCON), 2012 IEEE International Conference on.* IEEE, 2012, pp. 1–5.

[13] S.-J. Ahn, S.-R. Nam, J.-H. Choi, and S.-I. Moon, “Power scheduling of distributed generators for economic and stable operation of a microgrid,” *IEEE Transactions on Smart Grid*, vol. 4, no. 1, pp. 398–405, 2013.

[14] Y. Huang and S. Mao, “On quality of usage provisioning for electricity scheduling in microgrids,” *IEEE Systems Journal*, vol. 8, no. 2, pp. 619–628, 2014.

[15] W. Shi, X. Xie, C.-C. P. Chu, and R. Gadh, “Distributed optimal energy management in microgrids.” *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1137–1146, 2015.

[16] B. Zhao, Y. Shi, X. Dong, W. Luan, and J. Bornemann, “Short-term operation scheduling in renewable-powered microgrids: A duality-based approach,” *IEEE Trans. Sustain. Energy*, vol. 5, no. 1, pp. 209–217, 2014.

[17] W. Su, J. Wang, and J. Roh, “Stochastic energy scheduling in microgrids with intermittent renewable energy resources,” *IEEE Transactions on Smart Grid*, vol. 5, no. 4, pp. 1876–1883, 2014.

[18] M. Alipour, B. Mohammadi-Ivatloo, and K. Zare, “Stochastic scheduling of renewable and chp-based microgrids,” *IEEE Transactions on Industrial Informatics*, vol. 11, no. 5, pp. 1049–1058, 2015.

[19] S. Talari, M. Yazdaninejad, and M.-R. Haghifam, “Stochastic-based scheduling of the microgrid operation including wind turbines, photovoltaic cells, energy storages and responsive loads,” *IET Generation, Transmission &amp; Distribution*, vol. 9, no. 12, pp. 1498–1509, 2015.

[20] A. Khodaei, “Microgrid optimal scheduling with multi-period islanding constraints,” *IEEE Transactions on Power Systems*, vol. 29, no. 3, pp. 1383–1392, 2014.

[21] ——, “Resiliency oriented microgrid optimal scheduling,” *IEEE Transactions on Smart Grid*, vol. 5, no. 4, pp. 1584–1591, 2014.

[22] X. Wu, X. Wang, and C. Qu, “A hierarchical framework for generation scheduling of microgrids,” *IEEE Transactions on Power Delivery*, vol. 29, no. 6, pp. 2448–2457, 2014.

[23] H. Nafisi, V. Farahani, H. A. Abyaneh, and M. Abedi, “Optimal daily scheduling of reconfiguration based on minimisation of the cost of energy losses and switching operations in microgrids,” *IET Generation, Transmission &amp; Distribution*, vol. 9, no. 6, pp. 513–522, 2015.

[24] A. Khodaei, “Provisional microgrids,” *IEEE Transactions on Smart Grid*, vol. 6, no. 3, pp. 1107–1115, 2015.

[25] A. H. Hajimiragha, M. R. D. Zadeh, and S. Moazeni, “Microgrids frequency control considerations within the framework of the optimal generation scheduling problem,” *IEEE Transactions on Smart Grid*, vol. 6, no. 2, pp. 534–547, 2015.

[26] Z. Wang, W. Wu, and B. Zhang, “A fully distributed power dispatch method for fast frequency recovery and minimal generation cost in autonomous microgrids,” *IEEE Transactions on Smart Grid*, vol. 7, no. 1, pp. 19–31, 2016.

[27] W. Gu, Z. Wu, and X. Yuan, "Microgrid economic optimal operation of the combined heat and power system with renewable energy," in *Power and Energy Society General Meeting, 2010 IEEE.* IEEE, 2010, pp. 1–6.

[28] Z. Suli, M. Zhongjing, and L. Xiangdong, "Optimal microgrid economic operations under progressive second price auction mechanisms," in *Control Conference (CCC), 2013 32nd Chinese.* IEEE, 2013, pp. 8891–8896.

[29] H. Kanchev, F. Colas, V. Lazarov, and B. Francois, "Emission reduction and economical optimization of an urban microgrid operation including dispatched pv-based active generators," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 4, pp. 1397–1405, 2014.

[30] R. Gupta and N. Gupta, "Robust microgrid operation considering renewable power uncertainties," in *Power Systems Conference (NPSC), 2014 Eighteenth National.* IEEE, 2014, pp. 1–6.

[31] Y. Liu, C. Yuen, N. U. Hassan, S. Huang, R. Yu, and S. Xie, "Electricity cost minimization for a microgrid with distributed energy resource under different information availability," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 4, pp. 2571–2583, 2015.

[32] J. Clavier, F. Bouffard, D. Rimorov, and G. Jos, "Generation dispatch techniques for remote communities with flexible demand," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 3, pp. 720–728, 2015.

