EXPERT ENERGY MANAGEMENT AND CONTROL OF MICROGRIDS USING VARIOUS META-HEURISTIC TECHNIQUES UNDER ENVIRONMENTAL UNCERTAINTIES

Thesis submitted by

MEENAKSHI DE

Doctor of Philosophy (Engineering)

Department of Power Engineering

Faculty Council of Engineering and Technology

Jadavpur University

Kolkata, India

Year: 2024

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1. Title of the Thesis:

Expert Energy Management and Control of Microgrids Using Various Meta-Heuristic Techniques under Environmental Uncertainties

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I. LIST OF Ph.D. PUBLICATIONS

A. *In Journals*

1. Meenakshi De, Kamal Krishna Mandal, "Energy management strategy and renewable energy integration within multi-microgrid framework utilizing multi-objective modified personal best particle swarm optimization," Sustainable Energy Technologies and Assessments, publisher- Elsevier, (**SCI indexed** and UGC approved), vol. 53, 2022, https://doi.org/10.1016/j.seta.2022.102410.

2. Meenakshi De, G. Das, K. K. Mandal, "An effective energy flow management in grid-connected solar–wind-microgrid system incorporating economic and environmental generation scheduling using a meta-dynamic approach-based multiobjective flower pollination algorithm," Energy Reports, publisher- Elsevier, (**SCI indexed** and UGC approved), ISSN: 2352-4847, vol. 7, pp. 2711–2726, 2021.

3. Meenakshi De, G. Das, K. K. Mandal, "Proposing intelligent energy management model for implementing price rate in microgrids using demand response program," Journal of The Institution of Engineers (India): Series B (IEIB), Springer, (**Scopus indexed** and UGC approved), ISSN: 22502106, E-ISSN: 22502114, vol. 102, no.3, pp.427–435, 2021.

4. Meenakshi De, G. Das, K. K. Mandal, B. Tudu. "A critical assessment of demand response programs applied for optimal energy management in microgrids," International Journal of Recent Technology and Engineering (IJRTE), (**Scopus indexed** and UGC approved), vol-8, ISSN: 2277-3878, pp. 344-349, 2019, https://doi.org/10.35940/ijrte.B1123.0782S719.

B. *In Proceedings of Conferences:*

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2. Meenakshi De, G. Das, K. K. Mandal, "Cost driven optimization of micro grid under environmental uncertainties using different improved PSO models," in *Proceedings of International Conference on Mathematical Analysis and Applications in Modeling (ICMAAM)*, Springer Proceedings in Mathematics & Statistics book series (PROMS, volume 302), Print ISBN-978-981-15-0421-1, pp. 173-185, 2018.

3. Meenakshi De, G. Das, K. K. Mandal, "A Review of demand response programs applied for energy management in microgrids, " in *Proceedings of International Conference on Clean and Renewable Energy (ICCARE), NIT Durgapur,* pp. 23, 2019.

4. Meenakshi De, G. Das, K. K. Mandal, “Energy management in microgrids for application in residential, commercial and industrial systems using soft computing technique,” in *Proceedings of International Conference on Frontiers in Engineering, Management and Applied Science (FEMAS-2019),* Technically co-sponsored by The Institution of Engineers (India) ISBN No: 978-93-5391-015-0, pp. 9, 2019.

II. Papers presented in conference

Sl. No.	Title of paper	Year	Type of conference	Organizing Institution
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2)	A Review of demand response programs applied for energy management in microgrids.	2019	International Conference	NIT Durgapur
3)	Energy management in microgrids for application in residential, commercial and industrial systems using soft computing technique	2019	International Conference	Guru Nanak Institute of Technology
4)	Cost driven optimization of micro grid under environmental uncertainties using different improved PSO models.	2018	International Conference	Jadavpur University

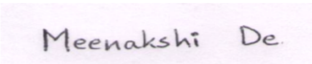
PROFORMA – 1

STATEMENT OF ORIGINALITY

I, **Meenakshi De** registered on 18/9/2017 do hereby declare that this thesis entitled, "**EXPERT ENERGY MANAGEMENT AND CONTROL OF MICROGRIDS USING VARIOUS META-HEURISTIC TECHNIQUES UNDER ENVIRONMENTAL UNCERTAINTIES**," contains literature survey and original research work done by undersigned candidate as part of Doctoral studies.

All information in this thesis have been obtained and presented in accordance with existing academic rules and ethical conduct. I declare that, as required by these rules and conduct, I have fully cited and referred all materials and results that are not original to this work.

I also declare that I have checked this thesis as per "Policy on Anti Plagiarism, Jadavpur University, 2019", and level of similarity as checked by iThenticate software is 5%.

Signature of Candidate: 

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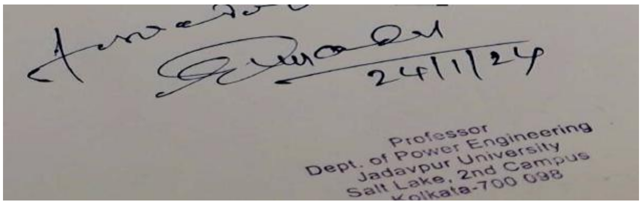

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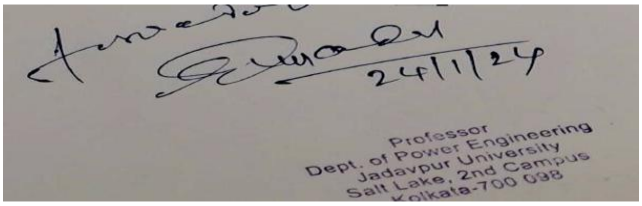
PROFORMA - 2

CERTIFICATE FROM THE SUPERVISOR

This is to certify that the thesis entitled, "**EXPERT ENERGY MANAGEMENT AND CONTROL OF MICROGRIDS USING VARIOUS META-HEURISTIC TECHNIQUES UNDER ENVIRONMENTAL UNCERTAINTIES**," submitted by **Meenakshi De**, who got her name registered on 18/9/2017 for the award of Ph. D. (Engineering) degree of Jadavpur University, Kolkata, India is absolutely based upon her own work under the supervision of **Prof. (Dr.) Kamal Krishna Mandal, Professor and Head of the Department, Department of Power Engineering, Jadavpur University, Kolkata, India** and that neither her thesis nor any part of thesis has been submitted for any degree/ diploma or any other academic award anywhere before.



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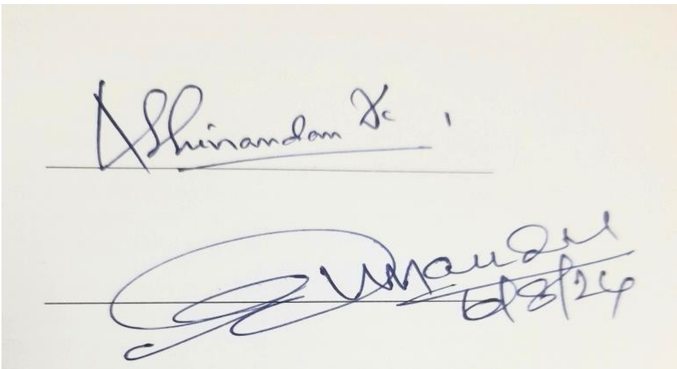
Certificate of Approval

The foregoing thesis entitled, "Expert Energy Management and control of Microgrids using various Meta-Heuristic Techniques under Environmental Uncertainties," submitted by Meenakshi De, is hereby approved as creditable study of engineering subject. This research work is carried out and presented in a manner satisfactory to warrant its acceptance as prerequisite for the award of Ph.D. (Engineering) degree from Jadavpur University for which it has been submitted and examined. It is understood that by this approval the undersigned approve the thesis for purpose for which it has been submitted.



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CHAPTER-1

INTRODUCTION

1.1. Introduction

Microgrid (MG) is a small power generating system comprising of distributed generators (DG). Microgrids (MGs) are linked with main utility through power electronic devices, i.e. voltage-source inverter system (VSI) and many other devices.

Various factors such as global warming, greenhouse gas effects, rapid depletion of fossil fuels encourage research in this domain. Recent research has put forward utmost focus in improvement of distributed generation units, energy management in microgrids, proper placement of DG units, design and sizing of DG units, along with improvement in areas of power electronics, inverter systems, their different application in diverse mechanism for operation such as grid-connected as well as islanded etc.

Energy management in microgrids is performed for optimizing microgrid operation. Integration of renewable energy resources viz. wind power and solar photovoltaic (PV) within MG considers factors such as environmental benefits, also sustained power productions. Point-of-coupling to utility becomes detached whenever MG operates in stand alone modes; also this increases reliability of MG functioning while conventional grid faces blackout. Renewable energy like wind as well as solar-power is impacted by varying weather conditions, thus including these uncertainties becomes important during formulation of power flow problems.

It is noteworthy that expert energy management in MG system is done for optimized operations in power from wind turbine (WT) as well as solar PV wattage production. Generations from renewable energy sources (RES) to cover uncertainty linked to these generation sources by minimization of costs as well as emissions using demand response (DR) programs. MGs are categorized in diverse manner. Figure 1.1(a) presents MG network. Figure 1.1(b) presents classification of microgrids.

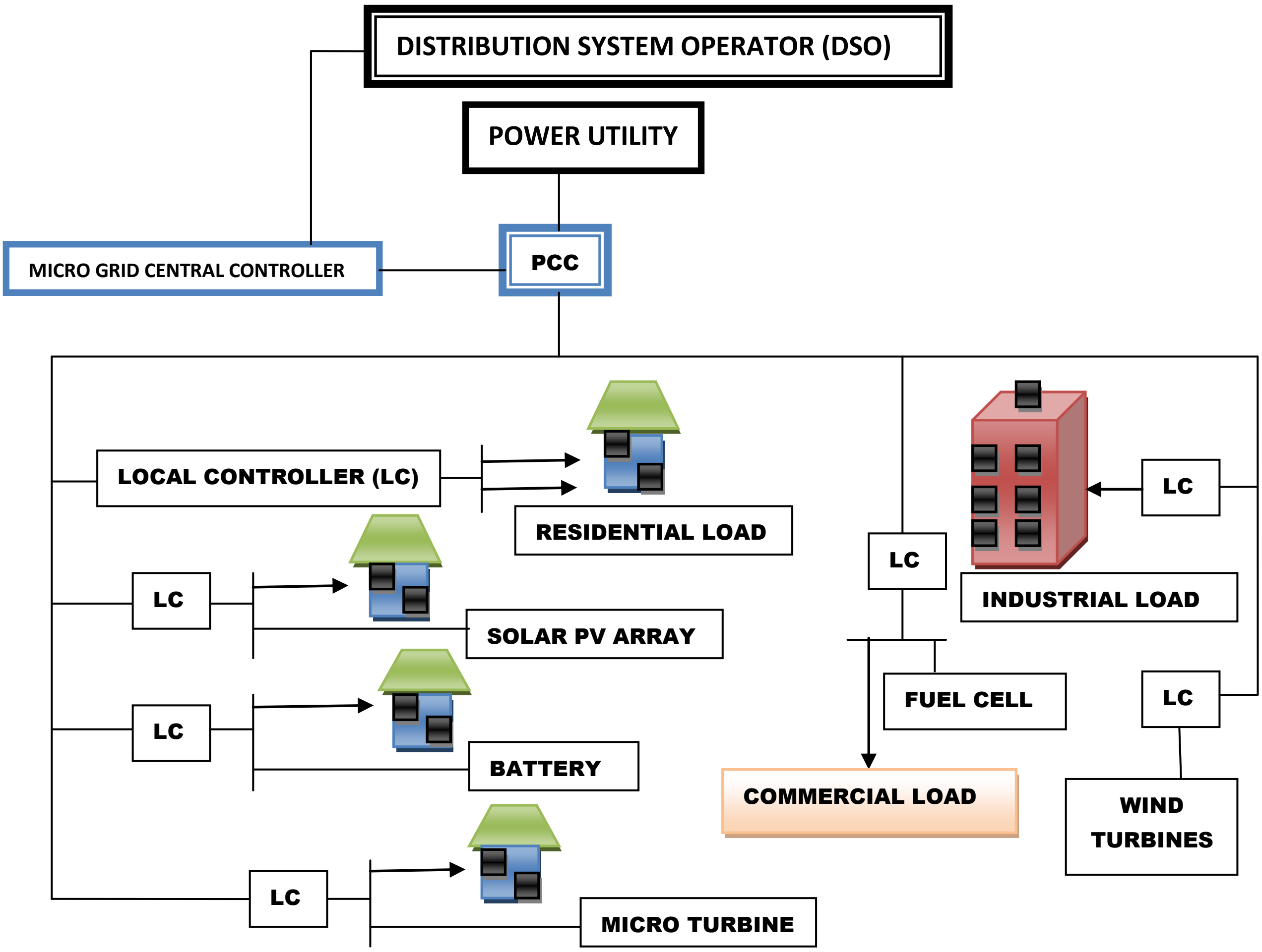


Figure 1.1(a). Microgrid network

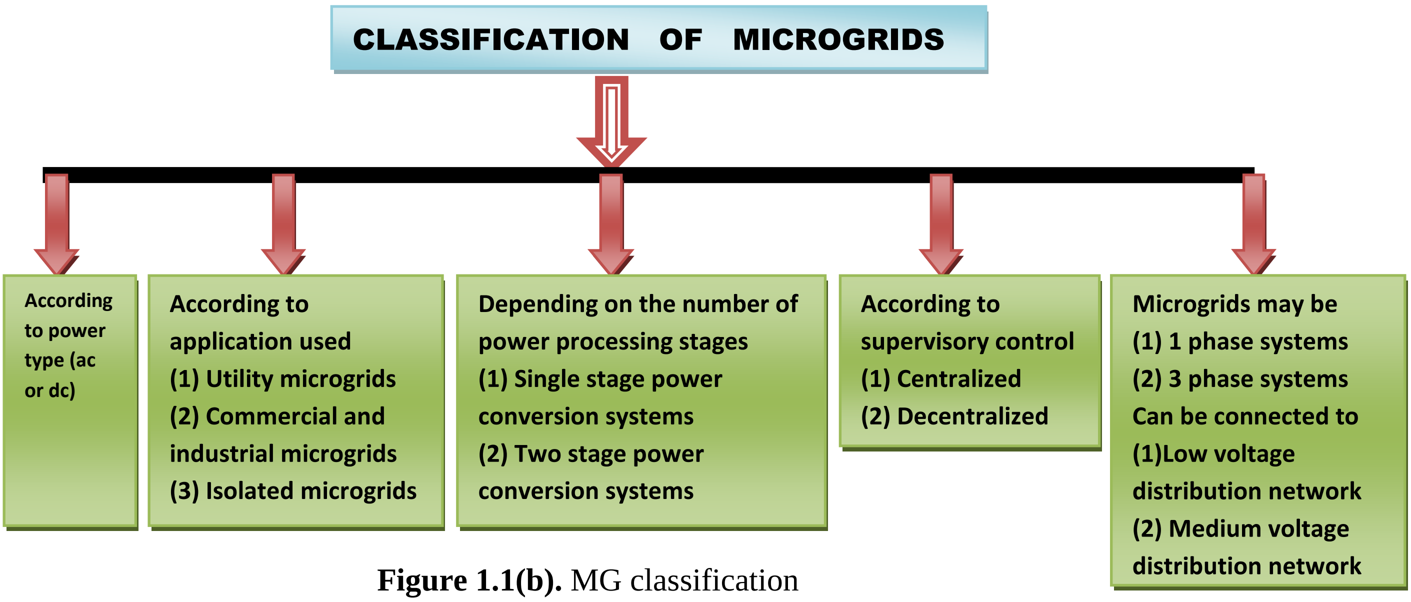


Figure 1.1(b). MG classification

1.2. Literature Review

Researchers over the years have focussed on domain of microgrid technology and aimed to provide clean and green energy supply to society. Wang et al. utilized Improved Interval Optimization technique devised upon differential evolution within MG economical schedule [1]. Improved particle swarm optimization (IPSO) algorithm was utilized in [2] for implementing day-ahead cooling in MG composed of combined cooling, heating and power (CCHP) units and electricity coordinated scheduling was also carried out. Mohammad H. Moradi et al. presented novel optimization technique on hybrid harmony search and genetic algorithms in finding optimized operation as well as location for DGs. MG operation was carried out by setting correct economically viable droop parameters in distributed generated units which operate on droop control. Alongside with this, multi-objective function was formulated for obtaining economic operation of distributed generation units. Multiple objectives in microgrid operation strategies included consumption cost, developing index for voltage stability, voltage deviations observed in system voltage profile etc [3]. Optimization of Hybrid Micro-Grid System (HMGS) was investigated in [4] where authors focussed on utilization of Multi-Objective Particle Swarm Optimization (MOPSO) technique for obtaining optimum configuration of microgrid system and for sizing its distributed generation units. Application of intelligent techniques for obtaining optimized control parameters in real time proved to be difficult task because controller design increased number of parameters. Research work focussed on different optimization methods for improving voltage-profile and attempt into optimize controlling parameters [5]. Genetic-Algorithm (GA) was used for optimization of microgrids [6]. In GA, convergence was obtained to local optimal solution than global optimal, whereas particle swarm optimization (PSO) algorithm utilized swarm dynamics to find global solutions. Researchers proposed a novel self-adaptive particle swarm optimization technique in [7] solving emission constrained economic dispatch. Metaheuristic algorithms such as Simulated Annealing, Particle Swarm Optimization, Harmony Search, and Genetic Algorithm were illustrated in [8]. For reliable and stable functioning in MG, it’s important for ensuring smooth transitions within its diverse methods for operations, i.e. islanded as well as grid-connected [9]. Economic optimal scheduling strategy was implemented by chance constrained programming particle swarm optimization [10]. Efficient management within MGs by improved multi-objective teaching learning-based technique was described in [11]. In [12] economic scheduling method was proposed for constituting utility-linked hybrid systems by improved inverter technology. Another research work [13] illustrated genetic algorithm approach for optimal scheduling of microgrid in isolated mode. Agent modelling method for robust optimization was proposed in another literature [14]. Some researchers studied wind-hydro-pump storage systems and economic viability analysis; profit maximization of same [15]-[18]. A study focussed on energy management in microgrid utilizing bald eagle search algorithm [19]. An improved indicator was suggested for estimating voltage stability margin for two-bus system [20]. Another improved method viz., Multi-Cross Learning-Based-Chaotic Differential Evolution (MLCDE) was represented in [21] for solving various engineering problems such as minimizing operation cost of MG in scheduling period considering fuel, operation, maintenance and emission costs which arise in MG operation. Within various engineering problems, regulating voltage as well as frequency becomes essential for robust as well as smooth operations [22]. An analytical approach was conducted to evaluate the droop control method in an islanding microgrid [23]. Performance characteristic in MG being mostly impacted by utility power system, so it’s needed for regulating active as well as reactive power-flows for controlling MGs output wattage [24]. Microgrids within its utility linked operations face various factors which impact quality of energy. Loads-sharing within DGs was controlled using requisite technique [25]. Research [26] demonstrated energy management within MGs amidst probability for occurrence of different uncertain circumstances such as electrical line's failures, higher demands of power as well as abrupt cost enhancements affects reliability in MG operations. In research [27], Net Present Value (NPV) was used as economic indicator for justifying MG investment. Optimized solutions were achieved using quadratic programming as well as PSO (QP-PSO) algorithms [27], [28]. A research study suggested stochastic methodology [29] that facilitated for investigating impact in uncertainties in managing as well as functioning within MGs. Authors [30] provided stochastic model which was utilized in day-ahead microgrid operation and management.

Increased occurrence of distributed generation and active distribution networks (DN), again necessity of cleaner power supports encourages developing newer concept in power networks referred as microgrids (MGs). Distribution networks face several challenges such as economic, technological and environmental problems. An important aspect for controlling such difficulties based upon developing renewable energy which can be provided in form of microgrids. Microgrid in distribution network combines distributed generators (DG), energy storages system (ESS) and load-demands, also incorporates the equipments such as converters [31], [32]. Energy management systems (EMS) play key role in microgrids. Charging strategy for PV-based battery switch stations was illustrated in [33]. A study introduced algorithms as well as optimizational model in energy management systems and utilized non-dominated sorting genetic algorithm (NSGA-II) [34]. An energy management system in hybrid power system was analyzed in [35]. Multi-microgrid (MMG) Smart distribution network (SDN) was considered as independent entity, where main objective for EMS being to reduce operational cost of each entity. In reference [36] bi-level decentralized algorithm was utilized in energy management system for the coordinated operation of networked microgirds. Robust-optimizations formulated in EMS for MG within [37] considering impact of uncertainty sources. EMS within MG system with DR as well as reserve capacities suggested [38]. As reported by [39], for minimizing MGs operating prices, decentralized-Markov process was illustrated.

Fathi et al. [40] proposed scheduling amidst MG within MMG systems. Some authors [41] have developed priority energy management system where characteristics of buyers and sellers were assigned to individual microgrids. Prevailing research on microgrids should emphasize evolving technologies also new operations as well as control strategies in planning for new distribution networks. Marnay et al. [42] discussed about MGs for improving electrical generations as well as supply systems.

Distributed energy resources (DERs) being tactically placed as well as operate in power systems to upgrade voltage-control, also to reduce cost [43]. DERs comprise of distributed generation units (DG) as well as energy storage systems (ESS). The effect of DERs upon utility depends upon capacity, placement of DG, ESS [44], [45]. In order to guarantee stability & reliability, consideration of reactive powers support within power network planning [46]. Authors in [47] utilized fuzzy genetic algorithm for reducing system losses. Review work being illustrated [48] for EMS within microgrid. Multi objective scheme for microgrid with higher environmental protectivity was illustrated [49].

A novel technique presented, on multi-criteria decision making (MCDM) was used in [50]. Approach of optimum capacitance installation was proposed in [51] which enhanced voltage-regulation. Researchers [52] represented unique method for installing capacitor for obtaining minimum network losses as well as emission. A detailed survey of optimal capacitor placement techniques on distribution lines to reduce loss was presented in [53]. The specifications in quality of service, suitable voltage-level must be conserved [54]. Demands in individual node depend upon node-voltages. Voltages controlling methods being utilized which lower network demands, costs. Concept for conservation of voltage-reduction (CVR) reduces cumulative demands by controlling voltages in substations. Implementing methods of voltage reductions can be categorized as: open loop as well as closed loop techniques [55]. Minimization of losses being advantageous to utilities revenue, also quantity in increased power savings should be investigated. Various works on CVR were represented in [56]–[59]. This shows that smaller reductions within system-voltages produce appreciable reductions of energy-costs annually. The modelling of CVR as well as the influence of voltages upon customer's demands and utilities was conducted; where majority loads possesses mixed-load-type features, method was investigated in a literature termed as ZIP-model [60]. Backward–forward technique was presented in power-flow within various studies [61]-[64].

An interesting study on hierarchical-technique in multi microgrid [65] coordinates MG's functioning as well as distributional networks. Cooperative energy management (EM) software for networked microgrids was presented [66]. Interactive EMS within networked MGs was proposed in [67]. Nested-EMS scheduling for MMGs was illustrated in [68]. Another literature [69] illustrated optimization models under uncertainty in distributed generation systems. Economical operations for MMGs were illustrated [70] considering uncertainties for loads consumptions as well as generated powers in renewable-DGs.

A study aims to solve Security Constrained Unit Commitment (SCUC) formulation by implementing novel optimization technique called modified imperialistic competition algorithm (MICA) [71]. A research study in [72] presented novel metaheuristic-innovative hybrid particle swarm optimization and differential evolution (ihPSODE) to tackle power dispatch formulation considering valve-point effect. Research in [73] utilized combinatorial particle swarm optimization (PSO) and Pattern searching methods also performs optimization of gas as well as power within microgrids (MGs), performance pointers were utilized for evaluation as well as assessing MGs. Study in [74] focussed on an optimized power managing in autonomous MGs using Imperialist-Competition-Algorithm (ICA). Another study, focussed in utilizing Multi-Objective Optimization (MOO) viz., backtracking search algorithm [75]. EMS in MG computed devised upon multi agent system's techniques [76]; this study illustrated deployment of secondary controlling strategy devised upon MG EMS model and network maintains MG frequencies as well as energy interchanges from/to utility in proximity to pre-specified value and obtained in a manner wherein production as well as consumer resources prevailing in optimal dispatching process. This system can function within grid-associated as well as autonomous mode. Researchers investigated fuzzy optimization in energy technologies [77]. New muddy soil fish optimization algorithm (MSFOA) proposed w.r.t fish's foraging manner focussed on minimizing production overheads and curtail expenditure in power imports from grid amidst consideration of system's limits; were studied in [78]. Interesting research explored link amidst magnitude in power's variation w.r.t torque of induction generators and devised transfer function illustrating relation with linearised differential equations thereby verifying the effectiveness by simulation in MATLAB-Simulink [79]. Focus in [80] was to deploy robust model based on PSO that coped with uncertainties of RES in MGs, wherein objectives for robust simultaneous active/ reactive power as well as reserve-schedule formulation within MGs illustrated as maximization of social welfare (SW). Presented approach being formulated utilizing a maxi-mini optimization technique. Robust design was obtained in a manner where maximizers in outer level aspire optimum solve amidst worst-case objective obtained by minimisers in inner level considering uncertain neighbourhood. This execution for proposed method was assessed upon standard MG. Simulation's outcomes substantiate that proposed robust-PSO method facilitates MG operators' in decreasing day-to-day operating prices also yields high SW. In another formulation, substantial solution of time-variant subsidy's prices along with equilibrium energy amounts, performing optimization of system welfare within different grid as well as system states [81] was presented. Here Quasi-Feed-In-Tariff (QFIT) policy being represented of MGs which incorporates RES including Policy Makers (PM) as well as Generation Companies (GENCOs) objective presuming two-stage multi-period computation which combines characteristics of utility; up-stage formulation corresponding to the PM, and low-stage decision devised within GENCOs. Researchers [82] provided, day-ahead scheduling methodology in smart-microgrid (SMG) formulated as multiobjective function consisting of: (i) operational costs & effusion pollutant optimization (ii) minimizing demand curtailment's costs incorporating strategic modification to truncate load (iii) correlation within shifted load & output wattage of WT. Efficient technique of optimal EM was aim for study wherein modified Porcellio Scaber algorithm was illustrated in [83] wherein EMS comprises of day-ahead as well as hour-ahead schedule; also economical dispatching in real-time operations. Optimum day-ahead unit commitment was obtained by two phases; control in power produced of sources in MGs as well as controlled demand management. Taking account of all storage dynamics to obtain EMS strategy; modified Moth-Flame Optimization (MFO) algorithm was developed in [84] wherein the problem formulation aims at minimizing Total Cost of Electricity (TCE) intending in improvement of reliability, enhancing functioning as well as exploiting RES in providing electricity. "Loss of Power Supply Probability (LPSP)" was taken into consideration in improving reliability rate within studied system. Efficient PSO incorporating quadratic transfer function for solving unit-commitment (UC) within battery ESS-integrated MGs was proposed in [85], where UC formulation done as MOO wherein objectives denote MG operating costs as well as battery energy storage (BES) degrading, whereby resultant MOO transformed in single objective optimization formulation. Here, impact of weighting factors upon MG operation costs as well as BES lifecycle was examined. A study presented dynamic battery-modelling for simulating stand-alone PV uses [86] wherein the researchers presented an enhanced battery model which utilized automatically parameter's extracting methods as well as solve for numerically computing formulations. In presented method, power dispatch was conducted utilizing Differential Evolution [87] where look-ahead approach being deployed within algorithm for identifying the number of previous periods for forward dynamic economic dispatch (DED) or subsequent periods for backward DED, that needs conventional DED for satisfying power-balance constraint. Researchers in [88] illustrated modeling & managing MG associated system, deploying improved Artificial Bee Colony (IABC) algorithm wherein optimum MG structure obtained devised upon loads; decreasing fuel costs, emissions, operational as well as maintaining costs. Utilizing inputs in MG system viz., WT, PV, fuel cell (FC), microturbine (MT), diesel units and ESS as well as correlated price function, presented technique devises requisite multi-objective formulation. Recent research [89] illustrated minimization of operating costs incorporating fuel expenses for DGs, unit start-up costs, market price linked with power trading in MG and grid, deploying quantum PSO technique. Unique arrangement of uncertainty modeling technologies in power networks for taking decisions was depicted in [90]. Research work [91] proposed unique methodology for MGs operation. Authors in [92] represented smart microgrid (SMG) infrastructure with hybrid resources. Prior study focussed on power loss optimization within power systems. Joint optimization being presented indicates coupling relations [93], wherein capacitor's placement along conductor's replacements formulated together which optimize power loss. Some research stress on involvement of RES & analysis of modified method to DR, also described small-scaled power generation within electricity framework. Researchers in [94] investigated Ghana's

RES amidst socio-economic factors along environmental evaluation. In [95], computation for technological efficiency during locally electric supply was illustrated. A research in [96] represented modification in DR with novel methodology where customers & electricity providers obtain highest performance. Impact in ancillary market involving extensive RES inclusion was implemented in [97]. Research work in [98] proposed novel stochastic configurations deploying genetic algorithm. Enhancement in power efficacy for isolated DN was illustrated in [99] by NSGA II. In another research study [100], authors presented an approach which deployed PSO for minimizing energy as well as operational costs for MG by adjusting control variables in energy operation management. An interesting research presented modified personal best particle swarm optimization for EMS in microgrids [101]. Study focussed on big bang–big crunch technique for reconfigurations of distributing networks within fuzzy domain [102]. Teacher-Learning-Algorithm (TLA) with Artificial Neural Network (ANN) was illustrated in [103]. In [104], an Artificial Bee Colony algorithm was presented for power dispatch. Interesting study in [105] presented shuffled frog-leap method which was devised aiming at combinational analysis. Unique control mechanism presented for coordination of networked MGs [106] wherein computation was performed with DN at upper level & MG in lower level. Intelligent multiagent method utilized for MMG infrastructure focussed on power optimization [107]. Adaptive robust method for scheduling within AC/DC MMGs was illustrated in [108]. Prior study [109] recommends EMS in MMGs utilizing online alternating-direction-method-of-multipliers-algorithm. EMS devised upon Mixed-Integer-Nonlinear-Programming aimed for MG standalone functioning [110].

Researchers also focussed on control aspects of microgrids in their studies.Various factors like increased electricity outages within power systems were caused by economic as well as several problems, e.g., 1) enhanced demands in supply which were being transferrable in prolonged distance, causing large quantities in dissipated energy; 2) continuous load-demand growth; 3) excessive swing in one day to next within wattage flows schedule, causing traditional offlined plans futile. Such factors propel power systems into physical limitations, wherein possibilities for compromising utility reliabilities exist. “Distributed energy resources (DER)” presents solutions which decrease electric as well as physical distances within loads as well as generators, improving reactive powers in enhancing grid voltage profile as well as power quality, eradicate constraints within distributions as well as transmissions line, reduces transmissions as well as distributions loss, utilize wasted heats, postponing necessities for establishing fresh transmissions line as well as large generating plant, keeping carbon emissions level lower. Review on various developments within smart-grids as well as micro-grids were illustrated in [111]. Performances for power-systems possessing higher penetrations in distributed-sources were investigated for assessing various categories of stability within bulk-system [112]. Challenge for possessing numerous DERs illustrated as following: 1) Current Control Strategy (CCS) being inadequate in functioning at islanding modes as there exists nil significant sources in energy. 2) Numerous DERs possess many energy generating curves as well as capacity; so, MG requires fast regulations within islanding modes against utility-connecting modes [113]. Controlling as well as implementing EMS envisioned for microgrid can be obtained devised upon utilized DERs techniques, load’s requirement, probable operating scenarios [114]. EMS within MGs possessing several DGs was investigated in [115]. Higher amount in DERs, especially within distributions system (either medium or lower voltages), causes problem like voltages enhancement as well as unbalanced network’s voltages also frequencies (while functioning in DERs or during abrupt trip) [116]-[118]. These problems can be resolved via MGs, and their characteristics stated as: 1) incorporating DERs not disrupting utility operation, viz., DERs were established that neither requiring reform nor rewire distributions network [119], implementing smart distribution and coupled MGs [120]; 2) enable electrical network for observing as well as controlling fault effeciently also in reducing damages because of DERs outages, thereby continuously supplying significant load [111], [118], [121]; 3) allow load-demand sheddings as well as automatic switchings via controlling algorithm, also shortening outages as well as electricity restoration times, also keep faulty sections within distribution lines secluded till utilities crew point-out fault's position [111], [121], [122]; 4) allow into operate within (utility-connecting or islanding) modes, [119], [123]-[125]; 5) improvement in infrastructure reliability as well as flexibility, via DERs [120], [126]-[129]; 6) DERs uses wasted heats for improving generating effectiveness [113], [120], [127], [130]. Detailed study on various power electronic applications utilized for integration of DG units was presented in [131]. A MG system can be conceptualized to be comprised of microsources as well as loads, along with energy storage systems, supplying heat load-demands as well as electricity into nearby areas [114], [119], [132], [133]. Consortium for Electric Reliability Technology Solutions (CERTS) [120] illustrated MGs comprising of aggregated DERs, storaging system, as well as loads; functioning as utility-linked or islanding modes.