[33] N. Nikmehr and S. Najafi-Ravadanegh, "Optimal operation of distributed generations in micro-grids under uncertainties in load and renewable power generation using heuristic algorithm," *IET Renewable Power Generation*, vol. 9, no. 8, pp. 982–990, 2015.

[34] Z. Yang, R. Wu, J. Yang, K. Long, and P. You, "Economical operation of microgrid with various devices via distributed optimization," *IEEE Transactions on Smart Grid*, vol. 7, no. 2, pp. 857–867, 2016.

[35] C. Cecati, C. Citro, A. Piccolo, and P. Siano, "Smart operation of wind turbines and diesel generators according to economic criteria," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 10, pp. 4514–4525, 2011.

[36] P. Li, D. Xu, Z. Zhou, W.-J. Lee, and B. Zhao, “Stochastic optimal operation of microgrid based on chaotic binary particle swarm optimization.” *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 66–73, 2016.

[37] P. Siano, C. Cecati, H. Yu, and J. Kolbusz, “Real time operation of smart grids via fcn networks and optimal power flow,” *IEEE Transactions on Industrial Informatics*, vol. 8, no. 4, pp. 944–952, 2012.

[38] Z. H. Dall Anese, Emiliano and G. G. B, “Distributed optimal power flow for smart microgrids,” *IEEE Transactions on Smart Grid*, vol. 4, no. 3, pp. 1464–1475, 2013.

[39] D. T. Nguyen and L. B. Le, “Risk-constrained profit maximization for microgrid aggregators with demand response,” *IEEE Transactions on smart grid*, vol. 6, no. 1, pp. 135–146, 2015.

[40] C. Chen, S. Duan, T. Cai, B. Liu, and G. Hu, “Smart energy management system for optimal microgrid economic operation,” *IET renewable power generation*, vol. 5, no. 3, pp. 258–267, 2011.

[41] F. Valencia, D. Sáez, J. Collado, F. Ávila, A. Marquez, and J. J. Espinosa, “Robust energy management system based on interval fuzzy models,” *IEEE Transactions on Control Systems Technology*, vol. 24, no. 1, pp. 140–157, 2016.

[42] V. Mohan, J. G. Singh, and W. Ongsakul, “An efficient two stage stochastic optimal energy and reserve management in a microgrid,” *Applied energy*, vol. 160, pp. 28–38, 2015.

[43] R. Zamora and A. K. Srivastava, “Controls for microgrids with storage: Review, challenges, and research needs,” *Renewable and Sustainable Energy Reviews*, vol. 14, no. 7, pp. 2009–2018, 2010.

[44] C. Chen, S. Duan, T. Cai, B. Liu, and G. Hu, “Optimal allocation and economic analysis of energy storage system in microgrids,” *IEEE Transactions on Power Electronics*, vol. 26, no. 10, pp. 2762–2773, 2011.

[45] S. Chen, H. B. Gooi, and M. Wang, “Sizing of energy storage for microgrids,” *IEEE Transactions on Smart Grid*, vol. 3, no. 1, pp. 142–151, 2012.

[46] S. Bahramirad, W. Reder, and A. Khodaei, “Reliability-constrained optimal sizing of energy storage system in a microgrid,” *perspectives*, vol. 1, p. 3, 2012.

[47] B. Bahmani-Firouzi and R. Azizipanah-Abarghooee, “Optimal sizing of battery energy storage for micro-grid operation management using a new improved bat algorithm,” *International Journal of Electrical Power & Energy Systems*, vol. 56, pp. 42–54, 2014.

[48] S. Mohammadi, B. Mozafari, S. Solymani, and T. Niknam, “Stochastic scenario-based model and investigating size of energy storages for pem-fuel cell unit commitment of micro-grid considering profitable strategies,” *IET Generation, Transmission & Distribution*, vol. 8, no. 7, pp. 1228–1243, 2014.

[49] H. Xiao, W. Pei, Y. Yang, and L. Kong, “Sizing of battery energy storage for micro-grid considering optimal operation management,” in *Power System Technology (POWERCON), 2014 International Conference on.* IEEE, 2014, pp. 3162–3169.

[50] F. A. Bhuiyan, A. Yazdani, and S. L. Primak, “Optimal sizing approach for islanded microgrids,” *IET Renewable Power Generation*, vol. 9, no. 2, pp. 166–175, 2014.

[51] T. Kerdphol, Y. Qudaih, and Y. Mitani, “Battery energy storage system size optimization in microgrid using particle swarm optimization,” in *Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), 2014 IEEE PES.* IEEE, 2014, pp. 1–6.

[52] Y. Sun, Z. Li, M. Shahidehpour, and B. Ai, “Battery-based energy storage transportation for enhancing power system economics and security.” *IEEE Trans. Smart Grid*, vol. 6, no. 5, pp. 2395–2402, 2015.

[53] L. N. An, T. Quoc-Tuan, B. Seddik, and N. Van-Linh, “Optimal sizing of a grid-connected microgrid,” in *Industrial Technology (ICIT), 2015 IEEE International Conference on.* IEEE, 2015, pp. 2869–2874.

[54] H. Khorramdel, J. Aghaei, B. Khorramdel, and P. Siano, “Optimal battery sizing in microgrids using probabilistic unit commitment.” *IEEE Trans. Industrial Informatics*, vol. 12, no. 2, pp. 834–843, 2016.

[55] T. Kerdphol, Y. Qudaih, Y. Mitani, and P. Garasi, “Optimal sizing of battery energy storage system in microgrid system considering load shedding scheme,” *International Journal of Smart Grid and Clean Energy*, vol. 4, no. 1, pp. 22–29, 2015.

[56] J. P. Fossati, A. Galarza, A. Martín-Villate, and L. Fontán, “A method for optimal sizing energy storage systems for microgrids,” *Renewable Energy*, vol. 77, pp. 539–549, 2015.

[57] I. Gyuk, P. Kulkarni, J. Sayer, J. Boyes, G. Corey, and G. Peek, “The united states of storage [electric energy storage],” *IEEE Power and Energy Magazine*, vol. 3, no. 2, pp. 31–39, 2005.

[58] P. C. Loh, L. Zhang, and F. Gao, “Compact integrated energy systems for distributed generation,” *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1492–1502, 2013.

[59] J.-H. Teng, S.-W. Luan, D.-J. Lee, and Y.-Q. Huang, “Optimal charging/discharging scheduling of battery storage systems for distribution systems interconnected with sizeable pv generation systems,” *IEEE Trans. Power Syst*, vol. 28, no. 2, pp. 1425–1433, 2013.

[60] A. Gabash and P. Li, “Flexible optimal operation of battery storage systems for energy supply networks,” *IEEE Trans. Power Syst*, vol. 28, no. 3, pp. 2788–2797, 2013.

[61] I. Atzeni, L. G. Ordóñez, G. Scutari, D. P. Palomar, and J. R. Fonollosa, “Noncooperative and cooperative optimization of distributed energy generation and storage in the demand-side of the smart grid.” *IEEE Trans. Signal Processing*, vol. 61, no. 10, pp. 2454–2472, 2013.

[62] Y. Levron, J. M. Guerrero, and Y. Beck, “Optimal power flow in microgrids with energy storage,” *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 3226–3234, 2013.

[63] C. Gouveia, J. Moreira, C. Moreira, and J. P. Lopes, “Coordinating storage and demand response for microgrid emergency operation,” *IEEE Transactions on Smart Grid*, vol. 4, no. 4, pp. 1898–1908, 2013.

[64] B. Zhao, X. Zhang, J. Chen, C. Wang, and L. Guo, "Operation optimization of standalone microgrids considering lifetime characteristics of battery energy storage system," *IEEE transactions on sustainable energy*, vol. 4, no. 4, pp. 934–943, 2013.

[65] D. Tran and A. M. Khambadkone, "Energy management for lifetime extension of energy storage system in micro-grid applications," *IEEE Transactions on Smart Grid*, vol. 4, no. 3, pp. 1289–1296, 2013.

[66] N. Eghtedarpour and E. Farjah, "Distributed charge/discharge control of energy storages in a renewable-energy-based dc micro-grid," *IET Renewable Power Generation*, vol. 8, no. 1, pp. 45–57, 2014.

[67] I. Wasiak, R. Pawelek, and R. Mienski, "Energy storage application in low-voltage microgrids for energy management and power quality improvement," *IET Generation, Transmission & Distribution*, vol. 8, no. 3, pp. 463–472, 2014.

[68] D. Wang, S. Ge, H. Jia, C. Wang, Y. Zhou, N. Lu, and X. Kong, "A demand response and battery storage coordination algorithm for providing microgrid tie-line smoothing services," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 2, pp. 476–486, 2014.

[69] D. Papadaskalopoulos, D. Pudjianto, and G. Strbac, "Decentralized coordination of microgrids with flexible demand and energy storage," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 4, pp. 1406–1414, 2014.

[70] K. M. M. Huq, M. Baran, S. Lukic, and O. E. Nare, "An energy management system for a community energy storage system," in *Energy Conversion Congress and Exposition (ECCE), 2012 IEEE.* IEEE, 2012, pp. 2759–2763.

[71] P. Malysz, S. Sirouspour, and A. Emadi, "An optimal energy storage control strategy for grid-connected microgrids," *IEEE Transactions on Smart Grid*, vol. 5, no. 4, pp. 1785–1796, 2014.

[72] C. Wei, Z. M. Fadlullah, N. Kato, and I. Stojmenovic, "On optimally reducing power loss in micro-grids with power storage devices," *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 7, pp. 1361–1370, 2014.