Microgrid classification was the focus of the study in several researches. MGs can be categorized diversely:1) According to power-types (either AC or DC) [134], emergency operation of MG (islanded mode) [135], [136], d.c. microgrid [134], higher-frequencies AC MG [137], [138] (that being utilized in solving power-quality due to presences in higher power converting appliances whereby reducing impacts in variations at renewables within MG), line frequency AC (LFAC) MG [134], also hybridized dc- as well as ac-coupling MGs [134].

2) Within conditions of applicability utilized [128], these being categorized into three types: a) utility MGs (city's-district operating as MG), b) commercial as well as industry-linked MGs, also c) island MGs,

3) According to network infrastructure, MGs categorized diversely, devised upon numbers in power processing states: a) singular-state power-converting system [134], [139], [140] as well as b) dual-state power-converting systems [134], [139], [141]-[143] (mostly found configuration in every electronics linked DERs). Dual-states converting networks possess dual converters, either on PV part, utilized for extracting maximized wattage off PV, whereas another being linked with utility as well as adjusted for following grid's necessities.

4) According to supervisory-controls, these being centralized/decentralized [134]; within centralized controls, centralized controllers within MGs send requisite prespecified-values into LCs via two-ways communicating linking, although method possesses lower reliability, as well as redundancy [144]; decentralized-methodology being multi-agent model, supplying flexibilities into systems also communications within the agents i.e., utilizing communications languages like Java-Jade [134], [145], [146].

5) According to DER connections with MG, i.e., electronically couplings (converters utilized) or traditional rotational DGs [114], [134]. MGs either being single/three-phase-networks also can be linked with lower/medium-voltages DNs [147]; the modes for operations being isolated or grid connected. MG controls strategies and control layers were investigated by several researchers.

Controlling power-converters within MGs denoted specifically significant [148]. Network controls utilized in islanding operations being voltage-regulations (VR), frequencies regulations (FR), as well as load-sharings (LS) optimizations. As there's absence in synchronous-machines within majority MGs, for achieving load-demands as well as power-supplying balances, voltage-source-inverters (VSI) being utilized in obtaining balances. Utilizing VSI for providing references in voltages as well as frequencies and enables MGs for operating within islanding modes. Research works in [149], [150] represented discussions upon various control techniques utilized in MG operations as well as implements experimental controlling strategies within MG. Grid-formation operations were utilized in regulating voltages as well as frequencies within MGs, while operating at islanding modes [114], [134], [148]. Controlling strategy, layered interconnected structure, as well as operating functions illustrated as follows.

A. Controlling Strategy

These being the major controlling strategy suggested in microgrids at islanding modes: a) single-master operations (SMO); b) multi-master operations (MMO) [151]. They utilize VSI in providing references of voltages as well as frequencies [150], also suitable secondary load-frequency controls were considered in maintaining frequencies within specific limitations whereby operating DERs at economical rate [152].

SMOs [151]: The method comprises single inverters operating in VSI (master) while others as in followers (slaves). Whenever main electricity supplies being interrupted, slaves takes voltage references originating at master as well as operates within P Q mode. LCs receives specific values at microgrid central controller (MGCC) for maintaining generations for active also reactive powers in specific limits.

MMO [151]: Within the operations; various VSI's function with pre-specified frequency/active powers as well as voltage/reactive power characteristic. VSI can be linked with storage-devices or to DERs.

B. Wired as well as Non-wire Interconnection

Instant Load Sharing (LS) [153], [154] within MGs being obtained via dual controlling strategies. Controlling strategies being categorized based upon controlled-wire-interconnection [153]. One scheme consists active-LS method, that possess parallelly-linked MG converter, incorporating master–slaves (MS) [155]-[165], parallel operation of standard UPSs [166, 167], average current sharing [168]-[175] currents limiting controls [176] as well as circular chain-controls (3C) [176], [177]. Such controlling strategies need intercommunicating links that leading to decreases in network reliabilities as well as expandabilities [178], [179]. Another controlling technique of parallel-inverters lie upon droop-methods [180]-[216]. Such method regulates output-voltages as well as frequencies as in function for active powers (P) also reactive powers (Q) provided by inverter. Droop-methods utilize locally electrical measurements; obtaining, high reliabilities as well as flexibilities being obtained at physical locations for units [178], [217].

C. Controlling Layers

MG controlling systems needs ensuring total control functionings should be fulfilled (viz., supplying electricity as well as thermal energies, continuously feeds significant loads, energy markets participations, auto reconnection following failures). Controlling objective obtained via central/decentral controls also via 3 controlling stages. Authors in [113] call supervisory controlling architectures multi-agent controllers. Controlling level denoted in following [113], [146], [218].

1) Distribution network operator (DNO) as well as market operator (MO);
2) Microgrid central controller (MGCC);
3) Local controllers (LCs).

DNO becomes essential whenever there exists multiple MGs beyond singular microgrid within DN. DNO as well as MO being utility's unit; neither belonging in MG. Secondary layer being MGCC, integrates DERs within MG. MGCC, after the optimization process was complete, sends to the LCs the set-points for active and reactive power [218]. LCs being low layerered controls [146]. LCs possess some intelligences also, implement decision's in local context for decentralize operations (but within central models, LCs obtain specified values from MGCC) [98], [218], [219]. Droop control in low voltage-grids was illustrated [220]. Research work in [221] illustrated intelligent-node (iNode) also intelligent-socket (iSocket) performs similar works as in MGCC and LC.

Voltage and frequency control of microgrids were also investigated by researchers in their studies. In grid linked MG, voltages as well as frequencies being achieved with main-grid. Robustness as well as reliability in operating MG depends significantly upon controlling schemes of DGs. A voltage controller at each DER unit provides local stability [219]. Hence, effective power controlling loops in inverter-based DG's provide significant part for fulfilling power-quality requisites. A novel strategy of design in load frequency control for MGs after islanding was presented in [222]. Current controlling loops being utilized in improving qualities in inverters outcoming currents, exterior power controlling loops can also be integrated with inner current controlling loops in regulating inverter output power. Also this ensures qualified specified current signal into current-controller. The, inverter-based DGs being controlled w.r.t imposed criteria like voltages, current, active as well as reactive-power [223]. Controlling power-flows within grid-linked condition was denoted being major function. These being due to that total MG operation to be completely controlled with larger main grid systems.

While, major operating hurdles occurs evidently whenever MG transfers into islanded operating modes. Such hurdles being mainly associated with voltage-drops as well as frequency-deviations linked to diverse characteristics for connected-DGs. Consumer demands share mechanisms being also significant issues which should be taken into considerations for obtaining better operations within all MG operating methods. No load, half load, full load mechanisms can be considered [223]. Detailed study upon power system stability issues as well as controls was illustrated in [224]. As functions for loads, management for MG voltages as well as frequencies being necessary controlling functions, as DC/AC converter also diverse types of DGs possesses various operating properties. Hence, local voltages, power quality, as well as occurrence of losses also affect electricity supplies to end-consumer [225]. So this becomes essential in explaining these issues in MG operating conditions within two-major categories. Firstly, within grid-linked condition, because of stiffness operational characteristic within utilities, controlling MG voltages as well as frequencies are not necessary as main-utility provides superior qualities. Secondly, within islanded condition, MG becomes totally accountable in providing voltages as well as frequencies at allowable limit. Hence, controlling approaches provides controlled voltages as well as frequencies; also cater loads swiftly along with higher power-quality by introducing artificial load-dependent droop-coefficients [226]. MG voltages generally impacted with several problems incorporating harmonic distortions in terms of deviations of shapes within voltages/current waveforms against standard sinusoids. Such deviation leads into disruption of normal functioning of equipments as well as system resonances with power-factor correction banks. Hence, attenuations for harmonic distortions within these networks being necessary, also generally obtained with coupling transformers or specified types of filters [227]. Transient periods present significant challenges to be addressed within microgrids. Switchings within respective operating modes as well as load-changes causes highly swift voltage deviations; hence additive protecting equipments generally necessary for maintaining load-demands. Microgrids comprise of inverter based DG units that require power electronic converters for connecting with main grid. The inverter can regulate the output real power rapidly and accurately [228]. Severely randomly fluctuating voltages are linked within WTs generation as well as PVs [229], [230]. Reactive powers sources like inverter DGs and Fuzzy Logic Controller (FLC) [231], shunt active filters [232], as well as synchronous compensators (DSTATCOMs) [232], [233] suggested in regulating voltages in point of common coupling (PCC) within MG. When traditional Proportional-Integral (PI) was used in controlling voltages against nonlinear dynamical errors, hence voltage-controllers cannot provide higher controlling performances until intelligent techniques implemented in finding optimized system parameters for dealing disturbances. Fundamental frequencies as well as voltages were controlled for stable closed loop systems in maintaining suitable voltage-regulations. Purpose of deregulation was providing customers better choice of energy providers at same time bringing costs down also providing upgraded service and reliability [234]. The droop-control method was suggested for regulating MG voltages as well as frequencies [235]. Total schemes in this control being comprising 3 controlling loops: 1) droop control loop which achieves reference voltages as well as frequencies also produces specified active as well as reactive powers devised upon drooping characteristics; 2) voltage controlling loops devised upon output signals for first loop as well as calculated points for voltages, active powers, reactive powers, in producing reference-current’s vector; 3) current controlling loops which provides specified voltage- signal utilizes Pulse Width Modulation techniques. Within the controller’s strategies, PI regulators utilized for second as well as third controls loops. Controlling performances highly depends upon droop control characteristics in regulating MG voltages as well as frequencies. Moreover owing to droop control characteristics, voltages as well as frequencies drops in values which make DG units operating at new low voltages as well as frequencies, but none was close to the nominal values. Research work also investigated optimization strategies in finding best locations for DGs for improving voltage profile [236] or in optimizing controlling parameters which offered reliable operations for MGs [237].

Active and Reactive Power Control in microgrids represent important aspects of research. Controls of active as well as reactive power flows are necessary in regulations of inverters output powers. The technique ensures reliability within linked DGs; helps reduce import powers of grids; as well as supports such contract arrangements within MG as well as utilities. So, active as well as reactive power control’s modes illustrated based upon MG operating modes. An example was islanding MG mode [238], controlling priorities being maintenance in system’s voltages as well as frequencies below thresholds for avoiding collapses. So, power-flow controls being obtained, given the regulations for MG voltages as well as frequencies are realized, hence network produces satisfactory power quality within the modes. Again owing to effect of bulk electrical systems within grid-connected modes, every DGs function as active-reactive power-sources. Here, controls for active as well as reactive-power flows being highly advantageous in maximizing generations at linked DGs; hence, economical operating strategies were deployed for optimized energy management within MG as well as grid. This facilitates higher markets penetrations in micro-source. Controls for combined active and reactive power generally suggested in facilitating connections within hybrid MG as well as electrical power supply infrastructure [239], where, controls structures were proposed for compensating current harmonics, injects active power into loads, supply redundancies to utility. Shunted active filters with energy-storages were designed for mitigating voltage-sags, also improving provided power into nonlinear-loads [240]. Ref [241] illustrated combinations in genetic-algorithms as well as power-flows computations were represented for allocating locations as well as sizings in DGs relative to electricity networks. The methodology was advantageous in DG installation for obtaining superior economical operation conditions. In [242], power-flows controls were illustrated in inverter-based DGs within grid-linked operating modes. The controller balances active power as well as reactive power whereby performing adjustments in power angles as well as filter's capacitor voltages. Considerations of controllable loads which implemented within MGs were illustrated in [243], [244].

Researchers in their studies investigated power sharing within microgrids. When MG configurations obtained within several DGs connected in parallel, sharing power amongst such entities being significant which improves electricity supplying qualities. Loads distributed amongst several DG units, also achieving stable systems operations. Conventional droop-control in voltages as well as frequencies was typically suggested, to share active as well as reactive-power. Ref [234] illustrated diverse EMS upon autonomous as well as non autonomous MG. Frequency-droops characteristics were utilized in controlling real power. Ref [245] presented transient stability analysis for power system along-with deployment in converter linked DG whereby comparison of behaviour in test-system with converter connected DG as well as behaviour in test-system when conventional synchronous machine being connected was performed. Event, occurring at pre-planned switchings as well as faults within islanded modes were described in [246]. Power-derivatives-integrals component was introduced for addressing slowed loads-sharing in conventional droop-control thereby improving transient performances [247]. A significant factor, with combinations for diverse categories of DGs as well as utilizing electronic-power-converters for interconnecting such units, was analyzed via small-signal dynamic model. Cumulative dynamic-model was obtained as linearized state-space formulations which defines individual components within systems. Thus, optimum performance was analyzed via eigenvalue calculations [248], frequency-domain characteristic for open-loop as well as closed loop was illustrated in [249]. In autonomous modes, [250] illustrated controlling approaches, in parallely linked inverters, within AC systems. Research work in [251], illustrated significance in sliding-mode controls thereby provides effective as well as robust strategy in control for nonlinear-multi-input converter. At times of utility voltage-sag instance, voltage-phasor in point-of-common-coupling (PCC) dips below its nominal-values, whereby load-voltage phasor was being regulated to remain relatively constant at its nominal value as to avoid trippings in sensitive loads, examined in [252]. Research work in [253], illustrated novel models for voltages as well as currents controllers in DG units also analyzed network stabilities within islanded modes. Small-signal modeling was presented which being configured within multiple-DGs [254].

Small signal model in power networks were investigated by researchers in several studies.
Small-signal stabilities denoted the abilities for electrical systems in returning into standard operational conditions after smaller load disturbances [255]. Within islanded MG operations, DGs maintains system voltages as well as frequencies whereby distributing actives as well as reactive-power within themselves. Complete small-signal models were linearised as well as utilized for defining system state matrix. Small-signal dynamic-models for MG categorized in 3 individual parts: Inverter, networks, also loads.
Models for individual inverters include dynamics for power-controllers; current controllers as well as LC filters. Such dynamic's illustrated based upon measured current and voltage converted to reference $D - Q$ frames [256].

State space model of three phase VSI systems was the focus of study in many research works. Controlled VSI systems categorized to two major categories. Firstly power-circuit incorporating inverters as well as output LC-filters. Secondly, control-circuit including power-controllers, current-controllers as well as power calculating loops which provides locally feedback-signals. Inverter possess high switchings frequencies; switching actions do not impacts states while better attenuations for switching frequencies ripples achieved via output LC filter [257]. Systems voltages controlled via Proportional-Integral (PI)/ Proportional-Integral Derivative (PID) controllers by PSO method [258], [259]. Objectives for the current controller being ensuring accurately trackings; also remove transients for inverter's output currents. Two PI regulators utilized in eliminating current's errors [256]. Another central controller performs MG operations whereby provides set-points into local controllers of the inverters utilized to integrate renewable power resources [260]. Control of microgrids also investigated in [261]-[264].

- Illustration of Test Systems considered in present research

Test System 1, consists of proposed problem formulation which aims in optimizing operational prices as well as pollutant-emission within utility-linked MG. A detailed study of literatures related to MGs is conducted. Novel contributions are discussed in the following:

- Presenting framework for implementation of demand response programs (DRPs) which concurrently decreased load-demands in peak-hours whereas increased in off-peak periods, also deals with unpredictabilities occurring due to power-productions via wind turbines (WTs) as well as photovoltaic (PV) panels.
- Simulations also evaluation of the objective function (O.F.) aimed at economical as well as environmental optimizations while satisfying different technical & operation constraints within MG system.
- Utilizing a unique meta-dynamic-approach-based multiobjective flower pollination algorithm with adaptive switch probability (MMOFPA) for generating schedule whereby Pareto criterion is used.

Test system-2 here consists of approach where firstly, each microgrid perform EM for scheduling the units like DGs, energy storage systems as well as load-demands that participates within DRPs. MGs operators inform SDN operator related to scheduling. After that Smart Distribution Network Operators (SDNOs) make priority-list (PL) in determining units having capacities for selling powers to SDN's. While developing PL, units with lower average power generating price, positioned on top in the list. Operational price for renewable based DGs are low in comparison to schedulable entities viz., diesel generators, priority list encourage usage of renewable sources. In final stage, SDNOs solve global-EM. Emission's constraint is formulated within EMS. Meta-heuristic method viz., multi objective modified personal best particle swarm optimization algorithm utilized for modeling uncertainties within output power for renewable based-DGs. Major contributions in Test System 2 are:

- Investigations of impacts for active-power losses upon EMS for MMG-SDN.
- Illustrating meta-heuristic multi-layered energy management system (MEMS).
- Propose persuasive approaches of inducing investors for cleaner power productions.
- Consider emission's constraint for limiting greenhouse gas emission.
- Implementing DRPs within EMS for MMG systems.

Test System 3 investigates significance in congestion problem-formulation for EMS of MMG based SDN wherein effect of power flow limits on operating prices of MMG based SDN are illustrated. But, inclusion of security-constraints within optimization problem-formulation causes increase in operational cost of the system. Here, individual MGs exchanges power with SDN incorporating power flow limitations. Next, to solve congestion problem, tie-lines between MGs are modelled and all MGs regarded as integrated unit whereby control is done by Microgrid central controller (MGC). Output results show that MGs functioning as single unit is economical. Here, the novelty is briefly stated:

- To model power-flows constrained EMS in MMG -DN.
- Investigate influence for congestion problem upon functioning in MGs and DN.
- Proposing meta-heuristic technique like improved flower pollination algorithm (IFPA) applied in MEMS.
- Compare MG operation functioning as per independent entities vs. functioning as per integrated system connected by tie-lines.
- Analyze influence in incorporating tie-lines for benefit of DN and MGs.

1.3. Objectives of Present Work

- To propose economic generation scheduling strategy in microgrids based on different optimization algorithms.

The primary objective is to obtain economic generation scheduling within microgrids. Power output from different units of microgrid system for 24 hours time horizon is presented in Test Systems 1, 2 and 3. Implementations of different recently developed nature inspired meta-heuristic algorithms are performed for obtaining this scheduling. This optimization should satisfy different constraints viz., achieving power balances as well as operation constraint in individual power supplying resources. Various cases of microgrid configuration are considered and data collected from various microgrid test systems are presented.

- To perform detailed analysis on effects of adding security constraints within the electrical network for maintaining power flow standards.

Diverse modifications are carried out in the optimization process for implementing security constrained energy management in Test System 3 which will maintain and control power flow standards in microgrid based distribution network.

- The focus in this study is to represent formulation which will maximize profits from microgrids.

Main objective function in microgrid consists of various components such as minimizing operating costs of distributed generation units and storage devices as well as minimizing emissions in Test System 1; such formulations maximize profits from microgrids. In Test System 2, cost and loss/benefit analysis is presented which maximizes profit from microgrid consisting of higher renewable energy resources. In Test System 3, inclusion of tie lines and incorporation of microgrid central controller helps reduce operating costs and maximize profits from microgrids.

- To devise unique operating strategies within MGs incorporating renewables and dealing with environmental uncertainties via demand response program (DRP).

The proposed work takes into account intermittent nature of wind and solar resources and offers improved model for achieving optimal demand response program. Multi-objective optimization viz. operation costs optimization and effusion minimizations are performed in cases excluding DR participations as well as including DRP. Also, forecasted level of power, power without demand response as well as output power with demand response of renewable energy resources is presented to verify generation levels of power with that of demand levels.

1.4. Contribution Area

- Improvement of meta-heuristic algorithms to solve optimization problem for finding best combination of optimal parameters of microgrid system.

This research aims to utilize recently developed state of the art optimization algorithms and their further improvement for finding generation scheduling model, smart energy management in microgrids presented in Test Systems 1, 2 and 3. Input parameters of meta-heuristic algorithms are chosen precisely to achieve optimal energy management in above cases.

- The multi-objective formulation is carried out in order to optimize both operating costs of microgrid as well as minimize emissions of harmful gases.

This work solves proposed multi-objective's optimization problems as well as Pareto sets of non-dominated-solutions are obtained in results. Implementation of proposed methodology under different operational scenarios highlights efficiency of applied scheme in Test System 1. Multi objective formulations are also carried out in Test system 2 wherein the study points out efficiency of proposed method.

- Considering microgrid central controller and tie lines within multi-microgrid based smart distribution network.

Multi-microgrid consists of several MGs which comprises of distributed generators (DGs), including renewable energy resources such as wind turbines, PV arrays as well as caters to loads. The impact of congestion as well as considering security constraints in multi-microgrid based smart distribution network increases operational costs. Incorporating tie-lines within microgrids enables them to act as an aggregated unit whereby the objective of cost minimization is obtained. Microgrid central controller and tie lines within multi-microgrid based smart distribution network is considered within Test System 3. Microgrid central controller becomes responsible and determines output scheduling of MGs as one aggregated unit. Energy management system reduces operating prices by enhancing generation during higher price hours & increase power purchasing during low prices. The aggregated MG unit and deployment of tie lines reduce shortages in power as well as enhanced excess power quantity.

- Expert energy management in microgrids while maintaining economic and environmental considerations.

Recent researches have put utmost importance for providing cost-efficient and reliable energy in 21st century society. High demands in electricity of diverse customers such as residential, industrial and commercial loads have intensified. In response to this demand, novel improvements in microgrid technology is established in this research and by virtue of efficient operation through inclusion of these new techniques, energy management in microgrids is carried out at same time maintaining economic, environmental and technical factors presented in Test Systems 1, 2 and 3.

1.5. Motivation behind Present Work

The main motivation for research in sector of microgrids arises from inherent necessity of clean energy production. Major motivating factors can be listed as follows:

1) Environmental considerations: Utilizing fossil fuels results green house gaseous effusions which contribute to global warming. Microgrids utilize renewables which use sun's radiation as well as power from WT to produce electricity. Hence they are more beneficial to environment.

2) Limited resources: Natural reserve of fossil fuels on Earth is limited and these will become harder to find in coming years. Renewable energy resources in this context can play vital role as there is unlimited supply of solar and wind energy.

3) Economy: Home owners and businesses can deliver great deal of energy themselves, so payments towards conventional utility reduce considerably.

Another distinct economic advantage is that fewer infrastructures need to be built compared to conventional utility, such that mostly energy is generated and delivered onsite. This means that costs are reduced.

4) Less reliance on fluctuating gas and oil prices: Due to on site power generation capability of microgrids, there is less dependency on gas and oil which add to economic benefits. This in turn means that people have more disposable income which leads to positive effect on economy.

5) Health factors: Effect of burning less quantities of fossil fuel is that emissions are reduced considerably and society will enjoy fresh water and clean air. As result of clean water and air, those patients with gastro-enteric problems or with respiratory problems will find health improvements and there will be fewer admissions to hospitals. So costs associated with healthcare will be reduced considerably.

6) Job market: New renewable source installation and microgrid infrastructure maintenance will require more manpower and hence create more job markets.

1.6. Overview of thesis

Chapter 1 illustrate introduction, Chapter 2 describes microgrids, Chapter 3 represents mathematical problem formulations, Chapter 4 presents meta-heuristic techniques, Chapter 5 presents results and discussions, and Chapter 6 presents conclusion and scope for future work, followed by appendix and references.

Next chapter illustrates microgrid components viz., solar PV, micro turbines, fuel cells, wind turbines, energy storage devices and elaborates concept of multi microgrids.

Chapter2. MICROGRID

Overview

Microgrid Components

Solar Photovoltaic

Micro-turbines

Fuel Cells

Wind Turbines

Energy-storage- devices

Multi-Microgrid

CHAPTER - 2

MICROGRID

2.1 Overview

Distributed generation refers to different types of technologies usually at sites where it will be used. Distributed generation may be in form of isolated structure such as in residential building or in business house. It may also be part of microgrid. Distributed generation can support delivery of clean, reliable power to customers and reduce power losses along transmission and distribution lines.

The location specified power resources being utilized for generating electricity constitutes microgrid that presents clusters in generators providing customers in particular area. Thus while power being produced as well as supplied by small-scale technology nearer to customers; also known by Decentralized Generation. Decentralized generation being smaller as well as provide immense advantages compared with traditional central system, which are listed below:

1) Absence of high-peak load’s shortage- Distributed generation system will decrease peak demands as well as provide efficient solutions for problems in high-peak load shortage.

2) Reduction in higher transmissions as well as distributions loss- Significantly reduces loss from distribution and transmissions in powers from central position.

3) Linking remote as well as unreachable regions- Distributed generation plays significant part and provides power to isolated as well as unreachable regions.

4) Fast responses into fresh energy demand- Microgrid (MG) networks’ being of smaller scale, also requirement of gestating period is low, hence enabling fast as well as easier capacities inclusions.

5) Improvement in reliabilities- Distributed generation system present effortless maintenance in power, voltages as well as frequencies. This provides another major advantage and immense possibilities for combination of energy storages as well as management’s system alongwith decreased congestions. Important essential feature of microgrid lies in the capability for separating as well as isolating from main grid or conventional power provider during disturbance in main grid without disrupting load-demands within microgrid.

MG spontaneously resynchronizes whenever mains return into usual operations. Then microgrid can again reconnect to main grid. Smart microgrids can provide clean, reliable, affordable electrical power. Microgrid provides benefit utilizing various types of renewable resources concurrently enhancing reliabilities, securities in power framework.

2.2 Microgrid Components

In residential sector, common types of distributed generation systems are:
1) Solar photovoltaic panels
2) Wind turbines
3) Fuel cells
4) Emergency backup generators usually powered by gasoline or diesel fuel
In commercial and industrial sector, common types of distributed generation systems are:
1) Combined-heat-power systems
2) Solar and wind generation
3) Hydropower
4) Biomass combustion
5) Fuel cells

2.2.1 Solar-PV

Solar cells are termed solar photovoltaic (PV) cells, converting sun's radiation to electric power. Traditionally PV normally comprises of silicon. They generally, are being flat-plate type, usually effective. Nowadays, thin-film PV cells utilize layered semi conductor material. Concentrated PV energy paybacks are approximately 8 months on sites possessing satisfactory PV resources and utilize commonly available constructing material like steel; plastic etc. PV systems are considered to be highly reliable also often chosen as they offer the lower life-cycle costs, especially in applications requiring lesser than 10KW [265].

2.2.2 Micro turbines

Micro-turbine (MT) being comparatively novel distributed generation's technique. MT yields heat as well as electricity in smaller size. Micro-turbines can be categorized via physical arrangement in components: one or dual shafts, simple cycle or recuperated, intercooled, re-heat etc [266].

- Unrecuperated (simple-cycle) MT- Within the MT, compress air being blended alongwith fuels, again burnt in uniform pressures; also have low investment cost, as well as highly reliable.
- Recuperated micro turbines- Recuperated MT utilize heat-exchanger which partly recovers heat from exhaust stream, transferring the same into incoming air, enhancing temperature of air supplied into combustor. Recuperated micro turbines can produce 30-40% fuel savings from pre heating.

2.2.3 Fuel Cells

Fuel Cell produces electrical power via chemical reactions. Each fuel-cell possesses dual electrodes namely anode and cathode. Reaction which produces electrical power occurs in electrode. Each fuel cell possesses electrolytes that carry electrical charged-particles from one electrode to another. Practically, numerous fuel cells being generally congregated in stacks.
Alkali Fuel Cell operates upon compressed hydrogen and oxygen, also utilize potassium hydroxide (chemically, KOH) in water as electrolytes. Efficiency is approximately 70%.

Molten Carbonate Fuel Cell (MCFC) utilizes higher temperature's salt's components (such as sodium or magnesium) carbonate (CO_3) in form of electrolytes. Efficiencies are around 60 to 80%, as well as working temperatures approximately, 650˚C.
Phosphoric Acid fuel cells (PAFC) utilize phosphoric acids in form of electrolytes. This type of cell has efficiency around 37%, but in hybrid systems the value achieved can be 87%, as well as working temperatures ranges within 160-220℃ [267]. Electrodes comprising carbon-paper coated with finely dispersed platinum catalyst.
Proton Exchange Membranes (PEM) Fuel Cell works alongwith polymer electrolytes as thinned, porous sheets. Efficiencies are 40-50%, as well as working temperatures 80˚C.
Solid Oxide fuel cells (SOFC) utilize harder, ceramic compounds of metals (like calcium or zirconium) oxide as electrolytes. Efficiencies are 60%, as well as working temperature around 1,000℃.
Direct Methanol fuel cells (DMFC) are similar with PEM cells in that they both utilize polymer membranes in electrolyte. Moreover, within DMFC, anode-catalysts drawing hydrogen from liquid methanol, eliminates necessity in fuel-reformer. Efficiency around 40% achieved in DMFC [268].

2.2.4 Wind turbines (WT)

WT technological development occurred rapidly recently with modern turbine's model possessing large rotor diameter and WT frame. Large WTs decreases costs of wind energy via capturing more power using lower installations in comparison to a group of smaller wind turbines. Generating electricity from winds comprises of number of steps, air pass on blade creating turning forces, and rotational blade turns shafts within nacelle, linked to gearbox. Gearbox enhances rotational speeds of generators that use magnetic fields and convert rotating energies to electricity. Amidst several types of WTs, commonly utilized are horizontal axis WTs [269].

2.2.5 Energy storage devices

Maintaining energy balances as well as stable systems possesses challenges within microgrid. Energy storage system (ESS) units are placed adjacent individual DGs also linked via each power electronic interface. ESS are flexible and dispatchable, such that they can respond to system changes quickly for helping the grid operator keep-up the system in balance. Within several scenarios during functioning, voltage-ranges are prespecified based upon storage-technologies. Voltage ranges for Li-ion batteries are generally within 2.5V upto 4.2V [270]. When MG connects with utility, as well as comprises of renewables, ESS becomes essential in ensuring that no power produced is wasted. An instance, when PV panels are linked with utility without ESS, surplus energy generated cannot be utilized in local areas. When microgrid operates in island mode, in cases where outage shuts main grid, MG has capability for load support uninterruptedly.

2.3 Multi Microgrid

A multi microgrid consists of several microgrids connected to the distribution network (DN). Multi-layered energy managements (MEMS) in multi-microgrid (MMG) smart distribution networks (SDNs) are generally carried out. Here, each MG executes energy management (EM) by scheduling units and determines shortage and surplus power. After that obtained data are sent to SDN's operators (SDNOs), and then global EM is executed for achieving minimum operational costs. Figure 2.1 illustrates MMG system structure.

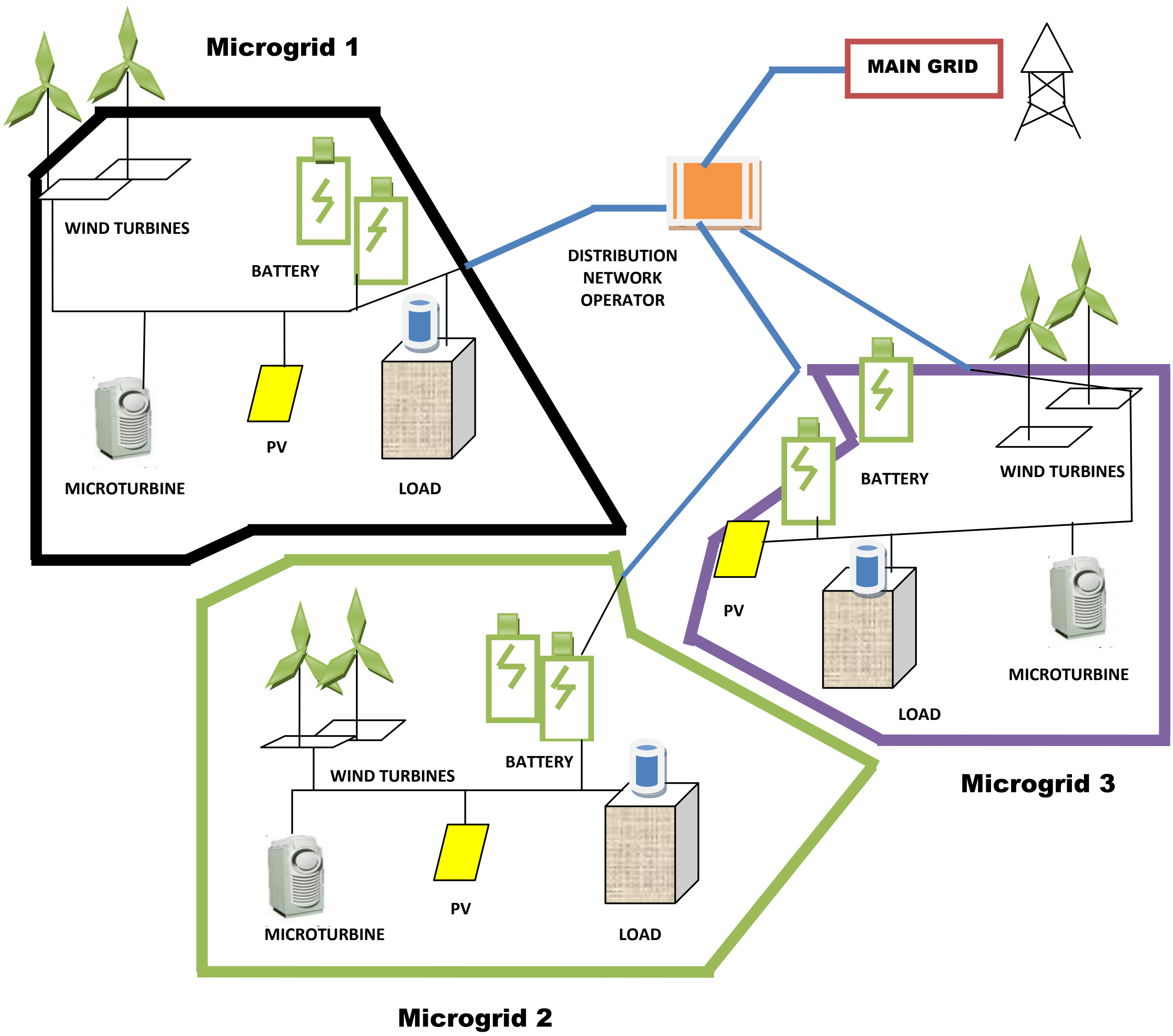


Figure. 2.1. MMG system structure illustration

Next chapter illustrates mathematical problem formulation of three test systems.

Chapter3 MATHEMATICAL PROBLEM FORMULATION

Introduction

Test System 1: Grid connected microgrid system including renewable energy resources

Fitness Function and constraints of cost optimization
Fitness Function and constraints of emission optimization
Constraint handling technique

Test System 2: Modified IEEE 33 bus system

Fitness Function and constraints for MG optimization
Fitness Function and constraints for DN optimization
Constraint handling technique

Test System 3: Energy Management System of Multi-Microgrid based Smart Distribution network considering power flow constraints

Fitness Function and constraints for MG optimization (without security constraints)
Fitness Function and constraints for DN optimization (with security constraints)
Fitness Function considering tie-lines
Constraint handling technique

CHAPTER-3

MATHEMATICAL PROBLEM FORMULATION

3. Mathematical Problem Formulation

3.1. Introduction

Mathematical problem formulations of energy management in microgrids (MGs) are carried out for several test systems where fitness functions and constraints for different cases are discussed.

In this section, detailed studies on cost and emission optimization is carried out for test system 1, cost and loss/benefit optimization is carried out for test system 2, security constrained energy management system is carried out for test system 3.

3.2. Test System 1: Grid connected microgrid system including renewable energy resources

In Test System 1, shown in Figure 3.1, the microgrid network possesses resources like photovoltaic (PV) array, wind turbine (WT), micro turbines (MT), fuel cells (FC) and battery where incentive based demand response programs (DRPs) are included covering uncertainty linked with renewable energy resources (RES). Here, scheduling period is considered as 24 hour time.

I. The objectives of research work done in Test System 1 are as follows:

1) Firstly, perform single objective optimization for cost minimization utilizing meta-dynamic approach based Time Varying Acceleration Coefficient Particle Swarm Optimization (TVACPSO), meta-dynamic approach based Non linear Decreasing Inertia Weight Particle Swarm Optimization (NDIWPSO), meta-dynamic approach based Exponential Decreasing Inertia Weight Particle Swarm Optimization (EDWPSO), meta-dynamic approach based Dynamic Inertia Weight Particle Swarm Optimization (DIWPSO), meta-dynamic approach based Flower Pollination Algorithm with adaptive switch probability.

2) Secondly, perform single objective optimization for emission minimization utilizing all above algorithms.

3) Consideration of demand response (DR) programs included for above formulations.

4) Then, perform multi objective optimization for cost and emission minimization utilizing meta-dynamic approach based multi objective Flower Pollination Algorithm (MMOFPA) with adaptive switch probability is carried out whereby obtaining a compromise solution.

5) Consideration of demand response programs included for above formulation.

II. System components in Test System 1 are as follows:

Microgrid network possesses resources like photovoltaic (PV) array, wind turbine (WT), micro turbines (MT), fuel cells (FC), battery as well as responsive loads as shown in Figure 3.1.

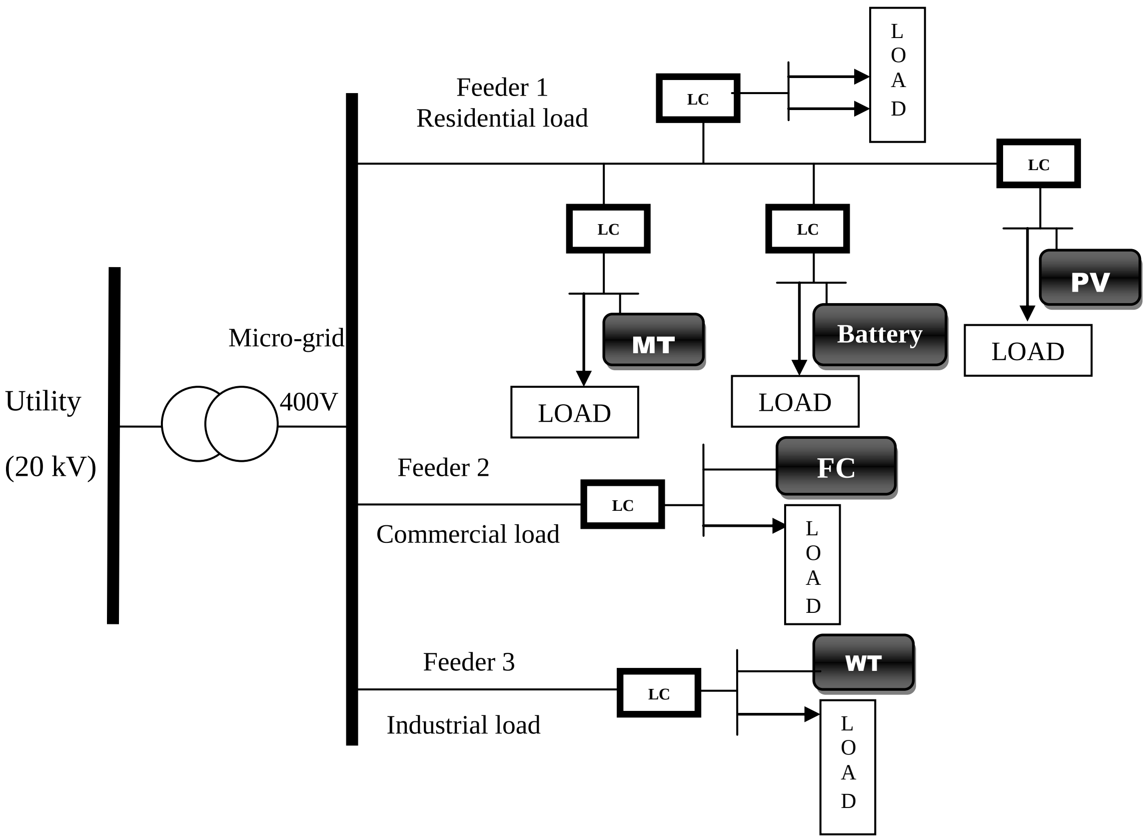


Figure 3.1. Microgrid considered in test system 1

3.2.1 Fitness Function and constraints of cost optimization

Subsequent sections present fitness function and constraints of cost optimization.

A. Specifications of Demand Response Contributors

Various categories of electricity customers specifying varying utilizing patterns is evaluated within the research. Here, customers include household, trade-commerce, and manufacturing/industry loads. The utilization behaviors of these three types of loads can be mathematically expressed as follows [271]:

$$RP(r,t) = RC(r,t) \times \pi_{r,t};\ RC(r,t) \le RC_t^{\max} \tag{3.1}$$

$$CP(c,t) = CC(c,t) \times \pi_{c,t};\ CC(c,t) \le CC_t^{\max} \tag{3.2}$$

$$IP(i,t) = IC(i,t) \times \pi_{i,t};\ IC(i,t) \le IC_t^{\max} \tag{3.3}$$

r , c and i represent the number of three types of customers; $RP(r,t)$ represents the indicator in prices owing to load reduction applied to household customers; $CP(c,t)$ represents cost owing to load reduction in trade-commerce customers. Similarly $IP(i,t)$ represents prices due to load reduction in the manufacturing sector, $RC_t^{\max}$, $CC_t^{\max}$ and $IC_t^{\max}$ represent the highest load curtailment in time t. $RC(r,t)$, $CC(c,t)$ and $IC(i,t)$ represents quantity of load reduction within consumers, $\pi_{r,t}$, $\pi_{c,t}$ and $\pi_{i,t}$ denotes incentives payments to each consumer, respectively.

B. Operating cost function

Objective function possesses component like cost of individual generation unit, starting as well as shutdown cost in generations, storage prices, cost of power exchanges amidst utility as well as cost in DRP and presented in following [271].

$$\min\ f_1(x) = \sum_{t=1}^{T} \left(\mathrm{cost}_{DG}(t) + ST_{DG}(t) + \mathrm{cost}_s(t) + \mathrm{cost}_{Grid}(t) + \mathrm{cost}_{DR}(t) \right) \tag{3.4}$$

$f_1(x)$ is the objective function to be optimized.

$$\mathrm{cost}_{DG}(t) = \sum_{i=1}^{Ng} u_i(t) P_{DGi}(t) B_{DGi}(t) \tag{3.5}$$

$$ST_{DG}(t) = \sum_{i=1}^{Ng} S_{DGi} \left| u_i(t) - u_i(t-1) \right| \tag{3.6}$$

$$\mathrm{cost}_s(t) = \sum_{j=1}^{Ns} \left[u_j(t) P_{sj}(t) B_{sj}(t) + S_{sj}(t) \left| u_j(t) - u_j(t-1) \right| \right] \tag{3.7}$$

$$\cos t_{Grid}(t)=u_{Buy}(t)P_{Grid-Buy}(t)B_{Grid-Buy}(t)-u_{sell}(t)P_{Grid-sell}(t)B_{Grid-sell}(t) \quad (3.8)$$

$P_{DGi}(t)$ as well as $P_{sj}(t)$ represent active power outputs for i^{th} generator; j^{th} storages within time t. $B_{DGi}(t)$, as well as $B_{sj}(t)$ represent bid for DG's as well as storages within t, T denotes the scheduling period. $ST_{DG}(t)$ presents start-up/ shut-down costs for all generating units. $S_{DGi}(t)$ as well as $S_{sj}(t)$ present start-up and shut-down prices of i^{th} DG's as well as j^{th} storages respectively. $P_{Grid-buy}(t)$ as well as $P_{Grid-sell}(t)$ is real power's purchased as well as sold-out at utility's within time t, $B_{Grid-Buy}(t)$ as well as $B_{Grid-sell}(t)$ denote bids purchased or sold-out at utility's within time t respectively. u, represents state vectors that indicate ON/OFF state within units in time t [271].

$$\cos t_{DR}(t)=P_{DR}(t)B_{DR}(t) \quad (3.9)$$

$$P_{DR}(t)=\sum_{r}RC(r,t)+\sum_{c}CC(c,t)+\sum_{i}IC(i,t) \quad (3.10)$$

$P_{DR}(t)$ as well as $B_{DR}(t)$ denotes real power as well as bid prices for participation at DRPs within time t.

$$\begin{aligned}
&X=[P_g,U_g]\\
&P_g=[P_{DG1},P_{DG2},......,P_{DGN_{DG}},P_{s1},P_{s2},.......,P_{sNs},P_{Grid},P_{DR}]\\
&U_g=[U_{DG1},U_{DG2},.....,U_{DGN_{DG}},U_{s1},U_{s2},...,U_{sNs},U_{Grid},U_{DR}]\\
&n=N_{DG}+N_s+2
\end{aligned} \quad (3.11)$$

X presents decisions vectors which comprises of unit's output power, quantity in energy exchanged at utility's, loads reductions quantity with DRPs also ON/OFF for visions of day's ahead's given in above equation, wherein n presents numbers for decision's variables, N_{DG} as well as N_s present total numbers for generations as well as storages, P_g presents real power's vectors incorporating DG's as well as storages, grid powers as well as real power participating in DRPs, U_g is state's vectors specifying ON/OFF within time t.

- **Constraints**

Constraints of the fitness function are described in following equations:

C. Load Balance

$$\sum_{i=1}^{Ng}P_{DGi}(t)+\sum_{j=1}^{Ns}P_{sj}(t)+u_{Buy}(t)P_{Grid-Buy}(t)=\sum_{L=1}^{N_L}P_{DemandL}(t)+u_{Sell}(t)P_{Grid-sell}(t)-P_{DR}(t) \quad (3.12)$$

where $P_{DemandL}$ represents quantity in L^{th} demands also N_L presents cumulative numbers for demand's level.

D. Real Power Generation Limit

Real power output from individual DG, storage units also grid should be within lower as well as upper limits.

$$\begin{aligned} & P_{DGi,\min}(t) \le P_{DGi}(t) \le P_{DGi,\max}(t) \\ & P_{sj,\min}(t) \le P_{sj}(t) \le P_{sj,\max}(t) \\ & P_{Grid,\min}(t) \le P_{Grid}(t) \le P_{Grid,\max}(t) \end{aligned} \tag{3.13}$$

wherein $P_{DGi,\min}(t)$, $P_{sj,\min}(t)$ as well as $P_{Grid,\min}(t)$ denote minimum real power for i^{th} DGs, j^{th} storages as well as utility in time t. $P_{DGi,\max}(t), P_{sj,\max}(t)$ as well as $P_{Grid,\max}(t)$ present maximum real power of unit's at time t.

A. Battery Limit

$$\begin{aligned} & \psi_j(t) = \psi_j(t-1) - \frac{1}{\lambda_{Dj}} u_{Dj}(t) P_{Dsj}(t) + \lambda_{cj}(t) u_{cj}(t) P_{csj}(t) \\ & u_{Dj}(t) + u_{cj}(t) \le 1 \\ & \psi_{\min} \le \psi_j(t) \le \psi_{\max} \\ & \psi_j(t) = \psi_e \end{aligned} \tag{3.14}$$

Initial expression denotes battery's-capacity that varies in hourly manner depends upon charge/discharge levels; whereas subsequent formulations present batteries to charge or discharge every hour and simultaneously charging/discharging not applicable. $\psi_j(t)$ as well as $\psi_j(t-1)$ denote reserve energies in present as well as preceding times. $P_{Dsj}(t)$ as well as $P_{csj}(t)$ represent permitted rate for discharging as well as charging within interval t. λ_{Dj} as well as λ_{cj} present battery efficiencies during discharging as well as charging.

3.2.2 Fitness Function and constraints of emission optimization

Subsequent sections present fitness function and constraints of emission optimization.

Pollution emission function comprises for emission from generating units, power reserve sources, as well as emissions resulting at utility during purchases from grids. The pollutants are Carbon dioxide (CO_2), Sulfur dioxide (SO_2), Nitrogen dioxide (NO_x). Mathematically pollutant function is expressed by the following equation [271]:

$$\min f_2(x) = \sum_{t=1}^{T} Emission\ (t)$$

$$= \sum_{t=1}^{T} \left\{ \sum_{i=1}^{N_g} [u_i(t) P_{DGi}(t) E_{DGi}(t)] + \sum_{j=1}^{N_S} [u_j(t) P_{sj}(t) E_{sj}(t)] + P_{Grid}(t) E_{Grid}(t) \right\} \tag{3.15}$$

where, $E_{DGi}(t)$, $E_{sj}(t)$ and $E_{Grid}(t)$ are amount of pollutants emission for each generator, storage device, utility in period t, respectively [271].

- **Constraints**

Constraints are described in following equations:

A. Load Balance

$$\sum_{i=1}^{Ng} P_{DGi}(t) + \sum_{j=1}^{Ns} P_{sj}(t) + u_{Buy}(t) P_{Grid-Buy}(t) = \sum_{L=1}^{N_L} P_{DemandL}(t) + u_{Sell}(t) P_{Grid-sell}(t) - P_{DR}(t) \tag{3.16}$$

where $P_{DemandL}$ represents quantity in L^{th} demands also N_L presents cumulative numbers for demand's level.

B. Real Power Generation Limit

Real powers output from individual DG, storage units also grid should be within lower as well as upper limits.

$$\begin{aligned} &P_{DGi,\min}(t) \le P_{DGi}(t) \le P_{DGi,\max}(t) \\ &P_{sj,\min}(t) \le P_{sj}(t) \le P_{sj,\max}(t) \\ &P_{Grid,\min}(t) \le P_{Grid}(t) \le P_{Grid,\max}(t) \end{aligned} \tag{3.17}$$

wherein $P_{DGi,\min}(t)$, $P_{sj,\min}(t)$ as well as $P_{Grid,\min}(t)$ denote minimum real power for i^{th} DGs, j^{th} storages as well as utility in time t. $P_{DGi,\max}(t)$, $P_{sj,\max}(t)$ as well as $P_{Grid,\max}(t)$ present maximum real power of unit's at time t.

C. Battery Limit

$$\psi_j(t) = \psi_j(t-1) - \frac{1}{\lambda_{Dj}} u_{Dj}(t) P_{Dsj}(t) + \lambda_{cj}(t) u_{cj}(t) P_{csj}(t) \tag{3.18}$$

$$u_{Dj}(t) + u_{cj}(t) \le 1 \tag{3.19}$$

$$\psi_{\min} \le \psi_j(t) \le \psi_{\max}$$

$$\psi_j(t) = \psi_e$$

Initial expression denotes battery's-capacity that varies in hourly manner depends upon charge/discharge levels; whereas subsequent formulations present batteries to charge or discharge in every hour and simultaneously charging/discharging not applicable. $\psi_j(t)$ as well as $\psi_j(t-1)$ denote reserve energies in present as well as preceding times. $P_{Dsj}(t)$ as well as $P_{csj}(t)$ represent permitted rate for discharging as well as charging within interval t. λ_{Dj} as well as λ_{cj} present battery efficiencies during discharging as well as charging.

3.2.3 Constraint handling technique

In his research, Coello discussed theoretical and numerical constraint-handling techniques using evolutionary algorithms [272]. Constraint handling comprise of various methods classified into different groups: methods based upon solution feasibility, penalty function method, and methods that utilize clear-cut distinctions within feasible and infeasible optimal points, and hybrid approaches [273].
In this study, the inequality constraints are included in the objective function (J) as penalty terms and transformed into an augmented objective function (J_{aug}), as in equation (3.20), where $\lambda_p, \lambda_{ps}, \lambda_u, \lambda_{us}$ are penalty factors.

$$J_{aug} = J + \lambda_p (P_{DGi} - P_{DGi}^{\lim})^2 + \lambda_{ps} (P_{sj} - P_{sj}^{\lim})^2 + \lambda_u (U_{DGi} - U_{DGi}^{\lim})^2 + \lambda_{us} (U_{sj} - U_{sj}^{\lim})^2 \quad (3.20)$$

where $P_{DGi}^{\lim}$ presents power generation limits for DG units, $P_{sj}^{\lim}$ presents power generation limits for storage units, $U_{DGi}^{\lim}$ presents ON/OFF status for DG units, $U_{sj}^{\lim}$ presents ON/OFF status for storage units.

3.2.3.1. Multiobjective energy management in microgrid system for cost and emission minimization using MMOFPA with adaptive switch probability

A. 24-hours energy scheduling with optimal operational cost and emission (with DR) are provided as follows:
Firstly perform single objective optimization for cost minimization utilizing meta-dynamic approach based Flower Pollination Algorithm with adaptive switch probability where 24 hours scheduling provided in Table 5.18. Fitness function for cost minimization is provided in equation (3.4).

Secondly perform single objective optimization for emission minimization utilizing meta-dynamic approach based Flower Pollination Algorithm with adaptive switch probability where 24 hours scheduling provided in Table 5.21. Fitness function for emission minimization is provided in equation (3.15).

Thirdly, multi objective optimization for cost and emission minimization utilizing meta-dynamic approach based multi objective Flower Pollination Algorithm (MMOFPA) with adaptive switch probability carried out whereby obtaining a compromise solution provided in Table 5.24. When considering DR, in multiobjective optimization here, fitness function formulation obtained from equation (3.4) and equation (3.15).

3.2.3.2. Multiobjective optimization and dominated, non-dominated solutions are explained as follows:

Multi objective optimization (MOO) problems [75], [271] comprise several objectives being resolved concurrently having equalities as well as inequalities constraints that being necessary for optimization.

$$Minimize \quad Y = \left(f_1(X), f_2(X), \ldots\ldots, f_k(X)\right) = F(X) \tag{3.21}$$

$$X \in \Omega$$

$$where \quad \Omega = \left\{X \in R^n : g(X) \le 0, h(X) = 0\right\} \tag{3.22}$$

$$F : R^n \to R^k$$

In MOO, no unique solution exists, but, there lies set of solutions denoted "Pareto optimal set" where $\phi = (\phi_1, \ldots\ldots, \phi_n)$ as well as $\psi = (\psi_1, \ldots\ldots, \psi_n)$ present dual solution's within "Pareto optimal set" whereby corresponding with objective's $F(\phi) = (f_1(\phi), \ldots\ldots, f_k(\phi))$ as well as $F(\psi) = (f_1(\psi), \ldots\ldots, f_k(\psi))$, solves ϕ dominate solve ψ illustrated as:

$$\phi < \psi \tag{3.23}$$

$$F(\phi) < F(\psi) \tag{3.24}$$

whenever subsequent criteria are satisfied. Solution ϕ is non dominated solution.

$$\forall i \in \{1, \ldots\ldots, k\} : f_i(\phi) \le f_i(\psi) \tag{3.25}$$

$$\exists i \in \{1, \ldots\ldots, k\} : f_i(\phi) < f_i(\psi) \tag{3.26}$$

Within MOO, objectives' possess contradictory characteristics whereas improvement in one deteriorates another. So, set of solutions are obtained and solution sets are non-dominating termed Pareto set. Non-dominated refers that method where one solve is never inferior to another as well as improvements in particular objective not achieved without deteriorating another.

$$F = (F_1, F_2) \tag{3.27}$$

$$F_{obj} = \min F \tag{3.28}$$

Objective function (O.F.) denoted as vectors for dual objectives whereby aiming in finding schedule which satisfy constraints' as well as minimize vector function F .

In Figure 3.2(a), circled-points denote "Pareto optimal set," bigger circle are non-dominated solves; connecting line of those points denote Pareto front. Set of Pareto front i.e., P can be expressed as in following equations.

$$P(Y) = \{Y_1 \in \theta : \{Y_2 \in \theta : Y_2 < Y_1, Y_2 \ne Y_1\} = 0\} \tag{3.29}$$

$$\theta = \{Y \in R^k : Y = F(X), X \in \Omega\} \tag{3.30}$$

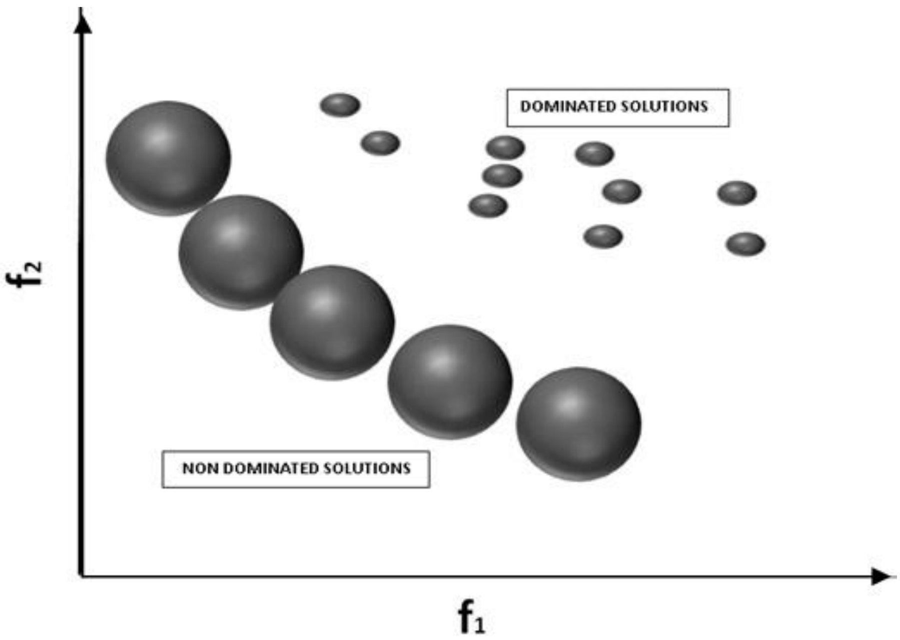


Figure 3.2(a). Pareto optimal set

- **Best compromise solution**

MOO produces Pareto front and any solutions within Pareto front not inferior with respect to other. A method in selecting solution which satisfies individual objectives whereby trade-offs within solves leads in best compromise solution.
Figure 3.2(b) represents fuzzy membership function. Generally, member function should be allotted for every O.F. as follows [75], [271]:

$$\zeta_i^k = \begin{cases} 1, & f_i \le f_i^{\min} \\ \dfrac{f_i^{\max} - f_i}{f_i^{\max} - f_i^{\min}} & f_i^{\min} < f_i < f_i^{\max} \\ 0, & f_i \ge f_i^{\max} \end{cases} \tag{3.31}$$

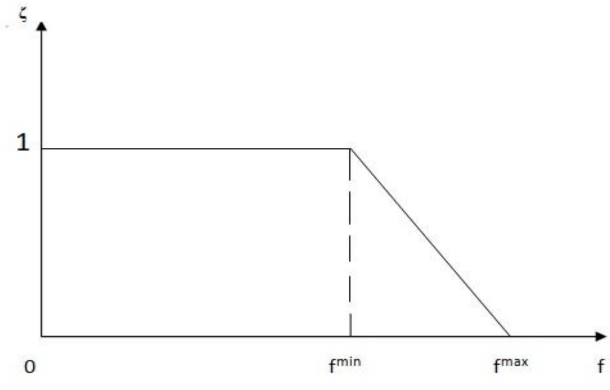


Figure 3.2(b). Fuzzy membership function

Membership function, ζ_i^k indicating optimality for objectives function i among Pareto-optimal solution k wherein $f_i^{\max}$ as well as $f_i^{\min}$ present highest as well as lowest value's for i^{th} objective function amongst total non-dominating solves. ζ_i^k , lies 0 up to 1 whereas $\zeta_i^k = 0$ indicating incompatibilities for solutions with-sets whereas $\zeta_i^k = 1$ indicates fully compatibility. Normalized membership's function's illustrated as follows [271]:

$$\zeta^k = \frac{\sum_{i=1}^{m} \zeta_i^k}{\sum_{k=1}^{n} \sum_{i=1}^{m} \zeta_i^k} \tag{3.32}$$

n presents numbers for non-dominating solution; m presents numbers for objective functions. Highest value for membership's functions presents best compromise solution.

3.3 Test System 2: Modified IEEE 33 bus system

In this research work, presented technique being analyzed upon smart distribution network (SDN) comprising MG, DG, WTs, PV networks, energy storage systems (ESSs), as well as loads, which are illustrated in Figure 3.3(a) and show the complete outline of the multi-microgrid (MMG) system. The ESS consists of Li-Ion batteries as well as inverters.

Concept of Smart Distribution Network aims to efficiently work along advanced techniques whereby accommodating diverse distributed generator (DG) categories as well as related-components; such as DGs with renewable sources, different storage-methods, Demand Response (DR) etc. Smart Distribution Network is illustrated in Section 5.2.1.

The loads are categorized as follows: I) Deferrable and sheddable that takes part in DRPs and II) fixed loads.

Figure 3.3(b) presents the modified IEEE 33 bus distribution network (DN). MGs are presumed to be radially structured [274]. The operating model has T=24 hours horizon where presumed period is 1 hour.