[73] M. Mahmoodi, P. Shamsi, and B. Fahimi, "Economic dispatch of a hybrid microgrid with distributed energy storage," *IEEE Transactions on Smart Grid*, vol. 6, no. 6, pp. 2607–2614, 2015.

[74] A. Ouammi, H. Dagdougui, and R. Sacile, "Optimal control of power flows and energy local storages in a network of microgrids modeled as a system of systems," *IEEE Transactions on Control Systems Technology*, vol. 23, no. 1, pp. 128–138, 2015.

[75] Y. Xu, W. Zhang, G. Hug, S. Kar, and Z. Li, "Cooperative control of distributed energy storage systems in a microgrid," *IEEE Transactions on smart grid*, vol. 6, no. 1, pp. 238–248, 2015.

[76] K. Rahbar, J. Xu, and R. Zhang, "Real-time energy storage management for renewable integration in microgrid: An off-line optimization approach," *IEEE Transactions on Smart Grid*, vol. 6, no. 1, pp. 124–134, 2015.

[77] A. Urtasun, E. L. Barrios, P. Sanchis, and L. Marroyo, "Frequency-based energy-management strategy for stand-alone systems with distributed battery storage," *IEEE Transactions on Power Electronics*, vol. 30, no. 9, pp. 4794–4808, 2015.

[78] T. Morstyn, M. Momayyezan, B. Hredzak, and V. G. Agelidis, "Distributed control for state-of-charge balancing between the modules of a reconfigurable battery energy storage system," *IEEE Transactions on Power Electronics*, vol. 31, no. 11, pp. 7986–7995, 2016.

[79] W. Shi, X. Xie, C.-C. P. Chu, and R. Gadh, "Distributed optimal energy management in microgrids." *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1137–1146, 2015.

[80] D. Wu, F. Tang, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, "A control architecture to coordinate renewable energy sources and energy storage systems in islanded microgrids," *IEEE Transactions on Smart Grid*, vol. 6, no. 3, pp. 1156–1166, 2015.

[81] E. Liegmann and R. Majumder, "An efficient method of multiple storage control in microgrids," *IEEE Transactions on Power Systems*, vol. 30, no. 6, pp. 3437–3444, 2015.

[82] S. A. Pourmousavi, M. H. Nehrir, and R. K. Sharma, “Multi-timescale power management for islanded microgrids including storage and demand response,” *IEEE Transactions on Smart Grid*, vol. 6, no. 3, pp. 1185–1195, 2015.

[83] A. K. Barnes, J. C. Balda, and A. Escobar-Mejía, “A semi-markov model for control of energy storage in utility grids and microgrids with pv generation,” *IEEE Transactions on Sustainable Energy*, vol. 6, no. 2, pp. 546–556, 2015.

[84] ——, “A semi-markov model for control of energy storage in utility grids and microgrids with pv generation,” *IEEE Transactions on Sustainable Energy*, vol. 6, no. 2, pp. 546–556, 2015.

[85] N. R. Tummuru, M. K. Mishra, and S. Srinivas, “Dynamic energy management of renewable grid integrated hybrid energy storage system,” *IEEE Transactions on Industrial Electronics*, vol. 62, no. 12, pp. 7728–7737, 2015.

[86] T. A. Nguyen and M. Crow, “Stochastic optimization of renewable-based microgrid operation incorporating battery operating cost,” *IEEE Trans. Power Syst*, vol. 31, no. 3, pp. 2289–2296, 2016.

[87] R. Rigo-Mariani, B. Sareni, and X. Roboam, “Integrated optimal design of a smart microgrid with storage,” *IEEE Transactions on Smart Grid*, vol. 8, no. 4, pp. 1762–1770, 2017.

[88] Z. Zhao, E. B. Makram, and Y. Tong, “Impact study of energy storage for optimal energy scheduling in microgrid,” in *Power and Energy Society General Meeting, 2012 IEEE.* IEEE, 2012, pp. 1–7.

[89] A. Nottrott, J. Kleissl, and B. Washom, “Storage dispatch optimization for grid-connected combined photovoltaic-battery storage systems,” in *Power and Energy Society General Meeting, 2012 IEEE.* IEEE, 2012, pp. 1–7.

[90] W.-j. Gao, T.-j. Jing, and M.-h. Yang, “A economic dispatch method of energy storage systems under time-of-use pricing in microgrids,” in *Electricity Distribution (CICED), 2012 China International Conference on.* IEEE, 2012, pp. 1–5.

[91] C. G. Codemo, T. Erseghe, and A. Zanella, “Energy storage optimization strategies for smart grids,” in *Communications (ICC), 2013 IEEE International Conference on*. IEEE, 2013, pp. 4089–4093.

[92] N. Femia, D. Toledo, and W. Zamboni, “Storage unit and load management in photovoltaic inverters for residential application,” in *Industrial Electronics Society, IECON 2013-39th Annual Conference of the IEEE*. IEEE, 2013, pp. 6800–6805.

[93] W. Alharbi and K. Bhattacharya, “Demand response and energy storage in mv islanded microgrids for high penetration of renewables,” in *Electrical Power & Energy Conference (EPEC), 2013 IEEE*. IEEE, 2013, pp. 1–6.

[94] V. Arya, P. Dutta, and S. Kalyanaraman, “On mitigating wind energy variability with storage,” in *Communication Systems and Networks (COMSNETS), 2013 Fifth International Conference on*. IEEE, 2013, pp. 1–9.

[95] Y. Yoon and Y.-H. Kim, “Charge scheduling of an energy storage system under time-of-use pricing and a demand charge,” *The Scientific World Journal*, vol. 2014, 2014.

[96] K. Rahbar, J. Xu, and R. Zhang, “An off-line optimization approach for online energy storage managementin microgrid system,” in *Acoustics, Speech and Signal Processing (ICASSP), 2014 IEEE International Conference on*. IEEE, 2014, pp. 7769–7773.

[97] A. Ahmadi, G. K. Venayagamoorthy, and R. Sharma, “Performance of a smart microgrid with battery energy storage system’s size and state of charge,” in *Computational Intelligence Applications In Smart Grid (CIASG), 2014 IEEE Symposium on*. IEEE, 2014, pp. 1–7.

[98] E. Oh, S.-Y. Son, H. Hwang, J.-B. Park, and K. Y. Lee, “Impact of demand and price uncertainties on customer-side energy storage system operation with peak load limitation,” *Electric Power Components and Systems*, vol. 43, no. 16, pp. 1872–1881, 2015.

[99] M. Sedghi and M. Aliakbar-Golkar, “Optimal storage scheduling in distribution network considering fuzzy model of pevs,” in *Electrical Power Distribution Networks (EPDC), 2013 18th Conference on.* IEEE, 2013, pp. 1–6.

[100] I. Strnad and D. Škrlec, “An approach to the optimal operation of the microgrid with renewable energy sources and energy storage systems,” in *EUROCON, 2013 IEEE.* IEEE, 2013, pp. 1135–1140.

[101] Q. Fu, A. Hamidi, A. Nasiri, V. Bhavaraju, S. B. Krstic, and P. Theisen, “The role of energy storage in a microgrid concept: Examining the opportunities and promise of microgrids.” *IEEE Electrification Magazine*, vol. 1, no. 2, pp. 21–29, 2013.

[102] M. T. Lawder, B. Suthar, P. W. Northrop, S. De, C. M. Hoff, O. Leitermann, M. L. Crow, S. Santhanagopalan, and V. R. Subramanian, “Battery energy storage system (bess) and battery management system (bms) for grid-scale applications.” *Proceedings of the IEEE*, vol. 102, no. 6, pp. 1014–1030, 2014.

[103] M. t Ions, “Flexible distribution of energy and storage resources,” 2015.

[104] S. Morozumi, “Japanese experience in energy storage for a distribution network with high-penetration renewable energy [technology leaders],” *IEEE Electrification Magazine*, vol. 3, no. 3, pp. 4–12, 2015.

[105] R. E. Hebner, K. Davey, J. Herbst, D. Hall, J. Hahne, D. D. Surls, and A. Ouroua, “Dynamic load and storage integration,” *Proceedings of the IEEE*, vol. 103, no. 12, pp. 2344–2354, 2015.

[106] T. S. Ustun, C. R. Ozansoy, and A. Zayegh, “Implementing vehicle-to-grid (v2g) technology with iec 61850-7-420,” *IEEE Transactions on Smart Grid*, vol. 4, no. 2, pp. 1180–1187, 2013.

[107] J. Chynoweth, C.-Y. Chung, C. Qiu, P. Chu, and R. Gadh, “Smart electric vehicle charging infrastructure overview,” in *ISGT 2014.* IEEE, 2014, pp. 1–5.

[108] M. Meiqin, S. Shujuan, and L. Chang, “Economic analysis of the microgrid with multi-energy and electric vehicles,” in *Power Electronics and ECCE Asia (ICPE & ECCE), 2011 IEEE 8th International Conference on.* IEEE, 2011, pp. 2067–2072.

[109] S. Mal, A. Chattopadhyay, A. Yang, and R. Gadh, "Electric vehicle smart charging and vehicle-to-grid operation," *International Journal of Parallel, Emergent and Distributed Systems*, vol. 28, no. 3, pp. 249–265, 2013.

[110] M. A. Ortega-Vazquez, "Optimal scheduling of electric vehicle charging and vehicle-to-grid services at household level including battery degradation and price uncertainty," *IET Generation, Transmission & Distribution*, vol. 8, no. 6, pp. 1007–1016, 2014.

[111] C.-Y. Chung, J. Chynoweth, C. Qiu, C.-C. Chu, and R. Gadh, "Design of fair charging algorithm for smart electrical vehicle charging infrastructure," in *ICT Convergence (ICTC), 2013 International Conference on*. IEEE, 2013, pp. 527–532.