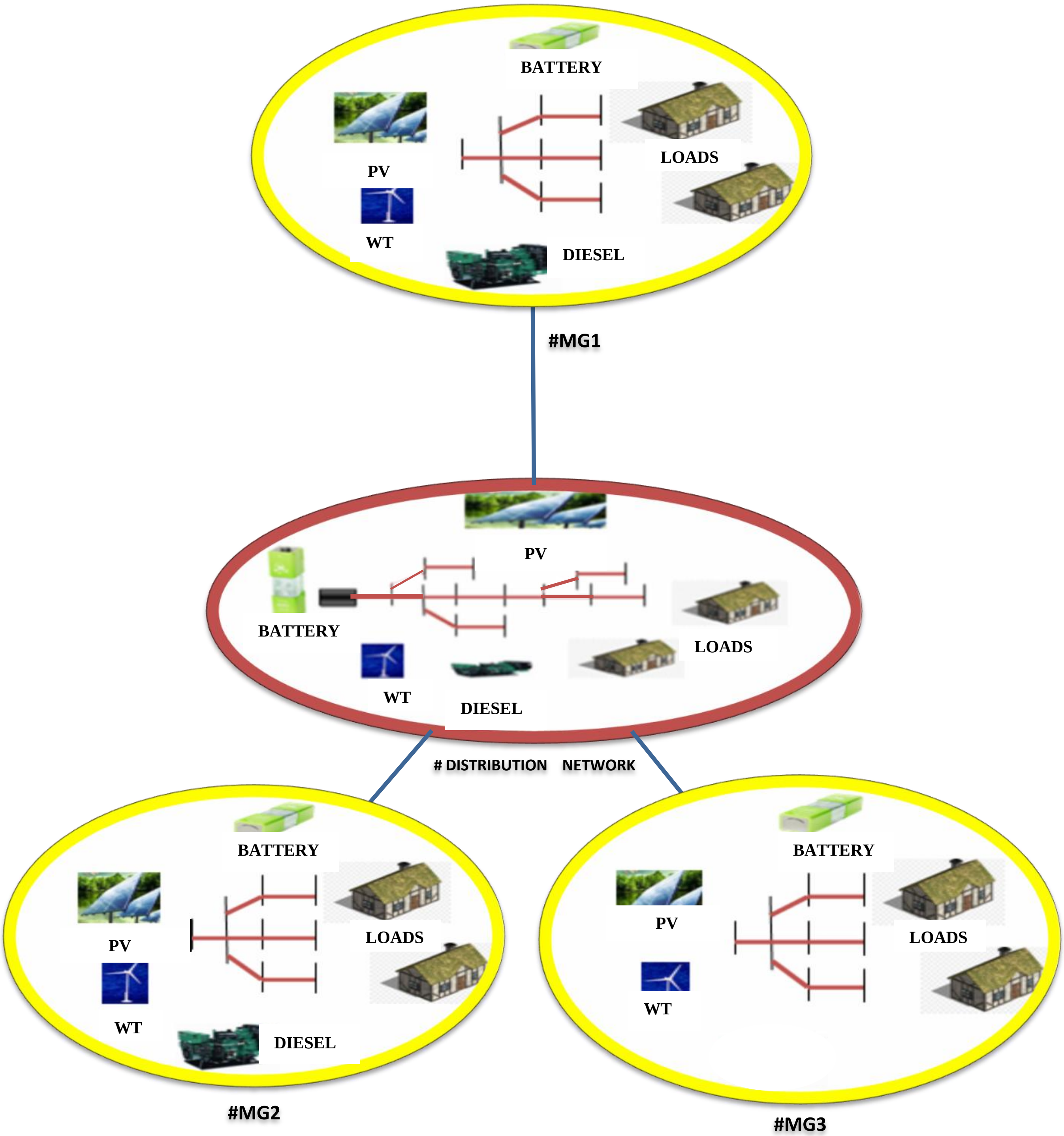


Figure 3.3(a). Illustration of the structure of MMG in Test System 2

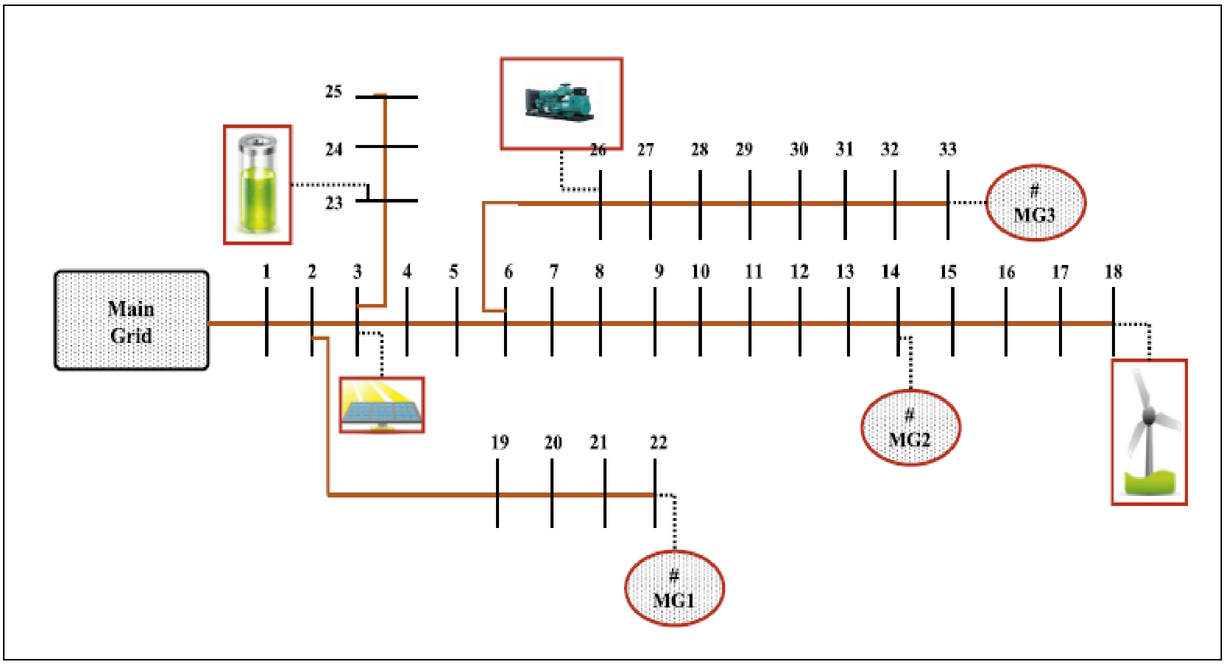


Figure 3.3(b). Altered-IEEE-33-bus-DN

- **System modeling**

This section presents a detailed system model, which is as follows.

- ***System structure***

System structure comprises of dispatchable-units viz., diesel generators, undispatchable entities viz., PV arrays as well as WTs, energy storage systems like batteries and loads viz., fixed-load demands, deferred as well as shed load demands.

- ***Dispatchable units***

Diesel generators are called dispatchable entities that possess controlled power outputs.

The equations (3.33)-(3.35) demonstrate production constraints for diesel generator [275]:

$$0 \le P_{gen}(t) \le U_{gen}(t) P_{gen}^{\max} \qquad U_{gen}(t) \in 0,1 \tag{3.33}$$

$$\left| P_{gen}(t) - P_{gen}(t-1) \right| \le r_{gen} \times P_{gen}^{\max} \tag{3.34}$$

$$P_{gen}^2(t) + Q_{gen}^2(t) \le S_{r,gen}^2 \tag{3.35}$$

Equations (3.33) and (3.34) illustrate generating limits as well as ramp-up rate constraint of specific generators. $P_{gen}(t)$ represents produced active-powers, $U_{gen}(t)$ represent binary-variable denoting on/off condition, $P_{gen}^{\max}$ represent maximum-capacity of generator, whereas r_{gen} represent ramp-up rate for generators. In addition, equation (3.35) represents its complex-power limitations. $Q_{gen}(t)$ and $S_{r,gen}$ represent reactive as well as complex power capacities for generator, respectively.

Price-function for diesel-generators possesses quadratic characteristics described in equation (3.36). Startup cost [275]-[278] is presented in equations (3.37) and (3.38).

$$C_t(P_{gen}) = \alpha_1 P_{gen}^2(t) + \alpha_2 P_{gen}(t) + \alpha_3 \tag{3.36}$$

$$C_{startup} = y(t) \times C^{SU} \tag{3.37}$$

$$y(t) = \max[U_{gen}(t) - U_{gen}(t-1), 0] \tag{3.38}$$

where α_1, α_2, and α_3 represent the price function coefficients of the generator and $y(t)$ represents the variation within states in generation units.

Dispatchable entities usually use fossil fuel like oils, gases, and coal that are treated as major causes of environmental pollution, which releases harmful gases viz., SO_2, NO_2, and CO_2. Therefore, the pollution limit is considered.

The quantity of greenhouse gas emissions depends on the cumulative utilized fuels within traditional production entities and is computed using following equation (3.39) [277], [278]:

$$E_{gen}(t) = E_m Coef_{gen} . \frac{C_t(P_{gen})}{\lambda_{f,gen}} \tag{3.39}$$

In above equation, $E_{gen}(t)$ is amount of CO_2 production, $C_t(P_{gen})$ refers to production cost, $\lambda_{f,gen}$ is fuel price of each generator, whereas $E_m Coef_{gen}$ denotes emission coefficient of generator. Equation (3.39) shows that a considerable quantity of fuel is utilized for power production and when multiplied by $E_m Coef_{gen}$, yields the amount of produced CO_2 achieved. The emission coefficient is devised upon net-thermal value $(NthV)$ of fuels, emission factor (EmF), as well as oxidation factor (OxF) of generator utilizing equation (3.40), and T=24 hours in equation (3.41) [276], [278].

$$EmCoef_{gen} = NthV_{gen} * EmF_{gen} * OxF_{gen} \tag{3.40}$$

The emission coefficient relies upon fuel-class as well as generation features that are illustrated in [278]. The price coefficient, starting prices, and ramp-up rates in diesel generators within individual MGs and DNs are taken from [278].
The amount of CO_2 restricted as in following equation:

$$\sum_{t=1}^{T} E_{gen}(t) \leq Emission_{Max} \tag{3.41}$$

where intervals are assumed to be 1 hour.

- ***Undispatchable units***

PVs as well as WTs are regarded as undispatchable entities owing to irregular power outcomes. The produced wattage depends upon several environment condition like PV radiation and air speed that possess irregular characteristics. Probabilistic model for WTs and PVs is represented in following part.

The output power of WT can be modeled based upon air-velocity fluctuation that influences power production. Wind-velocity possesses "Weibull-probability-density-function-(PDF)" where the shape factor k as well as scale factor c illustrated in following equation (3.42) [279], [280]:

$$f_v(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \qquad 0 \le v \le \infty \tag{3.42}$$

Wherein v presents wind-speeds.

Equation (3.42) presents the probabilities in air speed. Produced wattage in WTs are linked to air speed using equation (3.43) [281]:

$$P_{wind} = \begin{cases} 0 & v \le v_i \quad v \ge v_0 \\ \dfrac{v - v_i}{v_r - v_i} P_{wr} & v_i \le v \le v_r \\ P_{wr} & v_r \le v \le v_0 \end{cases} \tag{3.43}$$

Predictions for global horizontal solar irradiance performed [282]. The produced power from PV networks relies upon PV irradiation (I) that possesses log-normal-PDF as follows [278]:

$$f_I(I) = \frac{1}{I\sigma\sqrt{2\pi}} \exp\left[\frac{-(\ln I - \mu)^2}{2\sigma^2}\right] \quad I \ge 0 \tag{3.44}$$

In equation (3.44) μ denote mean, and σ denote standard deviation of "probability density function (PDF)," respectively.

Relation within PV-irradiance (I) with electrical power production for PV networks are described as follows (3.45) [283]:

$$P_{pv} = \begin{cases} P_{pvr}\left(\dfrac{I^2}{I_{std} I_C}\right) & I \le I_C \\ P_{pvr}\left(\dfrac{I}{I_{std}}\right) & I_C \le I \end{cases} \tag{3.45}$$

Wherein I_{std} represents PV irradiation within normal conditions, I_C represents the certain pre-specified irradiation value, and P_{pvr} denotes the specified output wattage for the PV network.

- ***Energy storage systems(ESS)***

ESS comprises lithium-ion battery as well as interfacing bi-directional converters. Technical limitations within ESSs are illustrated by equations (3.46)-(3.54) [278], [284]. Equations (3.46)-(3.47) represent constraints involved in charge and discharge wattage within batteries. Equation (3.48) presents constraints to avoid the concurrent charge/discharge of the battery. Equation (3.49) presents the calculation of state of charge (SOC) within battery that shows an indication of its stored energy levels. Energy limits in current iteration is associated to energy-levels of preceding count as well as charge/discharge in present count. Equation (3.50) illustrates SOC restrictions; 1 as well as 0 indicates completely charged as well as nil battery-charges, respectively. Equations (3.51) - (3.52) denote the initial as well as final SOC. Moreover, equations (3.53) - (3.54) present complex power constraints of ESSs.

$$0 \le P_{bat_{ch}}(t) \le U_{bat_{ch}}(t) P_{bat_{cap}} \tag{3.46}$$

$$0 \le P_{bat_{disch}}(t) \le U_{bat_{disch}}(t) P_{bat_{cap}} \tag{3.47}$$

The parameter data linked with ESSs for individual MG and SDN are taken from [278].

$$U_{bat_{ch}}(t) + U_{bat_{disch}}(t) \le 1 \quad U_{bat_{ch}}(t),\ U_{bat_{disch}}(t) \in \{0,1\} \tag{3.48}$$

$$SOC(t) = SOC(t-1) - \frac{1}{P_{bat_{cap}}} (P_{bat_{disch}}(t) - P_{bat_{ch}}(t)) \tag{3.49}$$

$$0 \le SOC(t) \le 1 \tag{3.50}$$

$$SOC(t_0) = SOC_{initial} \tag{3.51}$$

$$SOC(T) = SOC_{final} \tag{3.52}$$

$$P_{bat}(t) = P_{bat_{ch}}(t) - P_{bat\,disch}(t) \tag{3.53}$$

$$P_{bat}^2(t) + Q_{bat}^2(t) \le S_{r,bat}^2 \tag{3.54}$$

In preceding equations, $P_{bat_{cap}}$ denotes wattage transforming capability for charge/discharge ESSs. Moreover, $P_{bat_{ch}}(t)$ and $P_{bat\,disch}(t)$ denote charge and discharge in ESSs within interval t; $U_{bat_{ch}}(t)$ and $U_{bat_{disch}}(t)$ denote bipartite variable denoting the charge and discharge mode for

ESSs and $SOC(t)$ illustrates $SOCs$ of batteries in interval t, that shows battery's stored amount of energy.

- **Load modeling**

Various load types within MGs are taken into consideration viz., fixed-load-demands, deferrable as well as sheddable loads.

- ***Fixed load demands***

Fixed loads are crucial load-demands that are not permitted to be sheddable or shiftable.

- ***Deferrable as well as sheddable loads***

Deferrable loads are shifting-loads within an interval; however, it is essential for it to consume a specific amount of energy within a planned duration. Sheddable-load-demands are curtailed by remitting penalty payments. These loads will involve in DRPs. Equation (3.55) presents restrictions for the quantity of shifting; equation (3.56) presents the quantity of energy that is used by deferred load demands. Additionally, equations (3.57) and (3.58) present price functions to perform DRPs on deferrable and sheddable loads [278], [285].

$$P_{def-load}^{\min} \le P_{def-load}(t) \le P_{def-load}^{\max} \tag{3.55}$$

$$E_{def-load}^{\min} \le \sum_{t=1}^{24} P_{def-load}(t) \le E_{def-load}^{\max} \tag{3.56}$$

$$C_{def-load} = \xi \left[E_{def-load}^{\max} - \sum_{t=1}^{24} P_{def-load}(t) \right] \tag{3.57}$$

$$C_{shed-load} = \psi \left[\sum_{t=1}^{24} P_{sheded_{load}}(t) \right] \tag{3.58}$$

In the preceding equations, $P_{def-load}^{\min}$ and $P_{def-load}^{\max}$ denote power restrictions of deferrable-load-demands, $E_{def-load}^{\min}$ and $E_{def-load}^{\max}$ represent energy-limits for deferrable-loads and ξ presents a fixed parameter. Equation (3.58) presents penalties in curtailing sheddable-load-demands where $P_{shedded_{load}}(t)$ denotes the quantity of shedded-loads in interval t, ψ presents a fixed parameter.

- **Microgrid (MG) and Distribution network (DN) modeling**

MGs as well as DNs may be radial [278]. Bus 1 linked with higher grids as well as possesses adjustable wattage input. Figure 3.4 shows system modeling of the radial DN. Net complex power within every bus stated in following [278]:

$$S_i^{net}(t) = S_i^{bat}(t) + S_i^{load}(t) - S_i^{gen}(t) \quad (3.59)$$

$$S_i^{net}(t) = P_i^{net}(t) + jQ_i^{net} \quad (3.60)$$

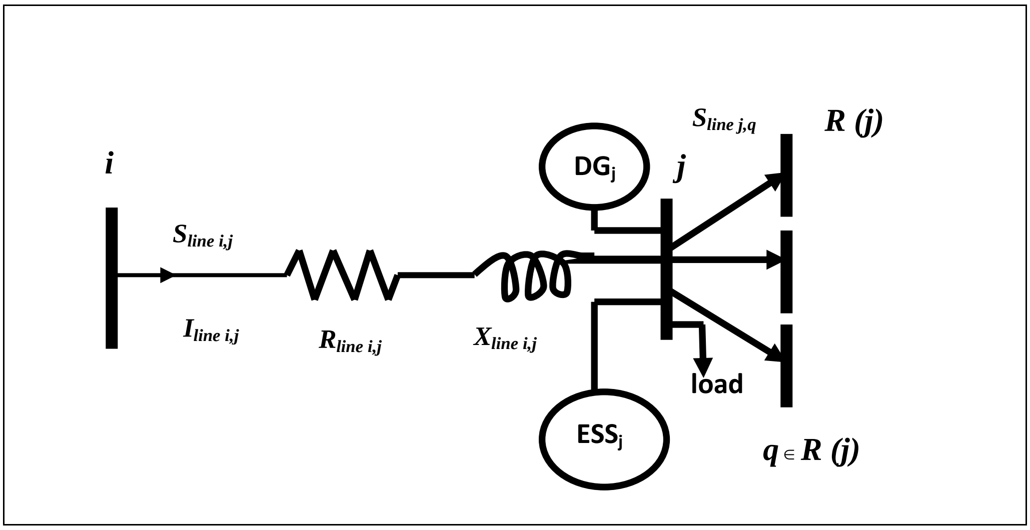


Figure 3.4 System modeling of a radial DN

In equations (3.59) and (3.60), $S_i^{net}(t)$, $S_i^{bat}(t)$, $S_i^{load}(t)$ and $S_i^{gen}(t)$ presents net complex power, complex power for battery, load-demand complex power, as well as produced complex-power in node i, respectively. Additionally, $P_i^{net}(t)$ and $Q_i^{net}(t)$ denote net active and reactive power, respectively. Every line joining bus i as well as j within the system possesses resistances $R_{line_{i,j}}$ also reactances denoted as $X_{line_{i,j}}$. Moreover, amperes as well as complex power via i, j are designated as $I_{line_{i,j}}$ and $S_{line_{i,j}}$, respectively; voltage within bus i designated by V_i.

Utilizing the system model illustrated in Figure 3.4, "Ohm's law" is represented in following:

$$V_i(t) - V_j(t) = Z_{line_{i,j}} I_{line_{i,j}}(t) \quad (3.61)$$

Power flow as well as power balance formulations can be written within following equations:

$$S_{line_{i,j}}(t) = V_i(t) I^*_{linei,j}(t) \quad (3.62)$$

$$S_{linei,j}(t) - Z_{linei,j} I^2_{linei,j}(t) - \sum_{q \in R} S_{linej,q}(t) = S_i^{net}(t) \qquad (3.63)$$

The net active as well as reactive powers calculated in following equations:

$$P_j^{net}(t) = P_{linei,j}(t) - R_{linei,j} I^2_{linei,j}(t) - \sum_{q \in R} P_{linej,q}(t) \qquad (3.64)$$

$$Q_j^{net}(t) = Q_{linei,j}(t) - X_{linei,j} I^2_{linei,j}(t) - \sum_{q \in R} Q_{linej,q}(t) \qquad (3.65)$$

Voltages can be calculated as follows:

$$V_j^2(t) = V_i^2(t) - 2(R_{linei,j} P_{linei,j}(t) + X_{linei,j} Q_{linei,j}(t)) + (R^2_{linei,j} + X^2_{linei,j}) I^2_{linei,j}(t) \qquad (3.66)$$

$$V_{\min} \le V_i(t) \le V_{\max} \qquad (3.67)$$

$$I^2_{linei,j}(t) = \frac{S_{linei,j}(t)}{V_i^2(t)} \qquad (3.68)$$

Besides, phase-angles for variables may be computed within radial systems [275].

- **Multi-layer energy management system (MEMS) for day-ahead scheduling**

MEMS have evolved for MMG with SDN, considering power losses as well as DRPs. During functioning of MGs, owing to fluctuating natures in power production from renewable energy sources (RES); also variation in power prices, surplus/shortage power concept is formulated.
In first layer of MEMS, individual MG units or MG operators, perform local optimizations (LO) for determining excess/deficit wattage into/out-of main grid, battery-charge, discharge state, as well as resultant power schedule for schedulable DG units.
Within subsequent layers, smart distribution network operator (SDNO) executes EMS depending upon obtained informations of several units; so SDN optimization is carried out in this layer [278].

3.3.1 Fitness Function and constraints for MG optimization

Stage 1: Optimization of MG

In stage-1, the MG's administrator intends to optimize the cumulative operating price within individual cases.

- *Objective function formulation with DR with loss*

Equation (3.69) elaborates the formulated objective function (O.F.) corresponding to χ^{th} MG, where χ denotes index of MG. Equation (3.69) consisting of the DG price, cost of sales, prices for shifting deferrable-loads as well as load-shedding, cost of power owing to losses, subject to the fulfillment of the constraints. $C_t\left(P_{gen}^{g}\right)$ and $C_{startup,t}^{g}$ present the generating as well as starting costs for generator g in MG χ . $pr_t^{buy,DN}$ and $pr_t^{sell,DN}$ represent the buying as well as selling price for power within SDN. $P_t^{shortage}$ and $P_t^{surplus}$ denote the deficit as well as excess power for MG χ in interval t . Additionally, P_t^{loss} denotes the cumulative power losses within MG network.

$$\min:\sum_t \left\{ \begin{array}{l} \sum_{g=1}^{N_{DG\chi}}\left[C_t\left(P_{gen}^{g}\right)+C_{startup,t}^{g}\right]+\left[pr_t^{buy,DN}P_t^{shortage}-pr_t^{sell,DN}P_t^{surplus}\right]+ \\ \left[C_{def_{load,t}}+C_{shed_{load,t}}\right]+pr_t^{buy,DN}P_t^{loss} \end{array} \right\} \tag{3.69}$$

Equation (3.69) comprises four terms. The initial part denotes generating prices for diesel-unit *g*. The next term illustrates energies exchange prices from/to main utility. The third part presents the cost for executing DRPs comprising of prices to shift deferrable loads as well as load shedding. The final component denotes the cost owing to power-losses to be minimized within MEMS [278]. Constraints for load balance illustrated in equation (3.70).

$$\sum_t P_{gen,g_{DN},t}^{\max}+\sum_k P_k^{surplus}\geq\sum_l P_l^{load}+\sum_i P_i^{shortage} \tag{3.70}$$

In equation (3.70), g_{DN} , k , l , i presents indices representing DGs within SDN, MGs retaining excess wattage, load-demands within SDN, and MGs with shortage power, respectively. Moreover, $P_{g_{DN}}^{\max}$ denotes capacity considering local g^{th} DG, $P_k^{surplus}$ is surplus power of k^{th} MG, P_l^{load} denotes the l^{th} local load and $P_i^{shortage}$ denotes shortage power of i^{th} MG [278]. Equation (3.71) illustrates the surplus power limits [278]. Constraints of individual units within MG are to be considered.

$$0\leq P_{t,i}^{surplus_{MG}}\leq P_t^{surplus_{MG\chi},\max} \tag{3.71}$$

$$Constraint\ s = \begin{cases} DG \quad units \quad of \quad MG \quad (3.33) - (3.41) \\ ESS \quad units \quad of \quad MG \quad (3.46) - (3.54) \\ Flexible\ Loads\ of\ MG\ (3.55) - (3.58) \\ Network\ Modelling\ of\ MG\ (3.59) - (3.68) \end{cases}$$

3.3.2 Fitness Function and constraints for SDN optimization

- *Stage 2: SDN Optimization and Priority list (PL) formulation*

Subsequent to local optimization pertaining to individual MGs, SDNO constitutes PL to determine which units to commit to supplying SDN demands and demands from MGs with a power deficit. It helps SDNO to accelerate computations where units with larger quantities of RES are preferable.
To constitute PL [286], SDNO collects information from MGs regarding excess/deficit of power and production price of DGs; it computes the average price of individual entities, categorizes them from low to high costs. When costs are similar, it prioritizes high-capacity units and chooses m entities at the top [278].

$$\min : \left[\sum_t \left\{ \begin{array}{l} \sum_{g=1}^{N_{DG_{DN}}} \left[C_t\left(P^g_{gen_{DN}}\right) + C^g_{startup_{DN},t} \right] + \left[pr_t^{buy,utility} P_t^{buy_{DN}} - pr_t^{sell,utility} P_t^{sell_{DN}} \right] + \left[C_{def_{load,DN,t}} + C_{shed_{load},DN,t} \right] \\ + \left[\sum_\chi pr_t^{buy,DN} P_{t,\chi}^{surplus_{MG}} + \sum_\chi pr_t^{sell,DN} P_{t,\chi}^{shortage_{MG}} \right] + pr_t^{buy,utility} P_t^{loss} \end{array} \right\} \right] \tag{3.72}$$

Formulated objective function (O.F.) within SDN optimization formulation aims in minimizing production price for nearby units as well as purchase electricity from MGs whereby serves load-demands. O.F. for SDN optimizing formulation can be given by equation (3.72), subject to fulfillment of the constraints where $C_t(P^g_{gen_{DN}})$ and $C^g_{startup_{DN},t}$ denote generating as well as starting costs for unit's g in SDNs within PL. $pr_t^{buy,utility}$ and $pr_t^{sell,utility}$ denote the buying and selling costs of energy from/to utility, $P_t^{sell_{DN}}$ and $P_t^{buy_{DN}}$ denote the quantity of power sold and purchased from the main utility in period t. $P_{t,\chi}^{surplus_{MG}}$ and $P_{t,\chi}^{shortage_{MG}}$ are quantities in power purchase/sales originating from/towards the χ^{th} MG, and P_t^{loss} denotes the cumulative real power loss in the SDN. $C_{shed\ load}$ and $C_{def\ load}$ represent cost of load shedding and cost of load shifting respectively [278].
Initial component in equation (3.72) denotes generating costs of diesel g in set of priority list. PL aids in accelerating computations in complex systems. Second component represents the price of energy exchange with the main grid. Third-component represents price to perform DRPs, whereas fourth-component elaborates the price for energy interchange from/to MG. Last term denotes costs owing to power-losses to be minimized in the procedure of MEMS. Constraints for load balance and surplus power limits are described in equations (3.73) and (3.74) respectively. Constraints of individual units within SDN are to be considered.

$$\sum_t P_{gen,g_{DN},t}^{\max} + \sum_k P_k^{surplus} \geq \sum_l P_l^{load} + \sum_i P_i^{shortage} \tag{3.73}$$

In equation (3.73), g_{DN}, k , l, and i represent indices representing DG within SDNs, MGs having excess wattage, load-demands within SDN and MGs with shortage power, respectively. Moreover, $P_{g_{DN}}^{\max}$ denotes the capacity considering local g^{th} DG, $P_k^{surplus}$ is the excess wattage for k^{th} MGs, P_l^{load} denotes the l^{th} local load whereas $P_i^{shortage}$ denotes the deficit power of the i^{th} MG [278]. Equation (3.74) illustrates the surplus power limits [278].

$$0 \leq P_{t,i}^{surplus_{MG}} \leq P_t^{surplus_{MG\chi},\max} \tag{3.74}$$

$$Constraint\,s = \begin{cases} DG \quad units \quad of \quad SDN \quad (3.33) - (3.41) \\ ESS \quad units \quad of \quad SDN \quad (3.46) - (3.54) \\ Flexible\,Loads\,of\ \,SDN\,(3.55) - (3.58) \\ Network\,Modelling\,of\ \,SDN\,(3.59) - (3.68) \end{cases}$$

3.3.3 Constraint handling technique

Constraint handling comprise of various methods categorized in diverse group: techniques devised upon solution's feasibility, penalty function method, as well as techniques which produce precise distinctions amidst feasible as well as infeasible optimum point, as well as hybrid approach [272], [273].

In this research, inequalities constraints are incorporated within O.F. (J) as penalty terms as well as converted to augmented O.F. (J_{aug}) given by following equation (3.75), wherein $\lambda_p, \lambda_{ESS}, \lambda_{def-load}, \lambda_{shedded_{load}}$ are penalty factors. The first term in equation (3.75) is the original objective function, second term presents active power limitations of DG units; third term denotes storage power limits; fourth term represents deferrable loading limits and final term denotes sheddable loading limits.

$$\begin{aligned} J_{aug} = J \ &+ \lambda_p (P_{DG,i} - P_{DG,i}^{\lim})^2 + \lambda_{ESS} \left(P_{ESS} - P_{ESS}^{\lim}\right)^2 + \\ &+ \lambda_{def-load} \sum_{i=1}^{l} \left(P_{def-load} - P_{def-load}^{\lim}\right)^2 + \lambda_{shedded_{load}} \sum_{i=1}^{l} \left(P_{shedded_{load}} - P_{shedded_{load}}^{\lim}\right)^2 \end{aligned} \tag{3.75}$$

wherein $P_{DG}^{\lim}$ presents power generation limits for DG units, $P_{ESS}^{\lim}$ presents power generation limits for energy storage system, $P_{def-load}^{\lim}$ presents power limitations for deferrable-loads, $P_{shedded_{load}}^{\lim}$ presents power limitations for sheddable-loads.

3.3.3.1. Test System 2-System modeling

Test System 2 consists SDN based microgrids, schedulable DG's, WTs, PV, ESS's as well as loads. Energy storage systems are Li-Ion batteries also two-direction power-electronics converter. Loads are of two categories: (I) loads, inclined in participating within DRPs (II) constant load-demands; load modeling described in equations (3.55)-(3.58).

3.3.3.2. Systems structures

Figure 3.3(a) depicts system outline. Operating model has 24 hours horizon where time's interval's is 1 hour.

3.3.3.3. Dispatchable Units

Entities viz., diesel generators are called dispatchable units described in equations (3.33)-(3.41).

3.3.3.4. Unschedulable Units

PVs as well as WT's unschedulable entities because stochastic power outputs. The produced wattage depend upon several environment conditions like sun's irradiances and winds velocities described in equations (3.42)-(3.45).

3.3.3.5. Energies storages systems (ESSs)

ESS comprises lithium-ion battery as well as interfacing bi-directional converters described in equations (3.46)-(3.54).

3.3.3.6. Load Modeling

Various load categories included within microgrids viz., fixed-load-demands, deferrable as well as sheddable-load-demands described in equations (3.55)-(3.58).

3.3.3.7. Fixed Loads

Fixed loads presents critical loads.

3.3.3.8. Deferrable and Sheddable Loads

Deferrable-load-demands shift with times, also essential to consume specific amounts for energies within planned duration.

3.3.3.9. MG as well as Distributions Networks

Microgrids as well as distributions systems are modeled as radial networks described in equations (3.59)-(3.68).

3.4. Test System 3: Energy Management System of Multi-Microgrid based Smart Distribution network considering power flow constraints

A. System modeling

A detailed system analysis is carried out in following section.

- *System Structure*

The research, propose a technique examined upon DN consisting MGs, DGs, WTs, PVs, ESS as well as load-demands that is explained within Figure 3.5 (a), shows complete outline of system. DN is connected to three MGs; MGs 1 and 2 consists of diesel generator, WTs, PVs, ESS as well as load-demands whereas within MG 3 there is no diesel generation. MG 3 consists of generating units viz., PV, WT and ESS. Figure 3.5 (b) presents the schematic of network node where R_{ij} and X_{ij} represent resistance and reactance between nodes i and j. Figure 3.6 shows altered-IEEE 33 bus DN where three MGs connected with altered-IEEE 33 bus DN. MG-1, MG-2 and MG-3 being connected to altered IEEE 33 bus DN at nodes 2, 26 and 22 respectively. Smart Distribution Network is illustrated in Section 5.2.1.