[112] L. Zhu, F. R. Yu, B. Ning, and T. Tang, "Optimal charging control for plug-in electric vehicles in smart microgrids fueled by renewable energy sources," *International journal of green energy*, vol. 10, no. 9, pp. 924–943, 2013.

[113] N. Jayawarna and M. Barnes, "Study of a microgrid with vehicle-to-grid sources during network contingencies," *Intelligent Automation & Soft Computing*, vol. 16, no. 2, pp. 289–302, 2010.

[114] D. T. Nguyen and L. B. Le, "Optimal energy trading for building microgrid with electric vehicles and renewable energy resources," in *Innovative Smart Grid Technologies Conference (ISGT), 2014 IEEE PES*. IEEE, 2014, pp. 1–5.

[115] Y. Guo, S. Xu, and W. Su, "Smart management system of plug-in electric vehicle charging service," in *Transportation Electrification Conference and Expo (ITEC), 2015 IEEE*. IEEE, 2015, pp. 1–6.

[116] L. K. Panwar, K. S. Reddy, R. Kumar, B. Panigrahi, and S. Vyas, "Strategic energy management (sem) in a micro grid with modern grid interactive electric vehicle," *Energy conversion and management*, vol. 106, pp. 41–52, 2015.

[117] E. Sortomme and M. A. El-Sharkawi, "Optimal scheduling of vehicle-to-grid energy and ancillary services," *IEEE Transactions on Smart Grid*, vol. 3, no. 1, pp. 351–359, 2012.

[118] S. Beer, T. Gómez, D. Dallinger, I. Momber, C. Marnay, M. Stadler, and J. Lai, "An economic analysis of used electric vehicle batteries integrated into commercial building microgrids," *IEEE Transactions on Smart Grid*, vol. 3, no. 1, pp. 517–525, 2012.

[119] L. Jian, H. Xue, G. Xu, X. Zhu, D. Zhao, and Z. Shao, "Regulated charging of plug-in hybrid electric vehicles for minimizing load variance in household smart microgrid." *IEEE Trans. Industrial Electronics*, vol. 60, no. 8, pp. 3218–3226, 2013.

[120] S. Shafiee, M. Fotuhi-Firuzabad, and M. Rastegar, "Investigating the impacts of plug-in hybrid electric vehicles on power distribution systems," *IEEE Transactions on Smart Grid*, vol. 4, no. 3, pp. 1351–1360, 2013.

[121] S. Derakhshandeh, A. S. Masoum, S. Deilami, M. A. Masoum, and M. H. Golshan, "Coordination of generation scheduling with pevs charging in industrial microgrids," *IEEE Trans. Power Syst*, vol. 28, no. 3, pp. 3451–3461, 2013.

[122] C. Gouveia, J. Moreira, C. Moreira, and J. P. Lopes, "Coordinating storage and demand response for microgrid emergency operation," *IEEE Transactions on Smart Grid*, vol. 4, no. 4, pp. 1898–1908, 2013.

[123] T. Wu, Q. Yang, Z. Bao, and W. Yan, "Coordinated energy dispatching in microgrid with wind power generation and plug-in electric vehicles," *IEEE Transactions on Smart Grid*, vol. 4, no. 3, pp. 1453–1463, 2013.

[124] M. H. K. Tushar, C. Assi, M. Maier, and M. F. Uddin, "Smart microgrids: Optimal joint scheduling for electric vehicles and home appliances," *IEEE Transactions on Smart Grid*, vol. 5, no. 1, pp. 239–250, 2014.

[125] J. Van Roy, N. Leemput, F. Geth, J. Büscher, R. Salenbien, and J. Driesen, "Electric vehicle charging in an office building microgrid with distributed energy resources," *IEEE Transactions on sustainable energy*, vol. 5, no. 4, pp. 1389–1396, 2014.

[126] C. Chen and S. Duan, "Optimal integration of plug-in hybrid electric vehicles in microgrids," *IEEE Transactions on Industrial Informatics*, vol. 10, no. 3, pp. 1917–1926, 2014.

[127] M. Zhang and J. Chen, “The energy management and optimized operation of electric vehicles based on microgrid,” *IEEE Transactions on Power Delivery*, vol. 29, no. 3, pp. 1427–1435, 2014.

[128] C. Corchero, M. Cruz-Zambrano, F.-J. Heredia *et al.*, “Optimal energy management for a residential microgrid including a vehicle-to-grid system,” *IEEE transactions on smart grid*, vol. 5, no. 4, pp. 2163–2172, 2014.

[129] G. Carpinelli, F. Mottola, and D. Proto, “Optimal scheduling of a microgrid with demand response resources,” *IET Generation, Transmission & Distribution*, vol. 8, no. 12, pp. 1891–1899, 2014.