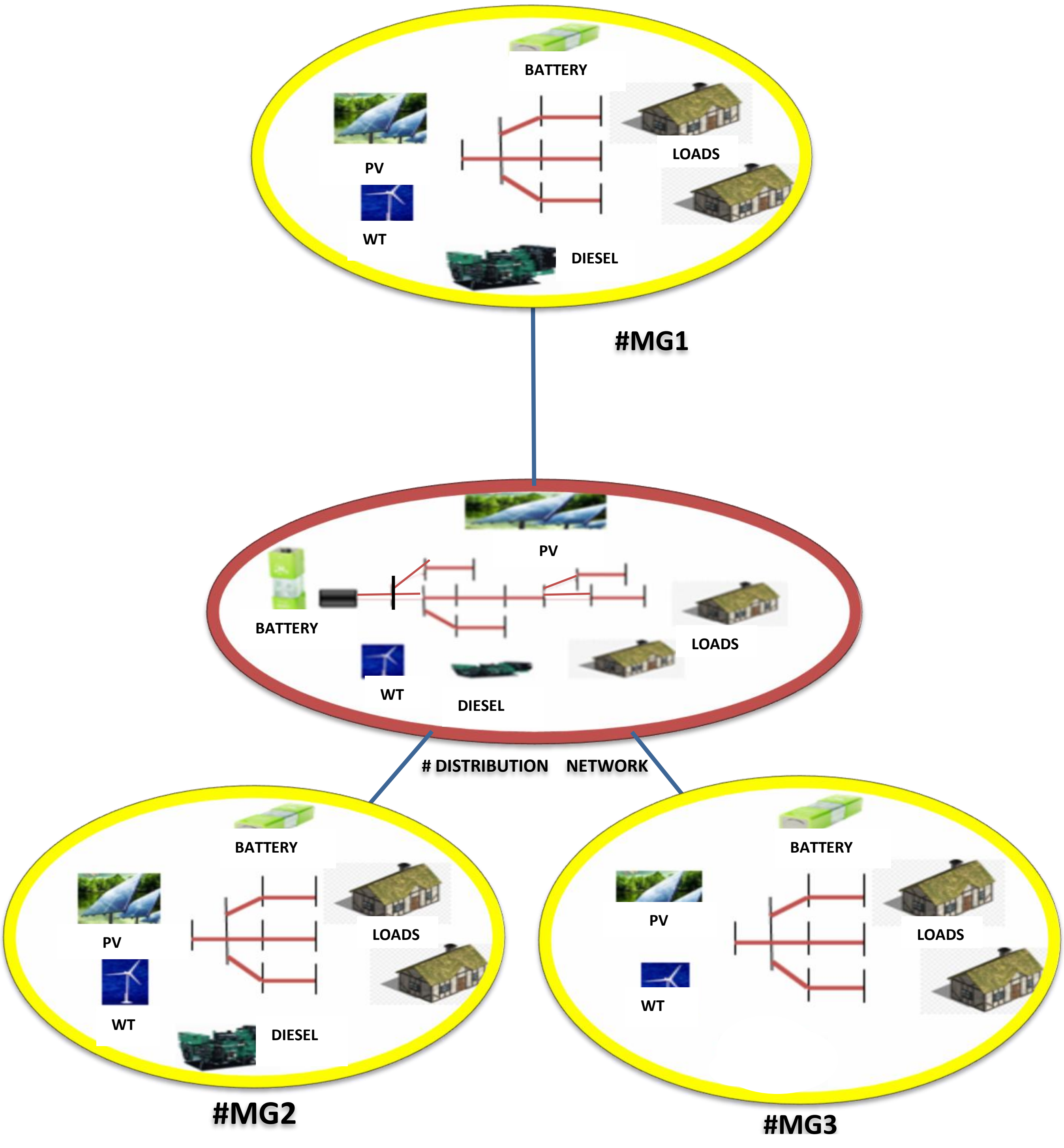


Figure 3.5 (a) Illustration of sample MMG's structure in Test System 3

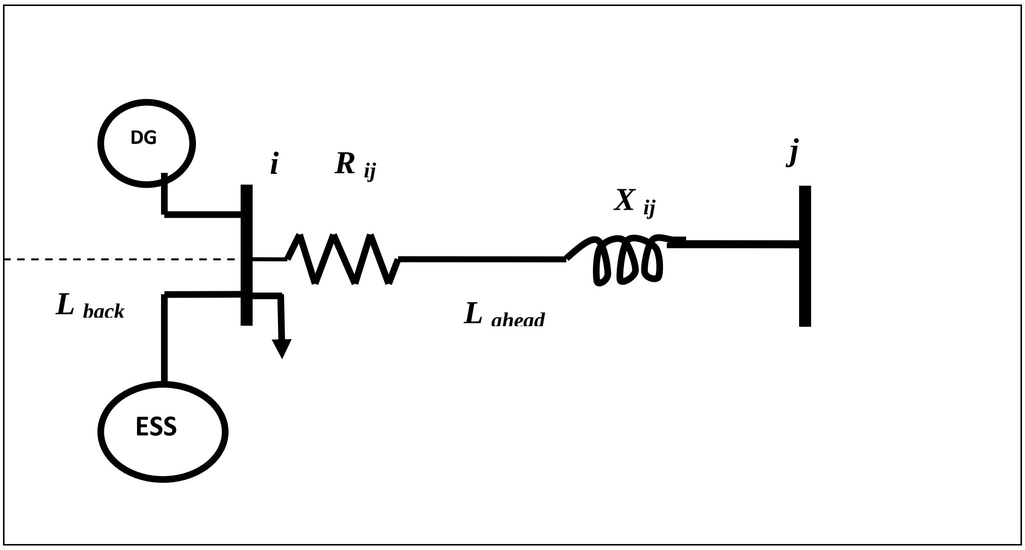


Figure 3.5 (b).Schematic of network node

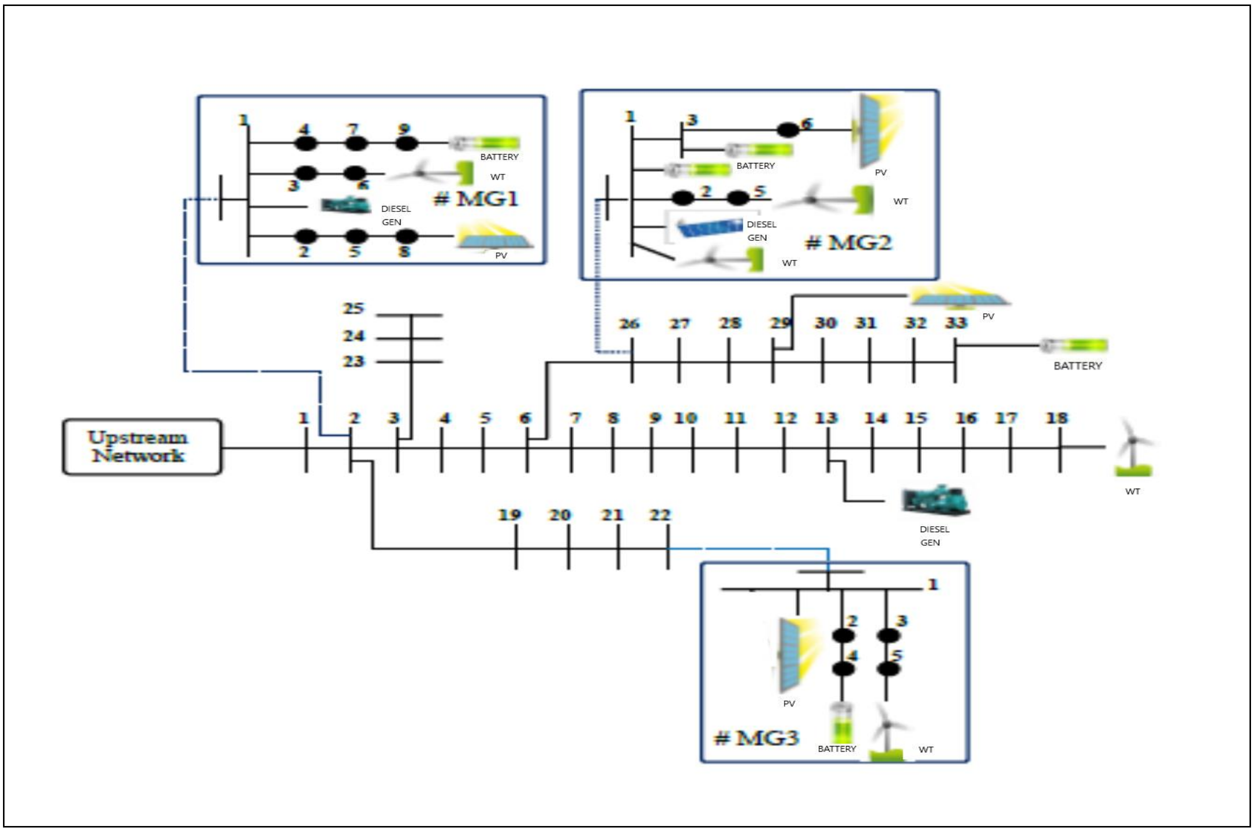


Figure 3.6.Altered-IEEE-33-bus-DN

Figure 3.7 shows radial distribution system whereas Figure 3.8 illustrates renewable energy resources i.e., PVs and WTs.

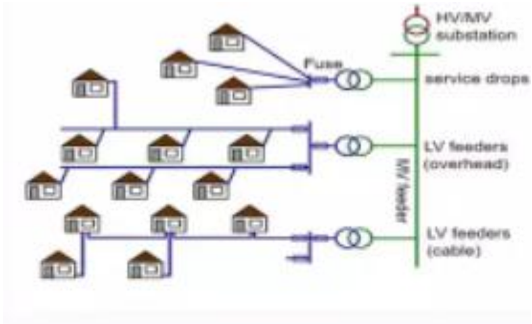


Figure 3.7. Radial distribution system **Figure 3.8.** Renewable energy- PVs &WTs

MGs are radially structured. Devised model possesses 24 hours horizon of period 1 hour.

- *Renewable units*

It is assumed that renewable sources have no cost whereby amount of output power from renewables are forecasted [287], [288].

- *Dispatchable units*

Entity viz., diesel-generator denoted as dispatchable entity. Equation (3.76), (3.77) and (3.78) illustrate generating limits for diesel generation [289].

$$P_{DG}^{\min} \times w_{diesel} \leq P_{DG,t}^{diesel} \leq P_{DG}^{\max} \times w_{diesel} \tag{3.76}$$

$$P_{DG,t}^{diesel} - P_{DG,t-1}^{diesel} \leq Ramp^{up} P_{DG}^{\max} \tag{3.77}$$

$$P_{DG,t-1}^{diesel} - P_{DG,t}^{diesel} \leq Ramp^{down} P_{DG}^{\max} \tag{3.78}$$

Equation (3.76) depicts maximum and minimum production constraints for individual DG. $Ramp^{up}$ and $Ramp^{down}$ denotes ramp up/ down co-efficient of diesel DG. Equations (3.77) and (3.78), present ramp up as well as, ramp down limits of each DG. Price functions possess quadratic characteristics depicted in equation (3.79). Startup costs [289] represented in equation (3.80).

$$Cost_{DG,t}^{diesel} = A_1 (P_{DG,t}^{diesel})^2 + A_2 (P_{DG,t}^{diesel}) + A_3 \tag{3.79}$$

$$C_{st-up} = y(t) \times start_{Cost}^{up} \tag{3.80}$$

$$y(t) = \max[\left(w_{diesel}(t) - w_{diesel}(t-1)\right), 0] \tag{3.81}$$

A_1, A_2 and A_3 represents diesel generator price function coefficients, P_{DG} denotes generated power of diesel unit, C_{st-up} presents start up cost of DG & $y(t)$ presents variations in states of generating unit. Equation (3.81) denotes change in status of generator. The cumulative cost of diesel generator is stated in equation (3.82) as follows [289]:

$$Cost_{DG,i,t} = C_{st-up} + Cost_{DG,t}^{diesel} \tag{3.82}$$

where, $Cost_{DG}$ denotes cost function of DG unit.

- *Energy Storage Systems (ESSs)*

Formulation of ESSs presented as follows [289]:

$$U_t^{ch} P_{B,ch}^{\min} \le P_{B,ch,t} \le U_t^{ch} P_{B,ch}^{\max} \tag{3.83}$$

$$U_t^{dis} P_{B,dis}^{\min} \le P_{B,dis,t} \le U_t^{dis} P_{B,dis}^{\max} \tag{3.84}$$

$$U_t^{ch} + U_t^{dis} \le 1 \tag{3.85}$$

$$SOC_{B,t} = SOC_{B,t-1} + (\eta_B^{ch} P_{B,ch,t} - P_{B,dis,t} / \eta_B^{dis}) * \Delta t \tag{3.86}$$

$$SOC_B^{\min} \le SOC_{B,t} \le SOC_B^{\max} \tag{3.87}$$

In equations (3.83) and (3.84), $P_{B,ch}^{\max}$ and $P_{B,dis}^{\max}$ denotes maximum charging and maximum discharging power of battery respectively; $P_{B,ch}$ and $P_{B,dis}$ represents charging and discharging power of battery. Also, in equations (3.83) and (3.84), $P_{B,ch}^{\min}$ and $P_{B,dis}^{\min}$ denotes minimum charging and minimum discharging power of battery; also U presents binary variable that indicates status of charging/discharging. In equation (3.86), η_B^{ch} and η_B^{dis} presents efficiency rate during charging/discharging of battery respectively.
Equations (3.83) and (3.84) present constraints of charging and discharging of units. Constraint (3.85) illustrates that concurrent charging and discharging of units cannot occur. State of Charge (*SOC*) for ESS within definite interval is computed in equation (3.86), wherein its acceptable limits are denoted in equation (3.87).

- *Power flow constraints*

In proposed methodology of EMS of each unit, power flow constraints are taken into consideration within SDN and also deployed for individual MG. In case of specific node *i*, as shown in Figure 3.5(b), power flow constraints are stated as follows [289]:

$$P_{DG,i,t}^{renew} + P_{DG,i,t}^{diesel} + P_{B,dis,t} + \sum_{l \in i_{back}} P_{line,l} = \sum_{l \in i_{ahead}} (P_{line,l,t} + R_l I_{line,l}^2 + P_{load,l,t}) + P_{B,ch,t} \tag{3.88}$$

$$Q_{DG,i,t}^{diesel} + \sum_{l \in i_{back}} Q_{line,l} = \sum_{l \in i_{ahead}} (Q_{line,l,t} + X_l I_{line,l}^2 + Q_{load,l,t}) \tag{3.89}$$

$$P_{load,i,t} = P_{load,i,t}^{demand} - P_{load,i,t}^{curt} \quad (3.90)$$

$$Q_{load,i,t} = Q_{load,i,t}^{demand} - Q_{load,i,t}^{curt} \quad (3.91)$$

$$V_i^2 - V_j^2 = \beta_{i,j,l} \times \left[2R_l P_{line,l,t} + 2X_l Q_{line,l,t} + R_l I_{line,l,t}^2 + X_l I_{line,l,t}^2 \right] \quad (3.92)$$

$$I_{line,l,t}^2 V_{j,t}^2 = P_{line,l,t}^2 + Q_{line,l,t}^2 \quad (3.93)$$

$$V_{\min} \leq V_i \leq V_{\max} \quad (3.94)$$

$$| I_{line,l,t} | \leq I_{line}^{\max} \quad (3.95)$$

In equation (3.88), $renew$ is superscript denoting renewable DG, R_{line} denotes branch resistance, P_{DG}^{renew} presents forecasted renewable unit active power. In equations (3.88) and (3.89); X_{line} denotes branch reactance, i_{back} presents set of lines which are connected to node i and i_{ahead} presents set of lines which are extracted from node i. In equations (3.90) and (3.91), P_{load}^{demand} and Q_{load}^{demand} presents active and reactive consumed power of each node whereas P_{load}^{curt} and Q_{load}^{curt} denotes curtailed active and reactive load of each node. In equation (3.92) $\beta_{i,j,l}$ indicates that l line exists between nodes i, j or not, I_{line} presents branch current. In equation (3.93), P_{line} and Q_{line} presents active and reactive power in each line. In equation (3.94), $V_{\max}$ and $V_{\min}$ denotes maximum and minimum voltage magnitude in each node. In equation (3.95), $I_{line}^{\max}$ denotes maximum allowable line current.

Equations (3.88)-(3.91) demonstrate active as well as reactive power balance at specific nodes. Voltage drops for individual line is illustrated in constraint (3.92). Relation between current and power for each branch is described in equation (3.93). Constraints for voltages are described in equation (3.94). Constraint (3.95) shows permissible quantity of current passing through individual line. Equations (3.94) and (3.95) represent security constraints of system. During power system functioning, it is requisite not to violate these inequalities thus ensuring network securities [290]. It is worth mentioning i.e., congestion within specific line occurs indicates highest permissible quantity of current passing through individual line. Loads are sheddable and operator sheds loads during congestion. Figure 3.6 illustrates altered IEEE 33 bus [289] SDN and system data is found in [291]. MGs are radially structured. Devised model possesses 24 hours horizon of period 1 hour. The energy management problem comprises of three layers. In initial stage, individual MG schedules DG units as well as ESSs; subsequently informs DN operator (DNO) regarding shortage/ surplus power within definite time period. In second stage, DNO performs energy management and optimizing procedure for DN taking account of achieved results obtained from MGs. In this stage, DN faces congestion problem wherein this impacts quantity of power that is bought/ sold originating at/ towards MGs. In last stage, individual MG performs re-scheduling & energy management w.r.t achieved results from DN.

3.4.1 Fitness Function and constraints for MG optimization (without considering security constraints)

Following part within this research illustrates objective function (O.F.) formulation of each unit and also constraints are discussed in details. Each MG as a distinct entity contains distributed conventional and renewable generators like diesel generator, WT and PV panel, ESS and flexible loads.
O.F. is written for MG as in following equation (3.96) [289]:

$$\min : Z_{MG\chi} = \sum_t \sum_i Cost_{DG,i,t} + \sum_t (price^{DN}_{buy,t} P^{lack}_t - price^{DN}_{sell,t} P^{extra}_t) + \sum_t \sum_i price^{curt}_t P^{curt}_{i,t} \qquad (3.96)$$

$$Constraints = \begin{cases} DG \quad units \quad (3.76)-(3.82) \\ ESS \quad units \quad (3.83)-(3.87) \\ Power \quad flow \quad (3.88)-(3.93) \end{cases}$$

In equation (3.96), $price^{DN}_{buy}$ and $price^{DN}_{sell}$ denotes price of buying and selling power from DN, $price^{curt}$ indicates price of curtailed load, χ represents set of MGs. O.F. formulation in individual MG along with correlated constraints can be stated as in equation (3.96) [289]. O.F. for individual MGs consists of four terms. First term denotes prices of powers that are generated by MGs. The second as well as third terms indicates prices and revenues for power interchange within MGs and DN. The final term illustrates prices of load-demands that are curtailed.

3.4.2 Fitness Function and constraints for DN optimization (considering security constraints)

Cost function is written for DN as in following equation (3.97) [289]. First term denotes prices of powers that are generated by MGs. The second as well as third terms indicates prices and revenues for power interchange within MGs and DN. The fourth term illustrates prices of load-demands that are curtailed. The final term represents price of exchanging power with upstream network.

$$\begin{aligned} \min : Z_{DN} = & \sum_t \sum_i Cost_{DG,i,t} - \sum_\chi \sum_t (price^{DN}_{buy,t} P^{lack}_{\chi,t} + price^{DN}_{sell,t} P^{extra}_{\chi,t}) \\ & + \sum_t \sum_i price^{curt}_t P^{curt}_{i,t} + \sum_t price^{up}_t P^{up}_t \end{aligned} \qquad (3.97)$$

Here, individual MGs are not connected to adjoining MG so power exchange restricted only with the DN. $price^{up}$ indicates price of buying/selling power from/to upstream network.

$$Constraints = \begin{cases} DG \quad units & (3.76)-(3.82) \\ ESS \quad units & (3.83)-(3.87) \\ Power \quad flow & (3.88)-(3.95) \end{cases}$$

Henceforth, quantity of exchange power within MGs here is nil.

Next, DN faces congestion issue, such that it cannot supply individual MG's required power that is computed in first stage for definite time period, which results in increment in price of individual MG for third stage due to divergence against optimal schedule.

3.4.3 Fitness Function considering tie-lines

For tackling above mentioned problem, it is conceptualized that all MGs are controlled centrally from MG controller (MGC), MGs have both data as well as power pathways among themselves and power trading is possible within them. Proposed methodology focuses on centralized MMG structure shown in Figure 5.16. In this condition, MGC conducts EMS optimization of all MGs as per obtained data from individual MG regarding DG, ESS and loads as in following equation (3.98) [289]:

$$\min : Z_{total,MG} = \sum_{\chi} Z_{MG_{\chi}} \tag{3.98}$$

$$subject \quad to:$$
$$All \quad constraints \quad of \quad each \quad MG$$

After that, MGC notifies DNO regarding excess/deficit power within individual time period. Then, the DN provides power at nodes; wherein individual MG is linked with DN in such manner that aggregate of provided powers are equal to requested power of MGC. In final stage, MGC disburses achieved power from DN within MGs loads requirements utilizing possibilities of interchanging power amidst themselves. Thereby, suggested methodology neutralizes effects of DN congestion problems on EMS of individual MG, henceforth decrease prices for each entity.

3.4.4 Constraint handling technique

Constraint handling comprise numerous methods categorized to various group: techniques devised upon solution's feasibility, penalty function technique, techniques which produce precise distinctions in feasible as well as infeasible optimum point, also hybrid approach [272], [273].

In this research, inequality's constraints are incorporated within O.F. (J) as penalty terms also converted to augmented O.F. (J_{aug}) denoted by following equation (3.99), where

$\lambda_p, \lambda_{ESS}, \lambda_V, \lambda_I$ denote penalty-factors. The first term in equation (3.99) is the original O.F., second term presents active power limitations of DG units; third term denotes storage power limits; fourth term denotes voltage limits and final term denotes line current limits.

$$J_{aug} = J + \lambda_p (P_{DG,i} - P_{DG,i}^{\lim})^2 + \lambda_{ESS} \left(P_{ESS} - P_{ESS}^{\lim}\right)^2 + \lambda_v \sum_{i=1}^{n} \left(V_i - V_i^{\lim}\right)^2 + \lambda_I \sum_{i=1}^{N_{line}} \left(I_{line} - I_{line}^{\max}\right)^2 \qquad (3.99)$$

where $P_{DG}^{\lim}$ presents power generation limits for DG units, $P_{ESS}^{\lim}$ presents power generation limits for energy storage system, $V_i^{\lim}$ presents voltage limitations, $I_{line}^{\max}$ presents current limitations passing through individual line.

Next chapter presents different meta-heuristic techniques utilized in this research.

Chapter4 META HEURISTIC TECHNIQUES

Literature Review- Introduction to Soft Computing Techniques

Particle Swarm Optimization (PSO)

Time varying acceleration coefficient PSO (TVAC PSO)

Exponential decreasing Inertia weight PSO (EDW PSO)

Non linear decreasing inertia weight PSO (NDIW PSO)

Dynamic inertia weight PSO (DIW PSO)

Flower pollination Algorithm (FPA)

Single objective optimization

Multi objective optimization

Meta-dynamic approach based Multi objective Flower Pollination Algorithm (MMOFPA)

Multiobjective Modified Personal Best Particle swarm optimization (MMPBPSO)

CHAPTER-4

META HEURISTIC TECHNIQUES

4.1 Literature Review-Introduction to soft computing techniques

Optimization techniques achieved significant result within statistics, engineering as well as diverse domains. Intensifications as well as diversifications techniques regarded significant aspects within designs for meta- heuristics. Diversification denotes abilities for searching amidst various regions in searching spaces, whereas intensifications illustrate abilities in finding superior solves. An efficient searching-algorithm should possess balances within the above aims.

The major advantages of evolutionary algorithms are: -

1) Robustness for dynamical change: Conventional methodologies for optimization have no robustness for dynamical change as well as they requires completed restarting in achieving solutions, whereas evolutionary algorithms produce solves adaptive to changeable situations.

2) Broad applications: Evolutionary algorithms are applicable onto diverse formulations which are computed in function's optimizing issues.

3) Hybridizations alongwith additional methodologies: Evolutionary algorithms can be aggregated alongwith additional optimizing methodologies.

4) Solutions to issues which possess nil solution ie difficult to solve otherwise: Advantages for evolutionary algorithms include abilities in addressing issues where exists no human's expertises. Consideration of such features are implemented to diverse application incorporating electrical system operations as well as controls, chemical processes, multi-objective optimization problem etc.

Many researchers over years have used these optimization techniques to solve power system problems. Some researchers studied glow worm optimizing method for constrained formulations [292] whereas economical environment dispatch (EED) schedule problems resolved in [293]. Solve for units-commitment's issue by integer-coded genetic-algorithm (GA), was discussed in [294] and performance assessment of multi-objective optimizers was carried out in [295]. Multi-objective differential-evolution was suggested in solving EED and obtained outcome for 3 testing system demonstrated superior abilities in formulated method [296].

4.2 Particle swarm Optimization (PSO)

Particle swarm optimization [297], [298] method of explorations for newer searching spaces aimed at obtaining optimum results for problems gets its concepts originating at fishes school as well as bird's flock behaviours noticed within wildlife. Particle swarm optimization denotes stochastical evolutionary algorithm that conducts searching processes utilizing sets for populace for particles/particulates representing each solution.

PSO conduct searches via populace of particulates associated with individuals. In particle swarm optimization algorithm, particulate flies around in multi-dimensioned searching spaces in finding optimum solutions for problem at hand. PSO consists of two components – social component and cognitive component. Social component indicates individual's ignoring self experiences thereby adjusting the behaviour in accordance with particles in neighbourhood. Cognitive component suggests that particles adjust their behaviour according to own previous experience. In PSO, particulates changes positions according to these two components.

- **PSO components**

Components for PSO illustrated in following:

i. *Particle*, $X(t)$ = The anticipated solve to problem at hand, illustrated as *m*-dimensioned vectors whereby *m* is numbers of optimization parameters. In interval- t, j^{th} particle $X_j(t)$ denoted by follows- $X_j(t)=[x_{j,1}(t), x_{j,2}(t), ..., x_{j,m}(t)]$, whereby $x_{j,k}(t)$ denotes positions for j^{th} particles in regards with k^{th} dimensions.

ii. *Populations*, $pop(t)$ = Comprising set for *n* particles in period t viz., $pop(t)=[X_1(t), X_2(t), ..., X_n(t)]^T$.

iii. *Swarms*= Represents unorganized populace for particles.

iv. *Particle's velocities*, $V(t)$ = The velocities for non-stationary particles illustrated as m dimensioned vectors. In interval- t, j^{th} particulates velocity $V_j(t)$ depicted in $V_j(t)=[v_{j,1}(t), v_{j,2}(t), ..., v_{j,m}(t)]$, wherein $v_{j,k}(t)$ represents velocities term for j^{th} particles in regard to k^{th} dimensions.

v. *Inertia weight*, $w(t)$ = This controlling parameter is utilized in managing influence for preceding velocity upon present velocities. So, this influences trade-offs within globally as well as locally explorating capabilities for particulates. In beginning states for searching processes, high inertia weight is given for enhancing global exploration but in later states inertia weight lowered to enhance locally explorating phenomena.

vi. *Individual best*, $X^*(t)$ = When particulates navigates within searching spaces, its comparing the fitness in present position's for superior fitness outcome until its achieved up to every period till present period. Superior positions linked to better fitness encountering until now denoted individual's best $X^*(t)$. Considering individual particulates within swarms $X^*(t)$ is evaluated as well as update done while searching. For minimizing problems in hand, wherein Objective function (O.F.) denoted J, individual bests within j^{th} particulates, $X_j^*(t)$ being evaluated where $J(X_j^*(t)) \le J(X_j(\tau)), \tau \le t$. Assuming, $J_j^* = J(X^*(t))$ of j^{th} particulates, individually obtained bests is denoted $X_j^*(t)=[x_{j,1}^*(t), x_{j,2}^*(t), ...x_{j,m}^*(t)]$.

vii. *Global-best,* $X^{**}(t)$ = Superior positions within total individual's best-positions obtained until now. Therefore global best evaluated whereby $J(X^{**}(t)) \le J(X^{*}(t)), j = 1,2,........, n.$

viii. *Stop condition*= They present circumstances whereby searching terminates. Within present research, searching stop whenever iteration reaches highest limits.

- **Steps for implementing PSO**

In PSO, populace comprises n particles/particulates whereby every particulate presents m dimensioned vectors, wherein m denotes numbers for optimization parameters. Computational steps for PSO are illustrated as follows:

Step 1: (Initialization): Setting time-count $t = 0$ whereby generating random n particulates, $\{X_j(0), j = 1,.........., n\}$, wherein $X_j(0) = [x_{j,1}(0), x_{j,2}(0),.........., x_{j,m}(0)]$. $x_{j,k}(0)$, includes random selection of values within uniform-probability in k^{th} parameter within search spaces $[x_k^{\min}, x_k^{\max}]$. Also, generating random initializing velocity for every particulates, $\{V_j(0), j = 1,.........., n\}$, whereby $V_j(0) = [v_{j,1}(0), v_{j,2}(0),.........., v_{j,m}(0)]$. $v_{j,k}(0)$, can be produced in random thereby choosing values within uniform-probabilities in k^{th} dimensions $[-v_k^{\max}, v_k^{\max}]$.

Every particulate within initializing population; being assessed as per O.F. - J. Conditions are adjusted to $X_j^{*}(0) = X_j(0)$ as well as $J_j^{*} = J_j, j = 1,2,........, n.$ Searching superior values for O.F. J_{best}. Setting particulate linked to J_{best} represented global best, $X^{**}(0)$ for O.F. of J^{**}. Setting initial values for inertia weight, ($w(0)$).

Step 2: (Time/Interval counter): Updating timer counters $t = t + 1$.

Step 3: (Weight updating): Updating inertia weight w. Suitably choosing inertia weight w produces balancing of globally as well as locally explorating capabilities in finding effective optimum solves. Value w ; declines sequentially from 0.9 into 0.4 within runs. Typically, inertia weight is expressed by following equation (4.1) [297]:

$$w = w_{\max} - \frac{(w_{\max} - w_{\min})}{iter_{\max}} \times iter \qquad (4.1)$$

wherein $iter_{\max}$ denotes highest numbers of iterations also *iter* presents current number of iterations.

Step 4: (Velocity updation): During searches of globally bests as well as individually bests within every particulates, j^{th} particulate velocities within k^{th} dimensions being upgraded as follows [298]:

$$v_{j,k}(t) = w(t)v_{j,k}(t-1) + c_1 r_1 (x_{j,k}^{*}(t-1) - x_{j,k}(t-1)) + c_2 r_2 (x_{j,k}^{**}(t-1) - x_{j,k}(t-1)) \qquad (4.2)$$

wherein c_1 , c_2 presents constant, also r_1 as well as r_2 present uniform distributed random number within [0,1]. Here, this can be mentioned, secondary component denotes cognitive term within PSO whereby particulates change position upon self thinkings as well as experience. Last component presents social-segment of PSO whereby particles change velocities upon socially-psychologically adaptating informations obtained from experiences of neighbouring particles.

Step 5: (Position updation): After obtaining upgraded velocities, every particulate change own positions as follows [298]:

$$x_{j,k}(t) = v_{j,k}(t) + x_{j,k}(t-1) \tag{4.3}$$

Step 6: (Individual-best update): Every particulate being assessed as per its new positions. When $J_j < J_j^*, j = 1,2,........, n,$ updating individuals bests in $X_j^*(t) = X_j(t)$ as well as $J_j^* = J_j$; proceed in stage 7.

Step 7: (Global best update): Searching of minimum values $J_{\min}$ among J_j^* wherein min presents indexes for particulate possessing minimum O.F., $\min \in \{j, j = 1,2,........, n\}$. When $J_{\min} < J^{**}$, updating global best in $X^{**}(t) = X_{\min}(t)$ also $J^{**} = J_{\min}$ proceed in stage 8.

Step 8: (Stop conditions): Whenever number for iteration reaches highest limitation then "STOP."

4.2.1. Time varying acceleration coefficient PSO (TVAC PSO)

Accelerating co-efficients c_1 as well as c_2 are fixed in classical PSO. Within upgraded PSO including TVAC-PSO [299] accelerating co-efficients c_1, c_2 are modified. Acceleration co-efficient c_1 is illustrated in following:

$$c_1 = c_{1f} - c_{1i} \times \frac{iter}{iter_{\max}} + c_{1i} \tag{4.4}$$

Similarly, acceleration co-efficient c_2 is illustrated in following [299]:

$$c_2 = c_{2f} - c_{2i} \times \frac{iter}{iter_{\max}} + c_{2i} \tag{4.5}$$

$iter$ denotes present numbers of iteration, $iter_{\max}$ is maximum numbers for iterations. c_{1i} as well as c_{2i} represents starting value wherein c_{1f} as well as c_{2f} represents final value for cognitive also social acceleration factor. Generally, limits of c_{1i} as well as c_{1f} are within 2.5 upto 0.5, whereas c_{2i} and c_{2f} remain within 0.5 to 2.5.

4.2.2. Exponential decreasing Inertia weight PSO (EDW PSO)

Inertia weight is criterion which regulates influences for preceding velocities over present attained velocities. This maintains balances of globally & locally exploring abilities within searching spaces. Within beginning processes for search, higher inertia weight is used for enhancing globally explorating abilities whereas in terminating states; inertia weight gradually diminished in enhancing locally explorating abilities.

In Exponent Decreasing Inertia Weight Particle Swarm Optimization [300] inertia weight given in equation (4.6) [301].

$$w = (w_{ini} - w_{end} - d_1)\exp(\frac{1}{1 + d_2 t / t_{\max}}) \qquad (4.6)$$

where $t_{\max}, t, w_{ini}, w_{end}$ presents highest interval count, current time, starting values for inertia weight as well as terminating values for inertia weight. Figure 4.1 illustrates variations in inertia weight with number of iterations.

In above equation, d_1 and d_2 represents control factor to control w between w_{ini} and w_{end}. Thus particle swarm optimization with exponent decreasing inertia weight (EDW PSO) [301] is obtained. Several trial runs shows algorithms performances enhances when $w_{ini} = 0.95, w_{end} = 0.4, d_1 = 0.2, d_2 = 7$.

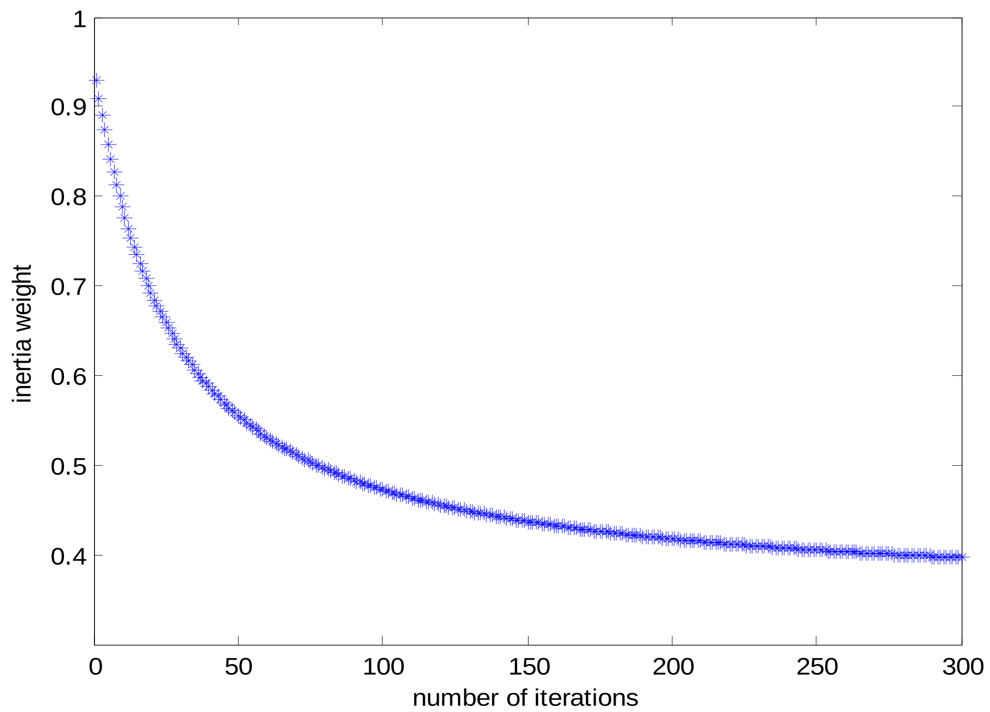


Figure 4.1. Exponent decreasing inertia weight with iterations

4.2.3 Non linear decreasing inertia weight PSO (NDIW PSO)

Huang Chongpeng [302], [303] provided novel methodology for PSO with non-linear decreasing inertia weight.

$$w_0 = w_{end} + (w_{end} - w_{start}) \times (1 - (t / t_{\max})^{k_1})^{k_2} \tag{4.7}$$

Wherein k_1, k_2 denote natural numbers, w_{start} presents starting inertia weight, w_{end} is endmost value for weighting-co-efficient, $t_{\max}$ is highest numbers for iterations also t denotes present iteration. Specified values for k_1, k_2 utilized are $k_1 > 1$ and $k_2 = 1$. Figure 4.2 shows Non linear decreasing inertia weight with iterations.

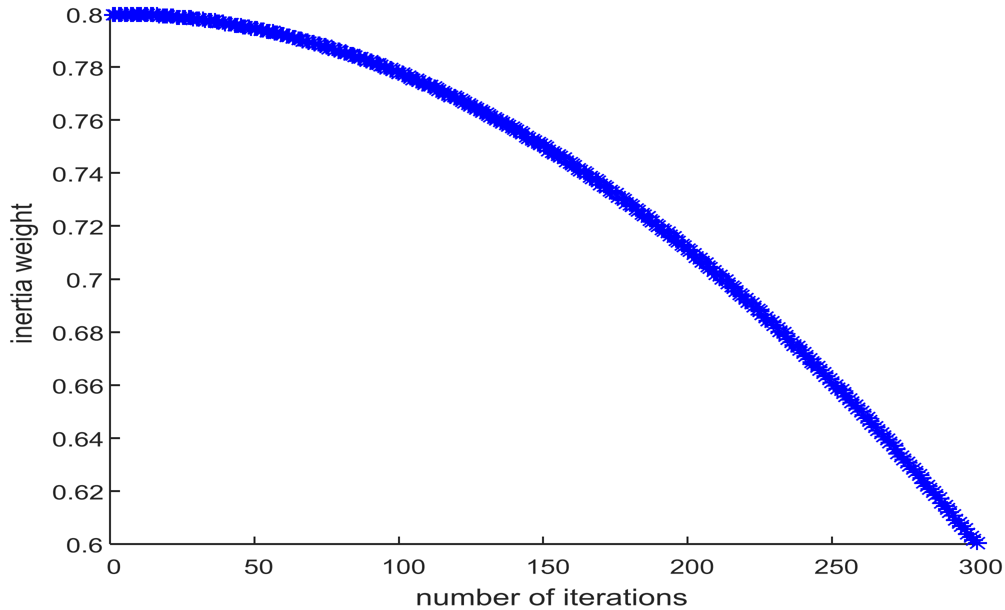


Figure 4.2. Non linear decreasing inertia weight with iterations.

4.2.4. Dynamic inertia weight PSO (DIW PSO)

Authors in [304] utilized subsequent formulation for setting inertia weight which yielded superior results.

$$w(t) = 0.9 - (\frac{t}{\max_t}) \times 0.5 \tag{4.8}$$

where *w(t)* represents inertia weight, *t* presents time count, $\max_t$ presents maximum time count.

4.3. Flower Pollination Algorithm (FPA)

FPA [305] gets inspiration from pollinating processes within flowering trees. X. S. Yang firsthand suggested this method [306] also henceforth obtained broad applicability for resolving diverse optimizational problem. The main forms in pollinations: abiotic as well as biotic [307].

4.3.1. Flower Pollination in nature

Pollination in flowering trees being interesting processes within environment. Evolution characteristic of flower pollination is utilized in designing flower pollination algorithm. Nature solves many challenging problems over course of time and several natural system evolved alongwith highly efficienct strategies for maximizing objective of reproductions. On successful features within natural system, several nature-motivated algorithm has evolved [308], [309], i.e., take instance of algorithm such as genetic algorithm draw its inspiration from Darwin's evolutional theories [310] also PSO algorithm upon swarms behaviours within bird's as well as fishes [311], [312], bats algorithms upon echolocating behaviours in micro bats [313], firefly algorithm on flash lighting pattern in tropical fire-flies [314].

Within various designing application amidst field of technology as well as industries one intend in finding optimum solutions for formulated problems due to high complexity constraint. Constrained optimizational problem being non linear and obtaining optimum solution remains challenge. Conventional optimization never suited for problems with non linearity and multi modality. Current trend focuses on use of nature inspired meta-heuristic techniques in solving these types of critical problem; also meta-heuristics being extremely effective. Meta-heuristic literature has expanded tremendously in past decades [308], [309].

For constructing flower pollination algorithm main characteristics of flower pollination are idealized into rules. Flower pollination conceptualization with respect to bees as well as floral traits analysed within [315]. Flowering-trees began in dominating landscapes starting at Cretaceous times [316], [317]. Figure 4.3 shows flower pollination in nature.

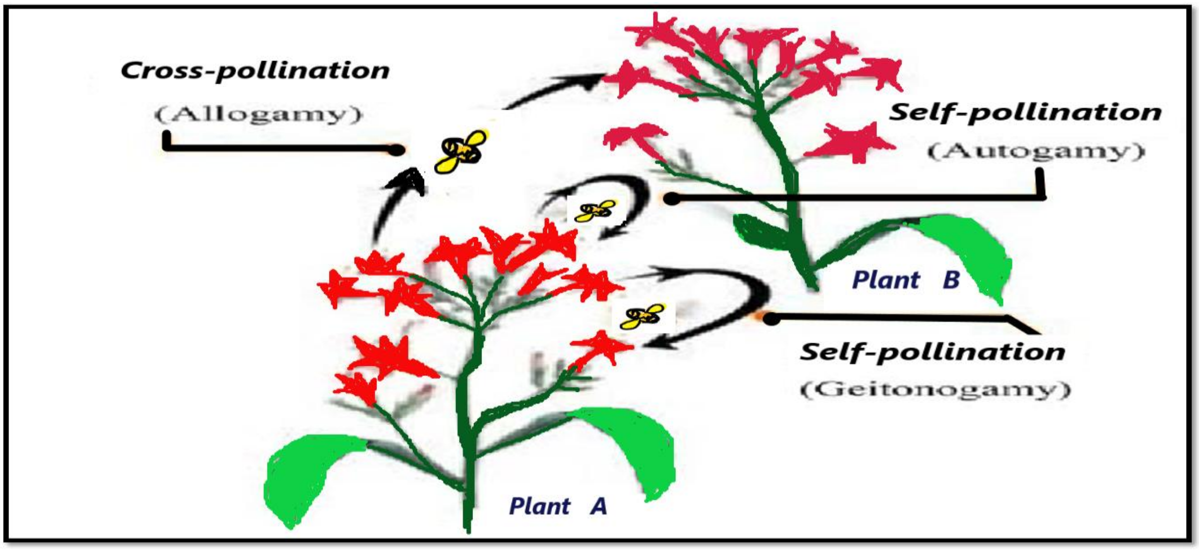


Figure 4.3. Flower pollination in nature

Pollination is natural phenomenon which constitutes transferring pollen's from anther to stigma. Main aim for flowers is reproduction by means of pollination. Flower pollination correlates with transfer of pollens; such transfers being linked with pollinators like insects, birds, bats etc.

Pollinations are of two main types: abiotic as well as biotic. Approximately 90% flowering plants depending upon biotic-pollinating processes, whereby pollens are transmitted with pollinator. Approximately 10% in pollinations follow abiotic-forms which doesnt requires pollinator. Air as well as water-diffusions helps for pollinating processes for these flowered trees [318], [319]. Pollinations obtained with self-pollinations or cross-pollinations. Self-pollinating indicates pollinating in one flower with pollens of that particular flower's. Cross-pollinations are pollinations with pollens of flowers in different plant.

Honey bees are pollinators as well as initiate flowers constancy concept [320]. Such pollinator visits exclusively specific flowering trees and ignoring others flowering plants. Phenomenon of flowering constancies possesses evolution benefits as it maximizes transferring pollens into same tree, also maximized reproduction-chances for particular flowering tree.

4.3.2. Flower Pollination Algorithm (FPA) Steps

The FPA comprises subsequent stages/rules:

1) Biotic as well as cross pollinations denote globally pollinated phenomenon whereby pollens carrying pollinator conduct L´evy flights.

2) Abiotic, self-pollinations denote locally pollinated phenomenon.

3) Flower constancies being triggered with insects, in parity to reproduction probabilities proportional to similarities within two flowers considered.

4) Locally as well as globally pollinated phenomenon being governed with switching probability p .

The fittest represented as g_*. Globally pollinating i.e., first-hand rule along flowering constancies being illustrated by following equation [306]:

$$x_i^{t+1} = x_i^t + L(x_i^t - g_*) \tag{4.9}$$

wherein x_i^t presents pollen's i / vectors x_i within iterations t, g_* illustrates superior solution. L, illustrates pollinations strengths which denotes step-sizes also computed by following equation (4.10) [306].

$$L \approx \frac{\lambda\Gamma(\lambda)\sin(\pi\lambda/2)}{\pi}\frac{1}{s^{1+\lambda}}, (s >> s_0 > 0) \tag{4.10}$$

$\Gamma(\lambda)$, is typical gamma function. Distributions possess validity within larger steps $s > 0$. Selected $\lambda = 1.5$, secondary criterion along flowering constancies denoted within subsequent equation (4.11) [306].

$$x_i^{t+1} = x_i^t + \in (x_j^t - x_k^t) \tag{4.11}$$

x_j^t, x_k^t, represents pollens in separate florescence within same tree genus, that mimic flowering constancies in specific neighbourhood. x_j^t, x_k^t , obtained at similar species / same populations, which form locally random-walks. $\in$, obtained within uniform-distributions amidst [0, 1]. Globally as well as locally pollinated criterion executed by utilizing switching probability (rule 4) p.

4.3.3 Pseudo code of FPA

Objective $\min f(x), x = (x_1, x_2, \ldots\ldots\ldots, x_d)$

Initializing populations for N flower's/ pollen-gamete's with random solves

Obtain superior solve g_* within initialized populations

Defining: Switching-probability $p \in [0,1]$

While (t<max-generation)

for $i = 1 : N$ (total N flowers in Populace)

if $rand < p$,

Define (d-dimensioned) step vector L that follows L´evy distribution

Global- Pollinations; $x_i^{t+1} = x_i^t + L(x_i^t - g_*)$

Else:

Define $\in$ within uniformly distributions [0, 1]

Random choosing j & k among total Solves;

Locally Pollinated; $x_i^{t+1} = x_i^t + \in (x_j^t - x_k^t)$

End if:

Compute Newer Solutions

When newer solutions being excellent; Updating them within populations;

End for

Finding present Superior Solve: g_*

End: While.

4.4 Improved Flower Pollination Algorithm (IFPA)

The observation of random selectivity in exploration and exploitation phase devised upon chosen resultant in switch probabilities caused FPA losing direction's thus moving further from global-best solve. To achieve best solution, various improvements proposed in the flower pollination algorithm. The improvements to the standard flower pollination algorithm are as follows [321], [322]:-

(i) Utilizing adaptive switch probability which helps to establish balance between exploitation and exploration capability of FPA.

$$P^{t+1} = P_{max} - \frac{t}{T}(P_{max} - P_{min}) \tag{4.12}$$

P_{min} as well as P_{max} denote low as well as higher bounds for P . The value of P_{max} is set to 0.6 whereas P_{min} is 0.4. These values indicate high global search at the initial generations whereas higher local search during end.

(ii) Simulate global pollination which improves exploration phase of the algorithm and done by following equation (4.13).

$$x_i^{t+1} = x_i^t + L(g_* - x_i^t) \times U(-1,+1) \tag{4.13}$$

where $U(-1,+1)$ generates uniform random number within range (-1, +1). $U(-1,+1)$, includes a random deviation with previous location of flower x_i^t which increases search around the search space.
After that researcher propose a two-layer improvement in local pollination.

(iii) Formulate first layer improvement in local-pollination-stage by equation (4.14).

$$x_i^{t+1} = x_i^t + r_1.\exp(-d_{ij}^m).(x_i^t - x_j^t) + r_2 \tag{4.14}$$

where r_1 presents uniform random variable within range [0, 1], d_{ij} denotes Euclidean distance between solutions x_i and x_j, $m \in [0,2]$ represents non-negative number, that adjusts importance of distance d_{ij}, and r_2 presents uniform random number within the range [-1,+1], d_{ij} is represented as follows:

$$d_{ij} = \| X_i - X_j \| \tag{4.15}$$

Again, in equation (4.14), when $m = 0$, implies that influence of flower x_j on x_i is same at any distance. Whenever, *m* increases, effect of flower x_j decreases.

(iv) Formulate second layer improvement in local-pollination-stage by scale factor F for mitigating variations within flowers.

$$X_i^{new} = X_i^{old} + F\left(X_j^{old} - X_k^{old}\right) \quad (4.16)$$

where F is scaling factor.

(v) Incorporate additional thorough exploitation stage for improving best solve.

$$X_i^{new} = X_{best} + [(rand_3 - rand_4) \times X_{best}] \quad (4.17)$$

Thorough Exploitation of best flower is performed by equation (4.17).

- *Pseudo code of IFPA*

Generating initial population for flowers/pollen with min/ max limit
Evaluating fitness for individual pollen; obtain best pollen X_{best}

State switching probability $P^{t+1} = P_{\max} - \frac{t}{T}(P_{\max} - P_{\min})$

-while- (t<iter_max)
-for $i = 1 : N_p$
If $rand_1 > p$
Represent step vector L *for* N_G *dimension obeying L´evy distribution*

$x_i^{t+1} = x_i^t + L(g_* - x_i^t) \times U(-1,+1)$ *(Global pollination)*
else

$x_i^{t+1} = x_i^t + r_1.\exp(-d_{ij}^m).(x_i^t - x_j^t) + r_2$ *(Local pollination-First stage improvement)*

$X_i^{new} = X_i^{old} + F\left(X_j^{old} - X_k^{old}\right)$ *: where F is scaling factor. (Local pollination Second stage improvement)*

End
End

for $i = 1 : N$

If $rand_2 > p$
$X_i^{new} = X_{best} + [(rand_3 - rand_4) \times X_{best}]$ *(Thorough Exploitation of best flower)*

End

End

Evaluate new solve

If new solution is found to be upgraded, update population

End
Obtain best solve X_{best}
End

- *Development of Proposed Algorithm*

Like any other evolutionary algorithm, the success of proposed method (IFPA) is heavily dependent on setting of control parameters and the methods of constraints handling. It is important to discuss these two issues before applying the proposed algorithm to the problem under consideration.

- *Initialization Process of Algorithm*

Population P comprises of N_p individuals. Every individual denotes decision variables. In this study, total number of iterations are taken as 300 and initial population size of 30.

4.4.1 Meta-dynamic approach based Flower Pollination Algorithm

Formulated meta-dynamic FPA improves normal FPA that use meta-dynamic feature motivated from clonal selection algorithm. Meta-dynamic steps initialized that increase populace diversities i.e., when superior solutions doesnt changes in successively 100 iterations, having values not higher than 10^{-6} so keeping superior solutions whereby replacing populations with newer random produced ones. Such modifications denotes concepts whenever no improvements for solutions being noticed in times for evaluating, improved meta-heuristics obtains superior solves achieved at previous populations as well as replace entire populace and as consequence newer populace being produced [323], [324].

4.4.2 Pseudo code of Meta-dynamic approach based Flower Pollination Algorithm

Objective $\min f(x), x = (x_1, x_2, ..., x_d)$

Initializing populations - n flowers/ pollens possessing randoms solves

Finding superior solve g_* *within starting populations*

Defining switching probability $p \in [0,1]$

While (t<MaxGeneration)

For $i = 1:n$ *(total n flowers amidst populations)*

If rand<p,

Defining (d-dimensioned) step vector L *which obeys L´evy distribution*

Globally pollinated; $x_i^{t+1} = x_i^t + L(g_* - x_i^t)$

else

Define $\in$ *for uniform distributions in [0, 1]*

Random selection of j *as well as* k *amidst total solves;*

Locally Pollinated; $x_i^{t+1} = x_i^t + \in (x_j^t - x_k^t)$

End if

Evaluation of fresh solutions

If new solution's superior, updating them within populations;

end for

Finding current superior solves g_*

Meta-dynamic approach-When g_* *doesn't changes in successively 100 iterations, possessing value's not higher from 10*$^{-6}$*,*

Keeping g_* *as well as replacing populace with newer random generated ones.*

gen=gen+1,

Ending while

Output of superior solve obtained

4.5. Single objective optimization

Single objective optimizations [325] are computed in following [326]:

$$\begin{aligned} &\min\ f(x_l), l = 1,2,.........., L \\ &subject\,to \qquad g_j(x_l) \leq 0 \qquad j = 1,...., J \\ &\qquad\qquad\qquad h_k(x_l) = 0 \qquad k = 1,....., K \\ &\qquad\qquad\quad x_{l,\min} \leq x_l \leq x_{l,\max} \end{aligned} \tag{4.18}$$

wherein x_l present L parameter's $x_1, x_2,..............., x_L$; g_j as well as h_k present J equalities $(J \geq 0)$ as well as K inequalities $(K \geq 0)$ constraint's also $x_{l,\min}$ as well as $x_{l,\max}$ denote low as well as high limit's for parameters.

4.6. Multi-Objective optimization (MOO)

MOO contains different inconsistent objective function (O.F.) also equalities as well as inequality constraints which need to be optimized [75], [271], [327], [328].

$$\begin{aligned} &\min \quad F(\overline{X}) = [f_1(\overline{X}), f_2(\overline{X}),........, f_N(\overline{X})]^T \\ &subject \quad to: \\ &g_i(\overline{X}) \leq 0 \quad i = 1,2,,......, N_{ueq} \\ &h_i(\overline{X}) = 0 \quad i = 1,2,........, N_{eq} \end{aligned} \tag{4.19}$$

Space amidst wherein O.F. being defined termed objective-spaces. Within MOO two solves will possess two diverse values; no solutions dominating others, illustrated within following equation [75], [271]:

$$\forall j \in \{1,2,....,n\}, \quad f_j(\overline{X}_1) \leq f_j(\overline{X}_2) \tag{4.20}$$
$$\exists k \in \{1,2,....,n\}, \quad f_k(\overline{X}_1) < f_k(\overline{X}_2)$$

4.6.1. Multiobjective Flower Pollination Algorithm (MOFPA)

MOFPA [318] comprises subsequent stages/rules:

1) Biotic as well as cross pollinations denote globally pollinations whereby pollens carrying pollinator conduct L´evy flights.

2) Abiotic, self-pollinations denote locally pollinated phenomena.

3) Flower constancies being triggered with insects', in parity to reproduction probabilities proportional to similarities within two flowers considered.

4) Locally as well as globally pollinated phenomena governed with switching probability p .

The fittest represented as g_*. Globally pollinating i.e., first-hand rule along flowering constancies being illustrated by following equation [318]:

$$x_i^{t+1} = x_i^t + \gamma L(\lambda)(x_i^t - g_*) \tag{4.21}$$

Wherein x_i^t presents pollen's i/ vectors x_i within iterations t, g_* illustrates superior solution. γ, presents scaling factor to control step size $\gamma = 0.1$. L, illustrates pollinating strengths computed by following equation [318].

$$L \approx \frac{\lambda \Gamma(\lambda) \sin(\pi\lambda/2)}{\pi} \frac{1}{s^{1+\lambda}}, (s >> s_0 > 0) \tag{4.22}$$

$\Gamma(\lambda)$, is typical gamma function. Distributions possess validity within larger steps $s > 0$. Selected $\lambda = 1.5$. Secondary criterion along flowering constancies denoted within subsequent equation (4.23) [318].

$$x_i^{t+1} = x_i^t + \in (x_j^t - x_k^t) \tag{4.23}$$

x_j^t, x_k^t, represents pollens in separate florescence within same tree genus, that mimic flowering constancies in specific neighbourhood. x_j^t, x_k^t , obtained at similar species' / same populations, which form locally random walks. $\in$, obtained within uniform-distributions of [0, 1]. Globally as well as locally pollinated criterion executed by utilizing switching probability (rule 4) p .

4.7. Meta-dynamic approach based Multi-objective FPA (MMOFPA)

Meta-dynamic approach based Flower Pollination Algorithm is described in Section 4.4.1. Multiobjective Flower Pollination Algorithm (MOFPA) is illustrated in Section 4.6.1. Multi-objective optimization with concept of dominated, non-dominated solution, Pareto optimal set and fuzzy membership function is described in Section 3.2.3.2. Figure 4.4 shows microgrid optimization model utilizing MMOFPA.

- **Development of Proposed Algorithm**

In present research, Meta-dynamic approach based Multi-objective Flower Pollination Algorithm that being utilized for implementing generating schedules within microgrids illustrated. Computations within Meta-dynamic approach based Multi-objective Flower Pollination Algorithm heavily depend upon decision-variables & constraint managing mechanism. Initialized input within devised algorithm is taken from [271].

- **Initialization process of algorithm**

Populace P consists of N_p individuals. Every individual represents decision-variables as well as within current formulations, this being produced wattage at DGs as well as storages, amounts for trade-offs wattages to grids, quantities for load-demand curtailments within demand response programs.

Afterwards initializing processes, power dispatching technique, being applied in every produced population, subsequently fitnesses are computed. Figure 4.4 illustrates microgrid optimization model by MMOFPA. In this work microgrid network consisting of FC, micro-turbine, PV, WT as well as battery are studied. A low voltage (LV) microgrid (MG) is taken in applying suggested method. Network information as well as detailed incentives schemes provided for diverse customers categories [271]. At starting of program, necessary inputs information should be given accurately. These informations include: microgrid configuration, operating characteristic for DGs as well as utility, forecasted powers for WT as well as PV in day-aheads, hourly bids in DGs as well as utility, O.F. also MG 24 hr loads profile. This being presumed that total DGs produces real-power in unity power factor; neither absorbing nor produces reactive-power. Figure 4.5 illustrates flowchart for power dispatch technique. Figure 4.6 represents flowchart of MMOFPA.