[130] N. Liu, Q. Chen, J. Liu, X. Lu, P. Li, J. Lei, and J. Zhang, “A heuristic operation strategy for commercial building microgrids containing evs and pv system,” *IEEE Transactions on Industrial Electronics*, vol. 62, no. 4, pp. 2560–2570, 2015.

[131] J. Pahasa and I. Ngamroo, “Phevs bidirectional charging/discharging and soc control for microgrid frequency stabilization using multiple mpc,” *IEEE Transactions on Smart Grid*, vol. 6, no. 2, pp. 526–533, 2015.

[132] Y. Guo, J. Xiong, S. Xu, and W. Su, “Two-stage economic operation of microgrid-like electric vehicle parking deck,” *IEEE Transactions on Smart Grid*, vol. 7, no. 3, pp. 1703–1712, 2016.

[133] T. Wang, D. O’Neill, and H. Kamath, “Dynamic control and optimization of distributed energy resources in a microgrid,” *IEEE transactions on smart grid*, vol. 6, no. 6, pp. 2884–2894, 2015.

[134] C. Changsong and D. Shanxu, “Microgrid economic operation considering plug-in hybrid electric vehicles integration,” *Journal of Modern Power Systems and Clean Energy*, vol. 3, no. 2, pp. 221–231, 2015.

[135] Y. Guo, S. Xu, and W. Su, “Smart management system of plug-in electric vehicle charging service,” in *Transportation Electrification Conference and Expo (ITEC), 2015 IEEE*. IEEE, 2015, pp. 1–6.

[136] Z. Wang, B. Chen, J. Wang, and C. Chen, “Networked microgrids for self-healing power systems,” *IEEE Transactions on smart grid*, vol. 7, no. 1, pp. 310–319, 2016.

[137] E. Sortomme and M. El-Sharkawi, "Optimal power flow for a system of microgrids with controllable loads and battery storage," in *Power Systems Conference and Exposition, 2009. PSCE'09. IEEE/PES*. IEEE, 2009, pp. 1–5.

[138] M. Fathi and H. Bevrani, "Statistical cooperative power dispatching in interconnected microgrids," *IEEE Trans. Sustain. Energy*, vol. 4, no. 3, pp. 586–593, 2013.

[139] ——, "Adaptive energy consumption scheduling for connected microgrids under demand uncertainty," *IEEE Transactions on Power Delivery*, vol. 28, no. 3, pp. 1576–1583, 2013.

[140] A. K. Marvasti, Y. Fu, S. DorMohammadi, and M. Rais-Rohani, "Optimal operation of active distribution grids: A system of systems framework," *IEEE Transactions on Smart Grid*, vol. 5, no. 3, pp. 1228–1237, 2014.

[141] Z. Wang, B. Chen, J. Wang, M. M. Begovic, and C. Chen, "Coordinated energy management of networked microgrids in distribution systems," *IEEE Transactions on Smart Grid*, vol. 6, no. 1, pp. 45–53, 2015.

[142] D. Gregoratti and J. Matamoros, "Distributed energy trading: The multiple-microgrid case," *iEEE Transactions on industrial Electronics*, vol. 62, no. 4, pp. 2551–2559, 2015.

[143] N. Nikmehr and S. N. Ravadanegh, "Optimal power dispatch of multi-microgrids at future smart distribution grids," *IEEE Transactions on Smart Grid*, vol. 6, no. 4, pp. 1648–1657, 2015.

[144] Y. Wang, S. Mao, and R. M. Nelms, "On hierarchical power scheduling for the macrogrid and cooperative microgrids," *IEEE Transactions on Industrial Informatics*, vol. 11, no. 6, pp. 1574–1584, 2015.

[145] G. Pepermans, J. Driesen, D. Haeseldonckx, R. Belmans, and W. D'haeseleer, "Distributed generation: definition, benefits and issues," *Energy policy*, vol. 33, no. 6, pp. 787–798, 2005.

[146] S. Han, S. Han, and H. Aki, "A practical battery wear model for electric vehicle charging applications," *Applied Energy*, vol. 113, pp. 1100–1108, 2014.

[147] C. Zhou, K. Qian, M. Allan, and W. Zhou, “Modeling of the cost of ev battery wear due to v2g application in power systems,” *IEEE Transactions on Energy Conversion*, vol. 26, no. 4, pp. 1041–1050, 2011.

[148] C. Ju, P. Wang, L. Goel, and Y. Xu, “A two-layer energy management system for microgrids with hybrid energy storage considering degradation costs,” *IEEE Transactions on Smart Grid*, vol. 9, no. 6, pp. 6047–6057, 2017.

[149] S. Han, S. Han, and H. Aki, “A practical battery wear model for electric vehicle charging applications,” *Applied Energy*, vol. 113, pp. 1100–1108, 2014.

[150] N. K. Meena, A. Swarnkar, N. Gupta, and K. R. Niazi, “Stochastic volt/var planning and operation for microgrids with renewables,” *Int. Journal of Elect. Energy*, vol. 4, no. 3, pp. 159–164, 2016.

[151] W. Su, J. Wang, and J. Roh, “Stochastic energy scheduling in microgrids with intermittent renewable energy resources,” *IEEE Transactions on Smart grid*, vol. 5, no. 4, pp. 1876–1883, 2013.

[152] S. Talari, M. Yazdaninejad, and M.-R. Haghifam, “Stochastic-based scheduling of the microgrid operation including wind turbines, photovoltaic cells, energy storages and responsive loads,” *IET Generation, Transmission & Distribution*, vol. 9, no. 12, pp. 1498–1509, 2015.

[153] Y. Atwa, E. El-Saadany, M. Salama, and R. Seethapathy, “Optimal renewable resources mix for distribution system energy loss minimization,” *IEEE Transactions on Power Systems*, vol. 25, no. 1, pp. 360–370, 2009.

[154] R. Eberhart and J. Kennedy, “Particle swarm optimization,” in *Proceedings of the IEEE international conference on neural networks*, vol. 4. Citeseer, 1995, pp. 1942–1948.

[155] G.-G. Wang, S. Deb, and L. d. S. Coelho, “Elephant herding optimization,” in *2015 3rd International Symposium on Computational and Business Intelligence (ISCBI)*. IEEE, 2015, pp. 1–5.

[156] G.-H. Tzeng and J.-J. Huang, *Multiple attribute decision making: methods and applications*. Chapman and Hall/CRC, 2011.

[157] K. Yoon, “A reconciliation among discrete compromise solutions,” *Journal of the Operational Research Society*, vol. 38, no. 3, pp. 277–286, 1987.

[158] C.-L. Hwang, Y.-J. Lai, and T.-Y. Liu, “A new approach for multiple objective decision making,” *Computers & operations research*, vol. 20, no. 8, pp. 889–899, 1993.

[159] N. K. Meena, A. Swarnkar, N. Gupta, and K. R. Niazi, “Dispatchable wind power generation planning for distribution systems,” in *2017 7th International Conference on Power Systems (ICPS)*. IEEE, 2017, pp. 491–496.

# List of Publications

## International Journals

1. Sonam Parashar, Anil Swarnkar, Nikhil Gupta, K.R Niazi, “A Modified Elephant Herding Optimization for Economic Generation Co-ordination of Distributed Energy Resources and BESS in Grid Connected Microgrid,” IET, Journal of Engineering, vol. 2017, pp. 1969-1973, no. 13, 2017.
2. Sonam Parashar, Anil Swarnkar, K.R Niazi and Nikhil Gupta, “Multiobjective Optimal Sizing of Battery Energy Storage in Grid Connected Microgrid, IET, Journal of Engineering, vol. 2019, pp. 5280-1983, no. 18, 2017.
3. Nand K. Meena,, Sonam Parashar, Anil Swarnkar, Nikhil Gupta and K. R. Niazi, “Improved Elephant Herding Optimization for Multiobjective DER Accommodation in Distribution Systems,” IEEE Transactions on Industrial Informatics, vol.14, pp. 1029-1039, no.13, 2017.
4. Nand K. Meena, Sonam Parashar, Anil Swarnkar, Nikhil Gupta, K. R. Niazi and Ramesh Bansal, “Mobile Power Infrastructure Planning and Operational Management for Smart City Applications,” Energy Procedia, vol.142, pp. 2202-2207,2017.
5. Sonam Parashar, Anil Swarnkar, K.R Niazi and Nikhil Gupta, “Operational Management of the Microgrid considering lifetime Characteristics of the Lithium-Ion Battery Energy Storage, Springer: Journal of Modern Power Systems and clean Energy.(under review).

## International Conferences

1. Sonam Parashar, Anil Swarnkar, Nikhil Gupta and K.R Niazi, “An Efficient AI-Based Approach for Dynamic Scheduling of Grid Connected Microgrid,” IEEE, ICACCS-2017, Coimbatore, India, 2017.

2. Sonam Parashar, Anil Swarnkar, K.R Niazi and Nikhil Gupta, "Optimal Integration of Electric Vehicles and Energy Management of Grid Connected Microgrid," IEEE International Transportation Electrification Conference, Pune, India, 2017.
3. Sonam Parashar, Anil Swarnkar, K.R Niazi and Nikhil Gupta, "Stochastic Operational Management of Grid Connected Microgrid under Uncertainty of Renewable Resources and Load Demand," Springer: Intelligent Computing Techniques for Smart Energy Systems, Jaipur, India, 2018.
4. Sonam Parashar, Anil Swarnkar, K.R Niazi and Nikhil Gupta, "Operational Management of Grid Connected Microgrid with Responsive Loads", IEEE: 8th International Conference on Power Systems (ICPS), Jaipur-India, December 2019.

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