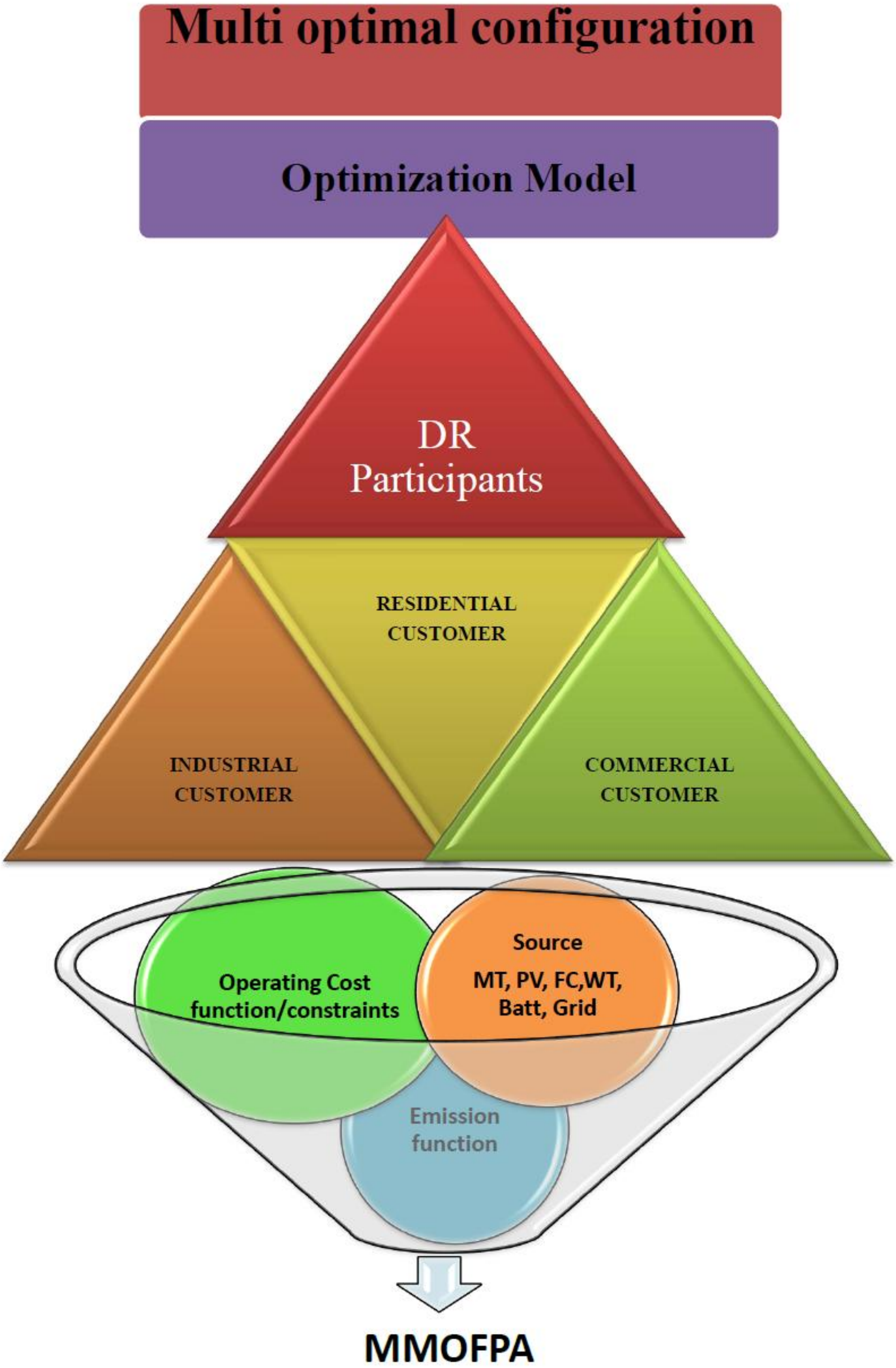


Figure 4.4. Microgrid optimization model by MMOFPA

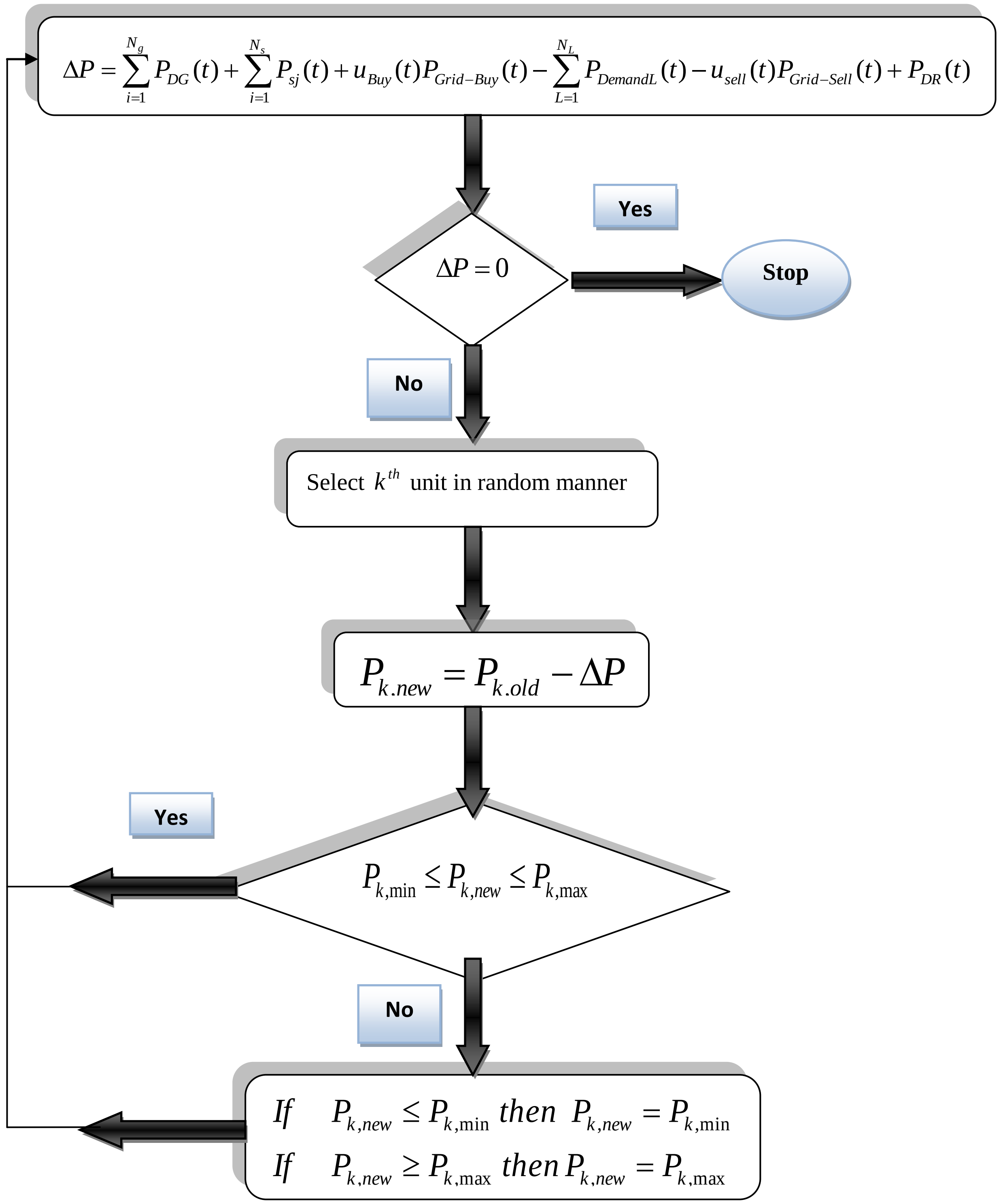


Figure 4.5. Flowchart for power dispatch technique

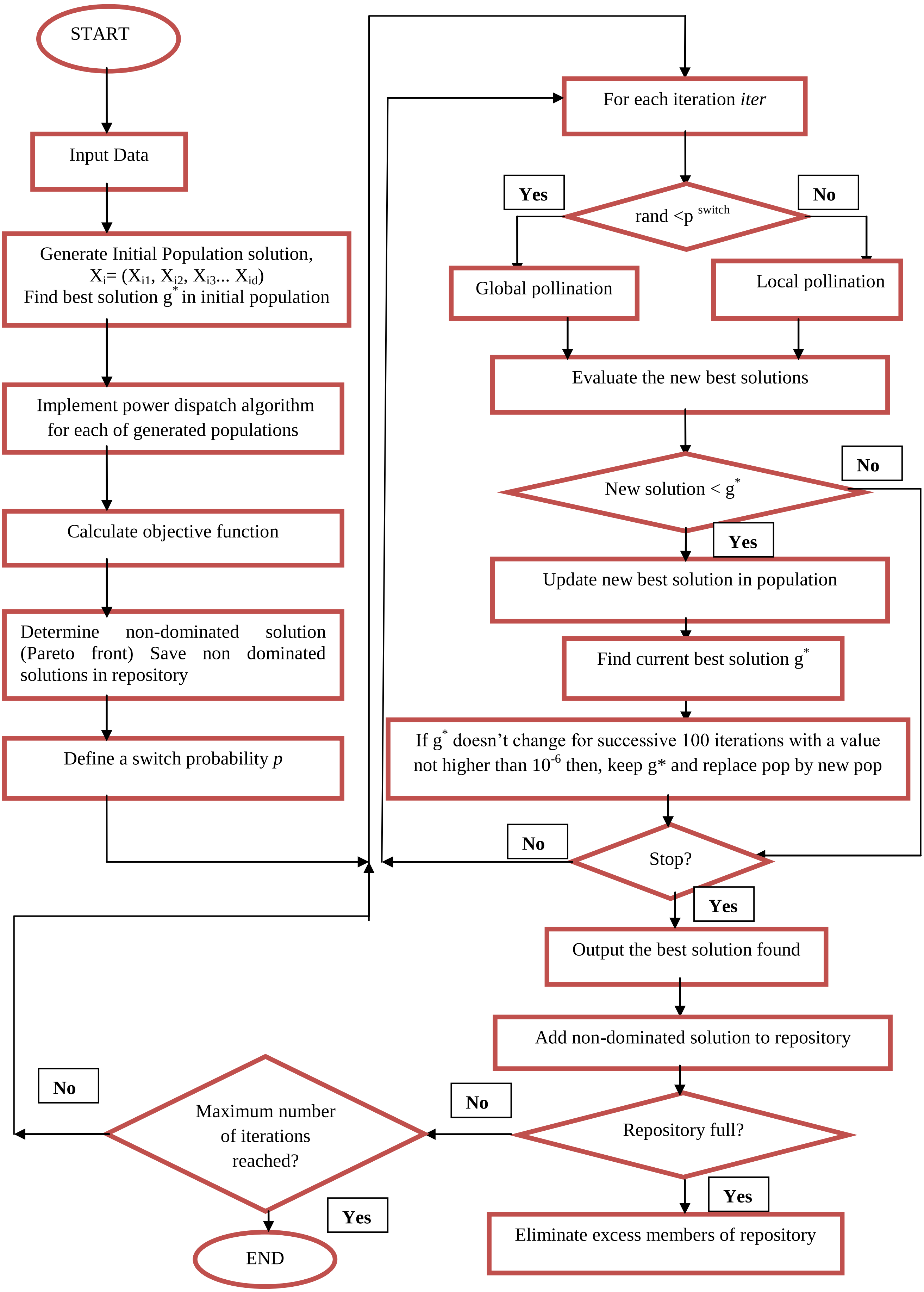


Figure 4.6. Flowchart-MMOFPA

4.8 Multiobjective Modified Personal Best Particle swarm optimization (MMPBPSO)

PSO is described in Section 4.2. Multi-objective optimization with concept of dominated, non-dominated solution, Pareto optimal set and fuzzy membership function is described in Section 3.2.3.2.

- *Concept of Multiobjective Modified Personal Best Particle swarm optimization (MMPBPSO)*

Within PSO, wherein new particulates being unacceptable within step of *Pbest* updates, it is immediately included into populace & utilized by succeeding populace. Within MMPBPSO, where-ever new particulates being unacceptable within stage for *Pbest* updates, these being replaced by new particulates in succeeding populace. Such technique is significant for improvement in performances for PSO technique whereby attaching fresh particle into populaces replacing inferior particulates [329] and illustrated in following:

If $fit(X_{i,NV}^{t+1}) < fit(Pbest_{i,NV}^{t})$ *then,*

$$Pbest_{i,NV}^{t} = X_{i,NV}^{t+1}$$

else if $rand[0,1] > P_c$ *then,*

for $j = [1, NV]$ *then,*

$$X_{i,j}^{t+1} = (\phi_1 \times Gbest + \phi_2 \times Pbest_{i,j}^{t}) + c_1 \times rand[0,1] \times (Gbest - X_{i,j}^{t})$$

Amend $X_{i,j}^{t+1}$ *between* LB_j *and* UB_j

end

else

for $j = [1, NV]$ *then,*

$$X_{i,j}^{t+1} = (\phi_2 \times Gbest + \phi_1 \times Pbest_{i,j}^{t}) + c_2 \times rand[0,1] \times (Pbest_{i,j}^{t} - X_{i,j}^{t})$$

Amend $X_{i,j}^{t+1}$ *between* LB_j *and* UB_j

end

if $fit(Pbest_{i,NV}^{t}) < fit(Gbest)$ *then,*

$$Gbest = Pbest_{i,NV}^{t}$$

end.

Here, $\phi_1 + \phi_2 = 1$ whereas P_c presents constant numeral & being chosen within [0.1, 1]. For simulation, parameters utilized are as: $c_1 = 2, c_2 = 2, w_{\max} = 0.9, w_{\min} = 0.4.$

Next chapter presents results and discussions of three test systems.

Chapter 5 RESULTS AND DISCUSSIONS

TEST SYSTEM 1: Grid connected microgrid system including renewable energy resources

Meta-dynamic approach

System Data

Energy management in microgrid system for cost minimization utilizing meta-dynamic approach based TVAC-PSO

Energy management in microgrid system for emission minimization utilizing meta-dynamic approach based TVAC-PSO

Energy management in microgrid system for cost minimization utilizing meta-dynamic approach based FPA with adaptive switch probability

Energy management in microgrid system for emission minimization utilizing meta-dynamic approach based FPA with adaptive switch probability

Multi objective energy management for cost & emission minimization utilizing Meta-dynamic approach based Multi objective Flower Pollination Algorithm with adaptive switch probability

TEST SYSTEM 2: Modified IEEE 33 bus system
Energy management of multi microgrid smart distribution network
Multilayer Energy Management System (MEMS)
Layer 1: MG Optimization
Layer 2: SDN Optimization
Simulation and Results

TEST SYSTEM 3: Energy Management System of Multi-Microgrid based Smart Distribution network with power flow constraints using Improved Flower Pollination Algorithm (IFPA)
Overview
Day ahead Energy management scheduling of individual entity
Defining decision variables
Simulations and Results

CHAPTER-5

RESULTS AND DISCUSSIONS

In this chapter, detailed analysis on cost and emission optimization of grid connected microgrid system including renewable energy resources is carried out for test system 1, cost and loss/benefit optimization of multi microgrid based smart distribution network is carried out for test system 2, security constrained energy management system wherein effect of congestion as well as inclusion of tie-lines is carried out for test system 3.

In Test System 1, shown in Figure 3.1, the microgrid (MG) network possesses resources like photovoltaic (PV) array, wind turbine (WT), micro turbines (MT), fuel cells (FC) and battery where incentive based demand response programs (DRPs) being used for covering uncertainty linked with renewable energy resources. Here, power provided for customers in 24 hour time. Simulations performed on test system utilizing MATLAB software.

5.1. TEST SYSTEM 1: Grid connected microgrid system including renewable energy resources

Objective of energy management in microgrid network denotes optimized operation of systems where efficient schedule used for minimizing operating cost. Microgrid includes WT as well as PV power generation with stochastic natural behaviour with environmental uncertainties where incentive based DRPs applied. Also emission minimization considered as single objective optimization. Subsequently cost and emission optimization carried out as multiobjective formulation.

5.1.1. Meta-dynamic approach

Suggested method on Particle Swarm Optimization (PSO) algorithm modifies standard algorithm which utilizes meta-dynamic property [323], [324] viz., when final solution remains unchanged in 100 iterations, having values not higher from 10^{-6} keeping best solution whereas replacing populations with newer random generated populations.

Energy management and generation scheduling are carried out using several optimization algorithms such as meta-dynamic approach based Time Varying Acceleration Coefficient Particle Swarm Optimization (TVACPSO), meta-dynamic approach based Non linear Decreasing Inertia Weight Particle Swarm Optimization (NDIWPSO), meta-dynamic approach based Exponential Decreasing Inertia Weight Particle Swarm Optimization (EDWPSO), meta-dynamic approach based Dynamic Inertia Weight Particle Swarm Optimization (DIWPSO), meta-dynamic approach based Flower Pollination Algorithm (FPA) with adaptive switch probability.

Simulations performed on test system comprise of PV, WT, schedulable distributed generators (DG) and Energy Storage System (ESS) as illustrated below.

5.1.1.1. System Data

System data presented for microgrid system where implementation of meta-heuristic techniques are performed.

Microgrid system in which demand response (DR) programs are carried out is shown in Figure 3.1. This consists of 30 kW micro-turbines, PV of capacities 25 kW, battery possessing capacity 30 kW, and Fuel-cells for 30 kW also wind power generations for 15 kW. Figure 5.1 presents incentives [271] offered.

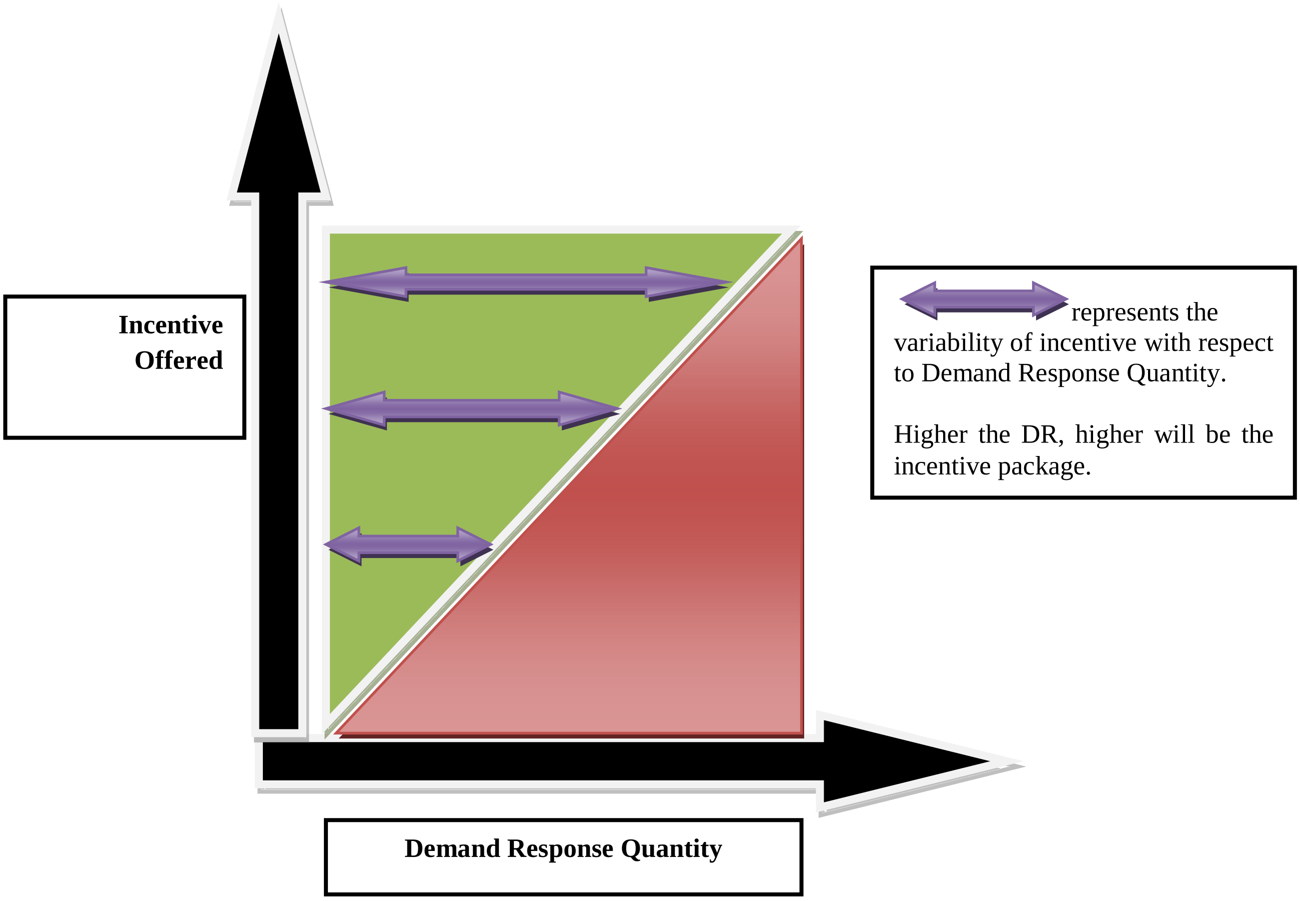


Figure 5.1. Schematic representation in incentive packages proposed w.r.t DR quantities.

The MG which is considered in this research work comprises of different generating as well as storages viz., micro-turbines, fuel-cells, batteries, as well as renewable energy sources including PV, WTs. Table 5.1 presents capacities in power productions for generations as well as storages within MG. Table 5.2 illustrates price quantity offered packages in residential, commercial, industry based consumer, Table. 5.3 represents bid co-efficient, start-up/shutdown costs & emission co-efficient; Table 5.4 describes residential, commercial, industrial load in 24 hours, Table 5.5 denotes forecasted values for WTs and PVs, Table 5.6 presents real-time market prices in 24 hours, Table 5.7 illustrates load demands including DR implementations and Table 5.8 presents load demands without DR implementations. The CO_2, SO_2 and NO_x emissions from grid are 950 kg/MWh, 0.5 kg/MWh and 2.1 kg/MWh respectively.

Table.5.1. Capacities of Power Productions in DGs

Unit	Generations; storages	Min. powers (kW)	Max. powers (kW)
1.	M.T.	6.0	30.0
2.	F.C.	3.0	30.0
3.	Battery	-30.0	30.0
4.	PV.	0.0	25.0
5.	WT.	0.0	15.0
6.	Utility	-30.0	30.0

Table 5.2. Prices Quantity offered packages in residential's, commerce, industry based consumer

Store's values DRPs	33% of total responses	66% of total responses	100% of total responses
Energy costs(€cts/kWh)	2.50	3.50	4.50

Table.5.3. Bid Co-efficient, Start-up/shutdown costs & emission co-efficients

Unit	Generations; storages	Bids (€cts/ kWhr)	Start-up/ Shut-down costs(€cts)	CO_2 (kg/MWh)	SO_2 (kg/MWh)	NO_x (kg/MWh)
1.	Micro-turbines	0.4570	0.9600	720	0.0036	0.1000
2.	Fuel-cells	0.2940	1.6500	460	0.0030	0.0075
3.	Batteries	0.3800	0.0000	10	0.0002	0.0010
4.	PVs	2.5840	0.0000	0.0000	0.0000	0.0000
5.	WTs	1.0730	0.0000	0.0000	0.0000	0.0000

In this proposed system 3 separate feeder viz., residence based, trade-commerce also industry consumers are considered [271]. Assuming reactive power necessary for load compensated locally with capacitor placements in appropriate buses. Cumulative load-demands (within 24 hours neglecting DR participations for responsive-load) are 1704.68 kW also load demands (including DR participations for responsive-load) are 1702.92 kW. The values of $\pi_{r,t}$, $\pi_{c,t}$ and $\pi_{i,t}$ in equations (3.1), (3.2) and (3.3) are $2.5 \in ct/kWh$, $3.5 \in ct/kWh$ and 4.5 $\in ct/kWh$ respectively.The values of maximum charging and discharging powers are $P_{csj}(t)$ =100% and $P_{Dsj}(t)$ = 10%, and efficiencies during discharge and charge are λ_{Dj} = λ_{Cj} = 94% as expressed in equation (3.14). After several trial runs, the values of penalty factors in equation (3.20) are found to be $\lambda_p = \lambda_{ps} = \lambda_u = \lambda_{us}$ =10^5.

Table 5.4 Residential, Commercial, industrial load in 24 hours

Hours	Residential load(kW)	Commercial load(kW)	Industrial load(kW)
1	16.00	8.00	25.42
2	16.93	8.69	25.59
3	17.18	9.00	26.18
4	18.12	9.03	28.73
5	19.98	9.80	31.95
6	21.51	11.07	35.60
7	24.48	12.09	37.98
8	25.59	12.94	38.40
9	26.27	13.19	40.27
10	26.30	13.70	39.17
11	26.86	13.28	37.38
12	24.91	12.60	36.36
13	24.31	12.34	36.53
14	25.16	12.43	38.57
15	26.43	13.02	41.37
16	27.79	13.62	40.44
17	29.23	14.47	42.98
18	28.80	15.15	44.51
19	29.23	15.06	45.36
20	29.57	15.23	44.00
21	25.03	14.72	39.34
22	24.78	13.37	35.69
23	22.49	12.09	33.05
24	19.35	9.80	28.73

Table 5.5: Forecasted values for WTs and PVs

Hours	WTs (kW)	PVs(kW)	Hours	WTs (kW)	PVs(kW)
1.	1.7850	0.0000	13.	3.9150	23.9000
2.	1.7850	0.0000	14.	2.3700	21.0500
3.	1.7850	0.0000	15.	1.7850	7.8750
4.	1.7850	0.0000	16.	1.3050	4.2250
5.	1.7850	0.0000	17.	1.7850	0.5500
6.	0.9150	0.0000	18.	1.7850	0.0000
7.	1.7850	0.0000	19.	1.3020	0.0000
8.	1.3050	0.2000	20.	1.7850	0.0000
9.	1.7850	3.7500	21.	1.3005	0.0000
10.	3.0900	7.5250	22.	1.3005	0.0000
11.	8.7750	10.4500	23.	0.9150	0.0000
12.	10.4100	11.9500	24.	0.6150	0.0000

Table 5.6: Real time market prices

Hours	Price (€cts/kWhr)
1	0.23
2	0.19
3	0.14
4	0.12
5	0.12
6	0.20
7	0.23
8	0.38
9	1.50
10	4.00
11	4.00
12	4.00
13	1.50
14	4.00
15	2.00
16	1.95
17	0.60
18	0.41
19	0.35
20	0.43
21	1.17
22	0.54
23	0.30
24	0.26

Table 5.7: Load demands including DR Implementation

Hrs.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
Loads (kW)	54.110	52.070	52.330	59.780	62.100	62.620	73.910	71.620	72.390	73.430	74.210	71.660
Hrs.	13.	14.	15.	16.	17.	18.	19.	20.	21.	22.	23.	24.
Loads (kW)	68.590	66.800	71.430	76.570	80.680	82.740	85.570	84.050	85.590	77.140	75.610	67.930

Table 5.8: Load demands without DR Implementation

Hrs.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
Loads (kW)	52.950	49.850	50.550	51.870	57.030	62.180	70.410	76.070	75.550	81.210	78.100	74.490
Hrs.	13.	14.	15.	16.	17.	18.	19.	20.	21.	22.	23.	24.
Loads (kW)	72.000	72.890	77.030	80.630	85.260	87.830	89.880	87.290	78.000	71.810	66.000	55.800

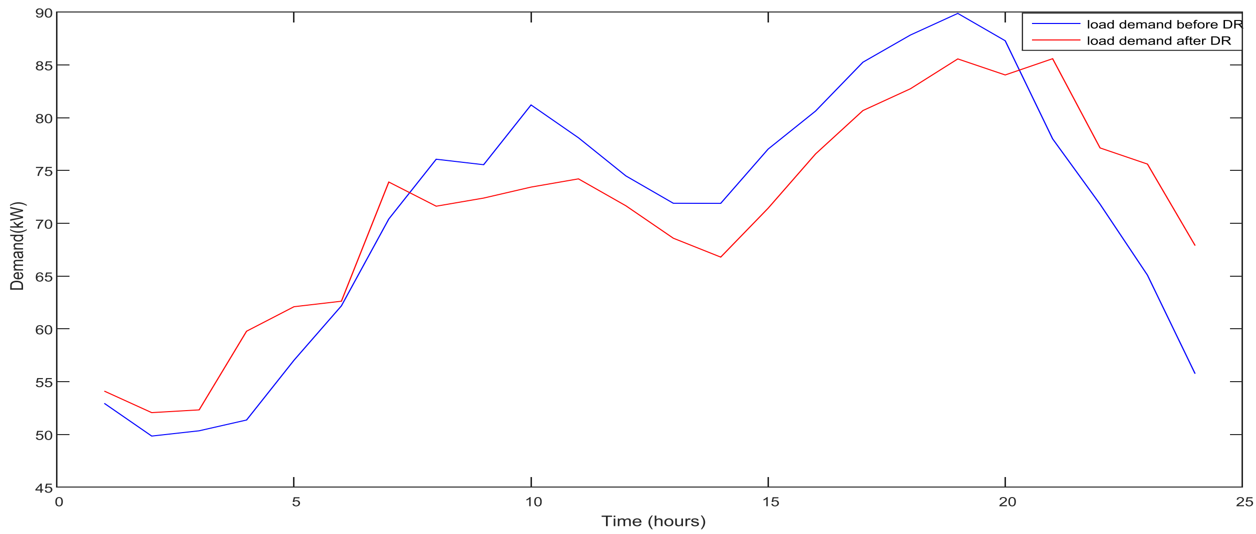


Figure 5.2 Load demands before and afterwards demand response execution.

Figure 5.2 represents load demands within systems whereby load-demands before DR implementations as well as load demands afterwards DR implementations are illustrated. Load demands are delivered in three forms, namely demands which can be interrupted (or reduced), and shifter and loads that cannot be altered [271]. Figure 5.2 also depicts that load demands neglecting DR points out load-demands being higher within peaking hours that being detrimental in systems. Due to incorporating DR, load-demands decreased in peaking hours whereas increased in off-peaking periods. Thereby DR facilitate balances within power productions as well as demands which enables continuous power supply and also helps covering uncertainties linked to WT and PV sources. Assuming reactive power necessary for loads are compensated locally with capacitor placements in appropriate buses.

Energy management in MG is carried out using meta-heuristic algorithms. It is worth mentioning here that the conventional techniques such as gradient method, lambda iteration method, linear programming, quadratic programming, etc. can be applied to solve planning problems. These conventional methods cannot perform satisfactorily as they are sensitive to initial estimates, converge into local optimal solution in addition to its computational complexity. Meta-heuristic optimization techniques on the other hand are easier to implement and faster to reach optimum solution [330].

Advantages of different variants of PSO over the classical PSO:
PSO is a meta-heuristic technique utilized for solving various engineering and mathematical problems. But classical PSO suffers from several limitations for which variants of PSO are proposed.
1) PSO is a stochastic algorithm and an excellent method for solving complex problems. But a drawback exists within PSO is that it stucks in local minima [303].
2) Classical “PSO pains from partial optimism [330].”
3) PSO algorithm fails to effectively work out some of the problems of scattering and optimization [330].
4) Different variants of PSO are more robust than classical PSO in the sense that while running multiple trials, they always converge to successful solutions.

For improving performances of PSO, several researchers proposed the different variants of PSO wherein introduced novel parameter like inertia weight and also defined different methods in inertia weight as well as in acceleration factors.

In this proposed approach meta-heuristic optimization viz., Time varying Acceleration Coefficient Particle Swarm Optimization (TVAC-PSO) is utilized.

System data for economic power schedule without demand response using meta-dynamic approach based TVAC-PSO is described in following section. MATLAB software utilized to implement aforementioned optimization technique and deployed upon microgrid system consisting micro turbines, fuel cells, batteries, PVs, WTs.

5.1.2 Energy management in microgrid system for cost minimization using meta-dynamic approach based TVAC-PSO

In this case, achieved outcomes of minimization of operating costs are analyzed without responsive loads. Subsequent Table 5.9 presents unit's optimal power generation allocation without inclusion of responsive loads.

Case 1: Economic power schedule without demand response (DR) using meta-dynamic approach based TVAC-PSO

System data is taken from Section 5.1.1.1.

Problem formulation obtained from equation (3.4), but neglecting DR term.

Optimization technique utilized is TVAC-PSO described in Section 4.2.1.

Optimization technique formulations for TVAC-PSO devised in equations (4.4)-(4.5), PSO described in Section 4.2 and meta-dynamic approach described in Section 5.1.1.

Optimization technique parameters are as follows: number of particles are 30, number of iterations are 300, limits of c_{1i}, c_{1f} are within 2.5 to 0.5, whereas c_{2i}, c_{2f} values remain within 0.5 to 2.5 and r_1, r_2 are random numbers within range [0, 1].

Table 5.9: Case 1: Economic power schedule without demand response using meta-dynamic approach based TVAC-PSO

Hours.	Units					
	MT (kW)	**FC (kW)**	**PV (kW)**	**WT (kW)**	**Battery (kW)**	**Utility (kW)**
1	30.0000	26.3191	0.0000	0.6513	1.2271	-5.2476
2	30.0000	30.0000	0.0000	0.3110	2.4128	-12.8737
3	30.0000	16.9372	0.0000	1.4858	5.0596	-3.1326
4	30.0000	30.0000	0.0000	1.0068	15.4139	-25.0507
5	18.4480	30.0000	0.0000	1.6977	1.9081	4.9763
6	30.0000	30.0000	0.0000	0.1415	-10.1211	12.1596
7	25.0051	25.9716	0.0000	0.4523	6.5823	12.3988
8	30.0000	30.0000	0.0514	0.6516	10.8359	4.5311
9	30.0000	30.0000	1.0243	0.8601	16.4803	-2.8147
10	30.0000	30.0000	0.7191	1.2511	7.8586	11.3812
11	30.0000	21.4758	0.7895	7.0004	6.3633	12.4710
12	28.1696	30.0000	5.2872	0.1747	13.7581	-2.8997
13	22.1217	30.0000	1.9308	3.1715	10.5257	4.1503
14	30.0000	25.5237	1.4769	2.2107	-0.8221	13.5008

15	30.0000	30.0000	1.4766	0.4346	-8.1924	23.3111
16	30.0000	30.0000	0.4431	0.5630	13.0403	6.5836
17	30.0000	30.0000	0.2287	1.3000	2.3261	21.4052
18	30.0000	30.0000	0.0000	1.7014	0.5046	25.6240
19	30.0000	28.2251	0.0000	0.1242	2.8836	28.6470
20	30.0000	30.0000	0.0000	1.0130	0.7809	25.4961
21	29.8662	30.0000	0.0000	0.1190	12.5665	5.4483
22	30.0000	30.0000	0.0000	0.9620	18.0478	-7.1998
23	30.0000	19.4048	0.0000	0.6181	15.3284	-0.2613
24	30.0000	18.6979	0.0000	0.5185	-1.5146	8.0983
Total cost= 220.3 €ct				Total emission= 355.5 kg		

MG within the research possess 3 feeders viz., house-hold, trade-commerce also industry customers. Optimal results are shown in Table 5.9. PV power is zero for 1-7 hours i.e., from 1 a.m. to 7 a.m. and from 18-24 hours i.e., 6 p.m. to midnight as PV arrays do not receive sunlight during that period as shown in Table 5.9. It is observed from the table that when battery has positive high values of power, indicate that during hours of day when prices are high, battery starts discharging. When battery has negative values of power, indicate that battery is in charging mode. Also it is observed from the table that when utility has negative power which means that utility purchase power from microgrid. As the simulation results indicate, applying this proposed method for economic scheduling leads to total cost of 220.3 €ct and total emission of 355.5 kg.

Case 2: Economic Power Schedule with demand response using meta-dynamic approach based TVAC-PSO.

In this case, there are responsive loads available in the system wherein achieved outcomes of minimization of operating costs are analyzed. Subsequent Table 5.10 presents unit's optimal power generation allocation with inclusion of responsive loads. Inclusion of demand response resulted in peak shaving in daily load curve as well as load shifting in off peak periods.

System data is taken from Section 5.1.1.1.
Problem formulation obtained from equation (3.4).

Table 5.10. Case 2: Economic Power Schedule with demand response using meta-dynamic approach based TVAC-PSO.

Hours.	**Units**					
	MT.(kW).	**FC.(kW).**	**PV.(kW).**	**WT.(kW)**	**Battery.(kW).**	**Utility.(kW).**
1	30.0000	30.0000	0.0000	0.0721	11.4075	-17.3696
2	30.0000	30.0000	0.0000	0.8404	-10.2518	1.4814
3	30.0000	30.0000	0.0000	1.3192	9.0404	-18.0295
4	30.0000	30.0000	0.0000	0.9452	9.0477	-10.2129
5	26.0000	30.0000	0.0000	0.4578	5.2057	0.4366
6	30.0000	30.0000	0.0000	0.1370	14.9814	-12.4983
7	30.0000	30.0000	0.0000	0.2329	0.1094	13.5677
8	30.0000	30.0000	0.1263	0.8657	-3.8959	14.5239

9	30.0000	30.0000	2.7684	0.4225	-7.9239	17.1230
10	30.0000	30.0000	0.9951	0.4737	-7.4159	19.3771
11	30.0000	30.0000	2.5017	1.4998	16.0039	-5.7954
12	30.0000	30.0000	6.2638	4.6448	10.9909	-10.2394
13	30.0000	30.0000	7.4359	3.3630	8.3161	-10.5250
14	30.0000	15.2904	16.3889	2.1611	-7.8868	10.8463
15	30.0000	21.1410	2.2303	1.5502	4.1221	12.3864
16	30.0000	30.0000	2.7127	0.6272	13.0826	0.1475
17	30.0000	30.0000	0.5029	1.3752	-1.3185	20.1204
18	30.0000	30.0000	0.0000	0.0681	0.4750	22.1970
19	30.0000	18.3588	0.0000	0.1410	11.3696	25.7006
20	30.0000	30.0000	0.0000	0.4256	-2.0124	25.6367
21	30.0000	30.0000	0.0000	0.2054	9.1716	16.2131
22	30.0000	30.0000	0.0000	0.0372	5.6517	11.4511
23	30.0000	30.0000	0.0000	0.3315	-5.2689	20.5474
24	30.0000	30.0000	0.0000	0.3631	-1.6944	9.2614
Total cost= 210 €ct				Total emission= 335.7 kg		

Optimal results are shown in Table 5.10. It is observed from the table that during hours of day when battery has positive values of power indicate that battery is in discharging mode. Also it is observed from the table that when utility has negative power which means that utility purchase power from microgrid. Table 5.9 and Table 5.10 present economic power schedule without and with demand response respectively using meta-dynamic approach based TVAC-PSO. Figure 5.3 shows converging characteristics for cost minimization considering DR using meta-dynamic approach based TVAC-PSO. Total number of iterations is taken as 300 beyond which no significant change in results is obtained.

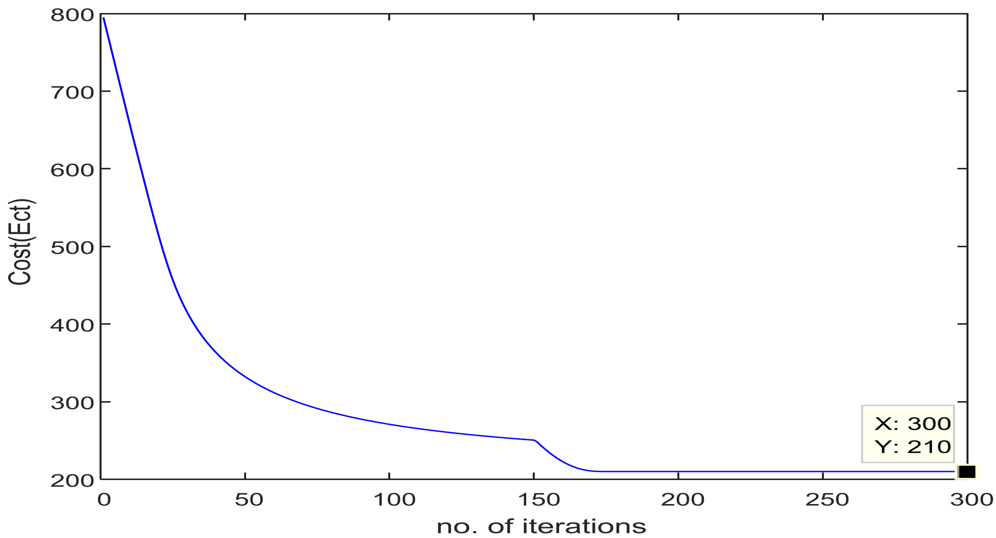


Figure 5.3.Convergence characteristics for cost minimization using meta-dynamic approach based TVACPSO (with DR)

Table 5.11.Comparison of results for cost optimization utilizing meta-dynamic approach based TVAC-PSO algorithm

Approaches	Parameter.	meta-dynamic approach based TVAC-PSO algorithm	PSO. [271]
neglecting DR	cost(€ct)	220.3	241.3
considering DR	cost(€ct)	210	231.3

Comparison of obtained results from Table 5.11 illustrates that operational costs decrease by 8.7% utilizing proposed approach compared to PSO in case neglecting demand response. Operational costs decrease by 9.2 % utilizing proposed approach compared to PSO in case considering demand response.

5.1.2.1 Energy management in microgrid system for emission minimization using meta-dynamic approach based TVACPSO

In this case, achieved outcomes of minimization of pollutant emissions are analyzed without responsive loads. Power generation by wind turbines as well as PV arrays are close to predicted values; since these types of resources are devoid of pollutants.

Case 3: Environmental Power Schedule without DR utilizing meta-dynamic approach based TVACPSO

System data is taken from Section 5.1.1.1.
Problem formulation obtained from equation (3.15), neglecting DR.

Table 5.12. Case 3: Environmental Power Schedule neglecting DR utilizing metadynamic approach included TVAC-PSO

Hours.	Units					
	MT.(kW).	FC.(kW).	PV.(kW).	WT.(kW)	Battery.(kW).	Utility.(kW).
1	16.7830	25.5151	0.0000	0.3099	30.0000	-19.6580
2	19.5825	30.0000	0.0000	1.2661	30.0000	-30.0000
3	9.0998	30.0000	0.0000	1.7068	30.0000	-20.4566
4	15.1190	30.0000	0.0000	1.5711	30.0000	-25.3201
5	22.9676	30.0000	0.0000	1.2325	30.0000	-27.1701
6	10.6408	19.7355	0.0000	0.5597	23.0146	8.2295
7	10.2864	25.8296	0.0000	1.3012	30.0000	2.9928
8	7.1856	30.0000	0.0724	0.6725	30.0000	8.1395
9	17.0383	28.1470	3.6849	0.9255	30.0000	-4.2457
10	16.6438	21.8835	6.7709	0.9671	30.0000	4.9446
11	18.1756	30.0000	4.7807	3.0671	30.0000	-7.9234
12	16.1413	19.2177	0.7740	1.0858	20.1582	17.1129
13	23.8904	30.0000	21.3454	3.0969	30.0000	-30.0000
14	20.9511	30.0000	15.7853	0.8212	30.0000	-25.6676
15	17.8128	29.8450	6.6472	1.0225	27.1600	-5.4575
16	6.7896	28.9380	2.5857	0.3271	30.0000	11.9895

17	6.0000	30.0000	0.5086	1.3506	30.0000	17.4009
18	14.5175	30.0000	0.0000	1.1958	30.0000	12.1167
19	9.3455	30.0000	0.0000	1.1237	30.0000	19.4108
20	13.5707	18.4802	0.0000	0.2295	30.0000	25.0096
21	11.5646	26.2333	0.0000	0.2819	28.9022	11.0180
22	6.0000	29.9480	0.0000	0.0063	30.0000	5.8558
23	11.1766	30.0000	0.0000	0.3649	30.0000	-6.4515
24	18.0666	30.0000	0.0000	0.1949	30.0000	-22.4615
Total emission= 264.7 kg				Total cost=412.6 €ct		

The power of individual microgrid component is illustrated in Table 5.12. The obtained results show that the total emission is reduced but at the same time total operating cost becomes higher. Also it is observed from the table that when battery has positive high values of power, battery is in discharging mode and microgrid sell extra power to grid. All the output powers in Table 5.12 are obtained by using meta-dynamic approach based TVAC PSO algorithm.

Case 4: Environmental Power Schedule considering DR utilizing metadynamic method included TVAC-PSO

In this case, there are responsive loads available in the system wherein achieved outcomes of minimization of pollutant emissions are analyzed. Utility makes purchase from MG during most operating periods, as utility possess higher quantities of pollutant emissions. Demand response significantly contributes for covering uncertainties linked to solar and wind power productions.

System data is taken from Section 5.1.1.1.
Problem formulation obtained from equation (3.15).

Table 5.13.Case 4: Environmental Power Schedule considering DR utilizing metadynamic approach based TVAC-PSO

Hours.	Units					
	MT.(kW).	**FC.(kW).**	**PV.(kW).**	**WT.(kW)**	**Battery.(kW).**	**Utility.(kW).**
1	12.5719	30.0000	0.0000	1.1278	30.0000	-19.5897
2	18.9385	30.0000	0.0000	1.4015	30.0000	-28.2700
3	13.7880	30.0000	0.0000	1.4172	30.0000	-22.8752
4	15.1940	30.0000	0.0000	1.1811	30.0000	-16.5950
5	10.7540	30.0000	0.0000	0.8228	30.0000	-9.4768
6	9.4640	20.0179	0.0000	0.8227	24.1526	8.1628
7	8.0018	18.0892	0.0000	1.0939	30.0000	16.7252
8	6.1981	29.4783	0.0690	0.5344	30.0000	5.3402
9	11.7910	30.0000	1.5617	0.5923	30.0000	-1.5550
10	6.5803	30.0000	5.7601	0.0732	30.0000	1.0164
11	22.7448	30.0000	1.9209	5.3130	30.0000	-15.7687
12	12.7503	30.0000	7.4907	5.8954	30.0000	-14.4764
13	6.0000	22.1144	0.7935	1.7475	30.0000	7.9346
14	17.9808	30.0000	0.5822	0.6681	30.0000	-12.4311

15	19.9029	23.0934	6.1480	1.6324	30.0000	-9.3467
16	6.0000	21.2102	3.3344	0.5953	30.0000	15.4301
17	16.9031	30.0000	0.1544	1.0536	30.0000	2.5689
18	17.5020	30.0000	0.0000	1.4913	30.0000	3.7467
19	11.9142	30.0000	0.0000	0.2550	30.0000	13.4008
20	20.6654	30.0000	0.0000	1.3009	30.0000	2.0837
21	6.4607	30.0000	0.0000	1.1522	30.0000	17.9771
22	12.2075	30.0000	0.0000	0.4186	30.0000	4.5139
23	14.2850	16.5452	0.0000	0.0653	30.0000	14.7145
24	23.4415	30.0000	0.0000	0.1104	30.0000	-15.6219
Total emission= 206.3 kg				Total cost= 361.6 €ct		

The performance characteristics of individual MG components wherein presenting their respective power outputs, are depicted in Table 5.13. Total emission obtained is 206.3 kg which is reduced but at the same time sacrificing the objective of operating cost obtained as 361.6 €ct which becomes enhanced. It is observed from the table that when battery has positive high values of power, battery starts discharging. Also it is observed from the table that when utility has negative power which means that utility purchase power from microgrid. Figure 5.4 shows convergence characteristics for emission pollutants minimization with DR using meta-dynamic approach based TVAC-PSO.

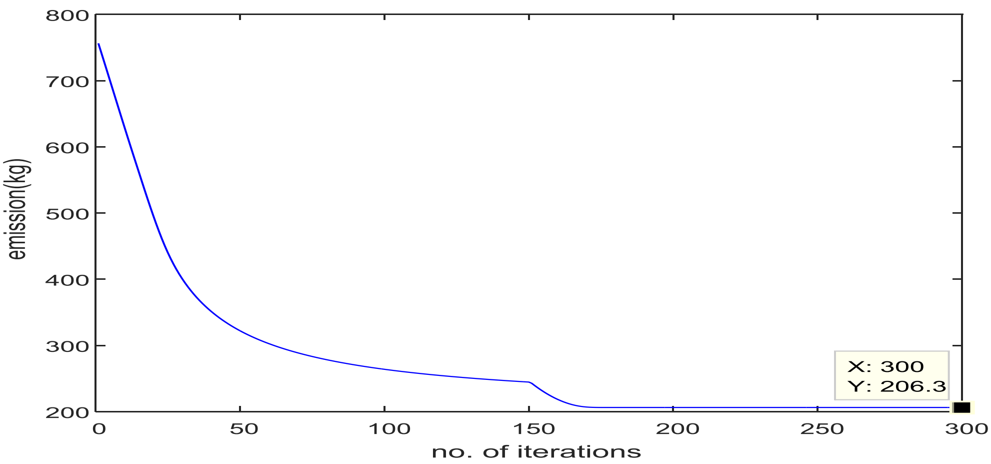


Figure 5.4. Convergence characteristics for emission pollutants minimization considering DR utilizing metadynamic method included TVAC-PSO

Table 5.14. Comparison of results-pollutant emissions utilizing meta-dynamic approach based TVAC-PSO algorithm

Approaches	**Parameter**	**meta-dynamic approach based TVAC-PSO**	**PSO [271]**
Without DR	Emission (kg)	264.7	299.7
With DR	Emission (kg)	206.3	234

Comparison of obtained results from Table 5.14 illustrates that total emissions decrease by 11.6% utilizing meta-dynamic approach based TVAC-PSO compared to PSO in case neglecting demand response. Emissions decrease by 11.8% utilizing meta-dynamic approach based TVAC-PSO compared to PSO in case considering demand response.

Result obtained from proposed method i.e., meta-dynamic approach based TVAC-PSO is compared with other variants of PSO. Table 5.15 and Table 5.16 present cost as well as emission minimization using different meta-heuristic techniques respectively.

Table 5.15: Comparison of costs

Cost minimization using different meta-heuristic algorithms

Methods	Parameters	PSO [271]	Meta-dynamic approach based algorithms			
			TVACPSO	NDIWPSO	EDWPSO	DIWPSO
Without DR	Operating cost (€ct)	241.3	220.3	220.5	222.1	224.1
With DR	Operating cost (€ct)	231.3	210	210.2	212.3	214.4

Table 5.16.: Comparative study for pollutant emission

Emission minimization utilizing various meta-heuristic algorithms

Methods	Parameters	PSO [271]	Meta-dynamic approach based algorithms			
			TVACPSO	NDIWPSO	EDWPSO	DIWPSO
Without DR	Emission(kg)	299.7	264.7	272.1	280.3	288.8
With DR	Emission(kg)	234	206.3	210.3	215.6	220.4

5.1.3 Energy management in microgrid system for cost minimization using meta-dynamic approach based FPA with adaptive switch probability

In this case, operating prices of units are taken into consideration, along with problem constraints in such manner; aiming at obtaining minimized operating costs without participation of responsive loads. Subsequent Table 5.17 presents unit's optimal power generation allocation without inclusion of responsive loads.

Case 5: Operating cost neglecting Demand Response utilizing meta-dynamic approach based FPA with adaptive switch probability

System data is taken from Section 5.1.1.1.
Problem formulation obtained from equation (3.4), but neglecting DR term.
Optimization technique utilized is meta-dynamic approach based FPA described within Section (4.4.2), FPA illustrated in Section (4.3), and meta-dynamic approach described in Section 5.1.1.

Optimization technique parameters are as follows: initial population of solutions are 30, numbers of iterations are 300; adaptive switch probability utilized illustrated in equation (4.12).

Table 5.17.: Case 5: Operating cost neglecting demand response utilizing meta-dynamic approach based FPA with adaptive switch probability

Hours.	Units					
	MT.(kW).	FC.(kW).	PV.(kW).	WT.(kW)	Battery.(kW).	Utility.(kW).
1	30.0000	30.0000	0.0000	1.5196	12.1289	-20.6985
2	30.0000	30.0000	0.0000	1.0736	10.2659	-21.4896
3	26.6023	30.0000	0.0000	0.9188	-6.0561	-1.1150
4	30.0000	27.1779	0.0000	1.4570	-3.1697	-4.0953
5	30.0000	9.7537	0.0000	0.5350	1.7988	14.9425
6	30.0000	30.0000	0.0000	0.7095	-6.8338	8.3043
7	28.5448	20.5353	0.0000	1.5267	4.9250	14.8783
8	30.0000	23.9376	0.0376	0.6999	1.7280	19.6669
9	30.0000	11.6911	0.1897	0.7504	11.5351	21.3838
10	30.0000	30.0000	2.1649	0.6360	9.3789	9.0303
11	30.0000	30.0000	1.5791	7.4064	-8.0787	17.1932
12	30.0000	22.3876	9.1996	7.1509	-0.6763	6.4283
13	30.0000	30.0000	21.1510	0.1047	9.1416	-18.4973
14	30.0000	28.6044	11.2141	1.6894	-7.1607	7.5428
15	30.0000	30.0000	2.5908	0.0609	14.8047	-0.4264
16	30.0000	30.0000	1.7599	0.7562	5.5515	12.5624
17	28.5192	30.0000	0.1174	0.3917	2.0592	24.1726
18	29.2630	30.0000	0.0000	0.6464	4.1753	23.7453
19	30.0000	30.0000	0.0000	0.5996	-6.1853	30.0000
20	30.0000	30.0000	0.0000	0.0676	4.2884	22.9340
21	30.0000	30.0000	0.0000	1.2642	-1.7522	18.4880
22	30.0000	19.8903	0.0000	0.8588	3.6421	17.4188
23	30.0000	27.3169	0.0000	0.2494	-4.1454	11.6691
24	30.0000	29.5018	0.0000	0.1322	-6.1830	2.3490
Total cost= 215.6 €ct				Total emission= 353.3 kg		

Economic generation scheduling for cost minimization of grid connected microgrid system without considering demand response program is illustrated, wherein power of DG units, battery and utility is presented in Table 5.17. When battery has negative values of power, as represented in tabular form above, indicates that battery is in charging mode. The total cost obtained 215.6 €ct is lower but at the same time sacrificing objective of total emission obtained as 353.3 kg which becomes higher.

Case 6: Economic scheduling with Demand Response using meta-dynamic approach based FPA with adaptive switch probability

In this case, within formulated problem, not only minimization of operating prices is considered, but also responsive loads are available. Uncertainties occurring due to power generation by WT as well as PV are covered utilizing demand response in such manner that participants can opt for incentive based programmes. Subsequent Table 5.18 presents unit's optimal power generation allocation with inclusion of responsive loads. Inclusion of demand response resulted in peak shaving in daily load curve as well as load shifting in off peak periods.

System data is taken from Section 5.1.1.1.
Problem formulation obtained from equation (3.4).
Optimization technique parameters are as follows: initial population of solutions are 30, numbers of iterations are 300; adaptive switch probability utilized, illustrated in equation (4.12).

Table 5.18.: Case 6: Operating cost with Demand Response using meta-dynamic approach based FPA with adaptive switch probability

Hours.	**Units**					
	MT.(kW).	**FC.(kW).**	**PV.(kW).**	**WT.(kW)**	**Battery.(kW).**	**Utility.(kW).**
1	30.0000	20.9998	0.0000	0.0279	1.9212	1.1611
2	30.0000	30.0000	0.0000	1.2506	16.2953	-25.4759
3	30.0000	30.0000	0.0000	0.5814	13.4691	-21.7205
4	30.0000	26.6457	0.0000	0.1896	-0.2091	3.1538
5	30.0000	30.0000	0.0000	0.1276	-3.4379	5.4104
6	30.0000	30.0000	0.0000	0.2395	12.2369	-9.8564
7	30.0000	29.3830	0.0000	0.8574	2.9828	10.6869
8	21.1266	30.0000	0.1309	0.0126	1.4135	18.9363
9	30.0000	30.0000	3.4479	1.5148	3.9642	3.4630
10	21.8512	30.0000	0.3404	2.1371	3.0060	16.0952
11	30.0000	30.0000	2.8727	4.2397	13.4887	-6.3911
12	30.0000	22.9859	10.7242	6.6950	-2.6690	3.9240
13	30.0000	30.0000	8.9608	0.1532	3.3861	-3.9101
14	30.0000	30.0000	7.7495	0.8178	11.8090	-13.5763
15	30.0000	30.0000	5.6407	0.8721	2.1304	2.7868
16	17.7568	30.0000	0.3753	0.3046	7.8157	20.3176
17	30.0000	27.9872	0.5224	0.2759	-3.4435	25.3381
18	30.0000	29.1262	0.0000	1.6753	7.8718	14.0667
19	30.0000	30.0000	0.0000	1.1796	4.7942	19.5962
20	30.0000	20.1078	0.0000	0.0074	8.8970	25.0378
21	30.0000	27.9738	0.0000	1.2108	0.7814	25.6239
22	30.0000	30.0000	0.0000	0.1552	-5.2893	22.2740
23	30.0000	11.6836	0.0000	0.4901	9.9655	23.4708
24	30.0000	24.7668	0.0000	0.0931	-3.4826	16.5526
Total cost= 204.4 €ct				Total emission= 329.1 kg		

Due to enhanced inclusion of renewable energy in power grids, it is imperative to consider the uncertainty of wind and solar power during cost optimization. Hence demand response programs are included in the formulation. The optimal results are shown in Table 5.18. The objective of minimizing operating cost considering demand response using meta-dynamic approach based FPA with adaptive switch probability is presented in above table. The total obtained cost is 204.4 €ct which is lower but increasing objective of total emission obtained as 329.1 kg.

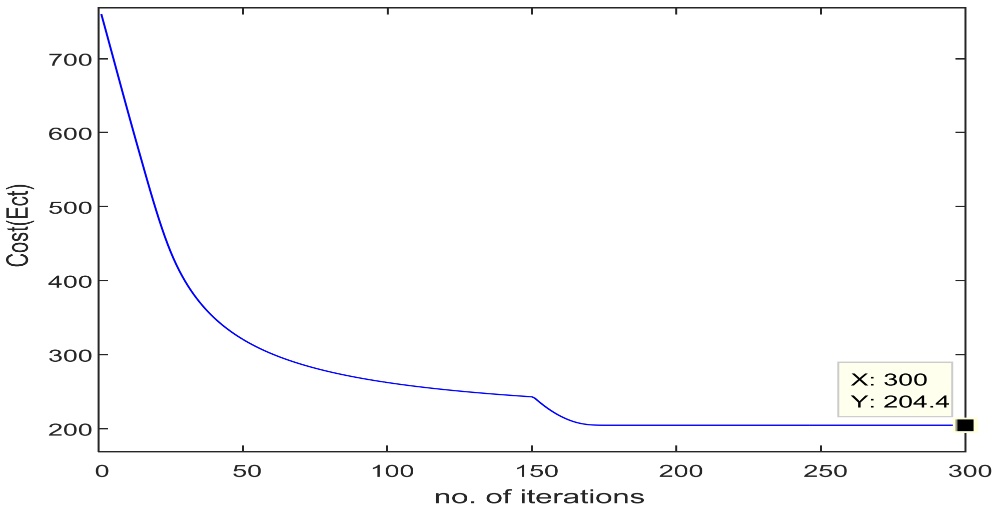


Figure 5.5. Convergence characteristics for cost minimization (considering DR) utilizing metadynamic approach based FPA with adaptive switch probability

Figure 5.5 presents convergence for cost minimization (considering DR) utilizing meta-dynamic approach based flower pollination algorithm with adaptive switch probability. Table 5.19 shows comparative study for cost optimization using meta-dynamic approach based FPA utilizing adaptive switch probability with particle swarm optimization (PSO).

Table 5.19 Comparison of results for cost optimization using meta-dynamic approach based FPA with adaptive switch probability

Method	**Parameter**	**meta-dynamic approach based FPA with adaptive switch probability**	**meta-dynamic approach based TVAC-PSO**	**PSO [271]**
Neglecting DR	Operational Costs (€ct)	215.6	220.3	241.3
Considering DR	Operational Costs (€ct)	204.4	210	231.3

Comparison of obtained results from Table 5.19 illustrates that operational costs decrease by 10.6% utilizing meta-dynamic approach based FPA with adaptive switch probability in case neglecting demand response compared to PSO. Operational costs decrease by 11.6% utilizing meta-dynamic approach based FPA with adaptive switch probability in case considering demand response compared to PSO.

Comparison of obtained results from Table 5.19 illustrates that operational costs decrease by 2.13% utilizing meta-dynamic approach based FPA with adaptive switch probability in case neglecting demand response compared to meta-dynamic approach based TVAC-PSO. Operational costs decrease by 2.6% utilizing meta-dynamic approach based FPA with adaptive switch probability in case considering demand response compared to meta-dynamic approach based TVAC-PSO.

5.1.3.1 Energy management in microgrid system for emission minimization using meta-dynamic approach based FPA with adaptive switch probability

In subsequent section, minimizing pollutant emissions is the main aim whereby considering all problem constraints such as loads balance, real power generation limits as well as battery limits. But no responsive loads are considered in this case. Power generation by wind turbines as well as PV arrays are close to predicted values; since these types of resources are devoid of pollutants.

Case 7: Environmental scheduling without Demand Response using meta-dynamic approach based FPA with adaptive switch probability

System data is taken from Section 5.1.1.1.
Problem formulation obtained from equation (3.15), neglecting DR.
Optimization technique parameters are as follows: initial population of solutions are 30, numbers of iterations are 300; adaptive switch probability utilized, illustrated in equation (4.12).

Table 5.20.: Case 7: Environmental scheduling without Demand Response using meta-dynamic approach based FPA with adaptive switch probability

Hours.	Units					
	MT.(kW).	FC.(kW).	PV.(kW).	WT.(kW)	Battery.(kW).	Utility.(kW).
1	13.8017	30.0000	0.0000	0.7261	30.0000	-21.5778
2	19.7711	30.0000	0.0000	0.0220	30.0000	-29.9431
3	8.0240	29.7314	0.0000	0.4790	30.0000	-17.8843
4	15.8299	23.0762	0.0000	0.2913	30.0000	-17.8274
5	12.5736	25.9885	0.0000	1.7494	30.0000	-13.2815
6	18.0505	16.1635	0.0000	0.8393	27.9066	-0.7798
7	8.4494	30.0000	0.0000	1.4001	30.0000	0.5605
8	7.3900	24.3702	0.1893	0.2702	30.0000	13.8502
9	6.1940	20.2595	3.2323	1.3388	30.0000	14.5255
10	13.8949	16.6100	3.6710	1.4880	28.7544	16.7918
11	10.5656	30.0000	5.8294	8.6819	30.0000	-6.9768
12	7.1709	11.3900	3.8470	4.0364	30.0000	18.0457
13	17.5005	30.0000	10.2390	3.7375	30.0000	-19.5771
14	16.1019	30.0000	11.5561	0.3353	23.8005	-9.9038
15	13.1917	30.0000	0.7097	0.7881	30.0000	2.3405
16	15.8662	23.0995	3.4320	0.8627	30.0000	7.3695
17	8.7554	27.6693	0.1231	1.1988	30.0000	17.5134
18	15.7066	30.0000	0.0000	1.5226	30.0000	10.6007
19	7.9535	30.0000	0.0000	0.9024	30.0000	21.0241
20	8.8093	30.0000	0.0000	1.6587	30.0000	16.8220
21	14.9122	20.9527	0.0000	0.8097	21.4106	19.9148
22	15.2119	30.0000	0.0000	0.0736	30.0000	-3.4755
23	8.2734	13.2469	0.0000	0.1809	30.0000	13.3888
24	18.8010	18.7631	0.0000	0.2063	29.0183	-10.9887
Total emission= 259.7 kg				Total cost= 400.5 €ct		

Environmental scheduling without demand response in grid connected microgrid system using meta-dynamic approach based FPA with adaptive switch probability is illustrated in Table 5.20. It can be seen from above table that to fulfil the objective of emission minimization, units with low emissions are given priority for scheduling purpose. Apart from utilizing renewable sources like PV and WT, battery and fuel cells are preferable here due to lower emissions. The obtained results are shown in Table 5.20. The power obtained from lower emission units viz., battery and fuel cells remain higher compared to higher emission unit viz., microturbine and utility. The total emission is reduced but sacrificing objective of total operating cost which is increased.

Case 8: Environmental scheduling with Demand Response using meta-dynamic approach based FPA with adaptive switch probability

The subsequent case aims to achieve minimum pollutant emissions while considering all problem constraints. Demand response is also taken into consideration within problem formulation in this case. In order to facilitate MG to have enhanced performance, possibility of power exchange with utility is considered. Utility makes purchase from MG during most operating periods, as utility possess higher quantities of pollutant emissions. Demand response significantly contributes for covering uncertainties linked to solar and wind power productions.

System data is taken from Section 5.1.1.1.
Problem formulation obtained from equation (3.15).
Optimization technique parameters are as follows: initial population of solutions are 30, numbers of iterations are 300; adaptive switch probability utilized, illustrated in equation (4.12).

Table 5.21.: Case 8: Environmental scheduling with Demand Response using meta-dynamic approach based FPA with adaptive switch probability

Hours.	Units					
	MT.(kW).	**FC.(kW).**	**PV.(kW).**	**WT.(kW)**	**Battery.(kW).**	**Utility.(kW).**
1	22.8618	30.0000	0.0000	1.2618	30.0000	-30.0000
2	17.8542	30.0000	0.0000	0.6617	30.0000	-26.4458
3	24.1282	30.0000	0.0000	0.4755	30.0000	-30.0000
4	16.6846	30.0000	0.0000	0.9361	30.0000	-17.8407
5	22.1934	30.0000	0.0000	1.1782	30.0000	-21.2716
6	20.9080	30.0000	0.0000	0.3814	30.0000	-18.6694
7	8.7993	30.0000	0.0000	0.3035	30.0000	4.8072
8	10.3569	30.0000	0.0610	0.6086	30.0000	0.5935
9	10.3157	30.0000	2.8364	0.6808	30.0000	-1.4429
10	12.0158	30.0000	6.2832	1.8460	30.0000	-6.7151
11	21.8010	30.0000	7.2778	6.6846	30.0000	-21.5533
12	9.8839	30.0000	8.2350	9.8788	30.0000	-16.3377
13	22.0170	30.0000	16.5646	2.6593	30.0000	-30.0000
14	17.9136	28.1828	15.8805	0.6228	30.0000	-25.7997
15	21.1031	30.0000	7.4636	0.9184	30.0000	-18.0551

16	17.5914	30.0000	3.1544	0.4871	30.0000	-4.6629
17	7.6003	30.0000	0.1014	1.1921	30.0000	11.7862
18	12.7265	30.0000	0.0000	1.1765	30.0000	8.8370
19	13.8813	21.9777	0.0000	0.6296	30.0000	19.0815
20	6.2554	30.0000	0.0000	1.5244	30.0000	16.2702
21	9.0016	30.0000	0.0000	0.0024	30.0000	16.5861
22	15.5239	30.0000	0.0000	0.4615	30.0000	1.1546
23	13.1452	30.0000	0.0000	0.0682	30.0000	2.3966
24	15.1349	30.0000	0.0000	0.3523	30.0000	-7.5572
Total emission= 202.2 kg				Total cost= 355.7 €ct		

The optimal results are shown in Table 5.21. The total emission of 202.2 kg is reduced but at the same time increasing total operating cost which is 355.7 €ct. Energy management in microgrid performed in such manner that when battery has positive high values of power indicate that the battery unit is in discharging mode as represented in above tabular form. Figure 5.6 presents convergence characteristics of pollutant emissions minimization with demand response using meta-dynamic approach based FPA with adaptive switch probability.

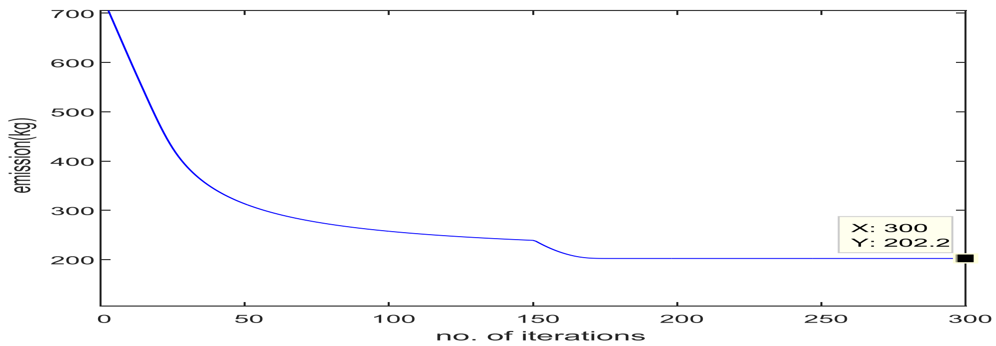


Figure 5.6. Convergence characteristics of pollutant emissions minimization with Demand Response using meta-dynamic approach based FPA with adaptive switch probability

Table 5.22. Comparative Analysis: Comparison of pollution emissions

Method	**Parameter**	**meta-dynamic approach based FPA with adaptive switch probability**	**meta-dynamic approach based TVAC-PSO**	**PSO[271]**
Neglecting DR	Emission (kg)	259.7	264.7	299.7
Considering DR	Emission (kg)	202.2	206.3	234

The optimal result obtained from above study shows that meta-dynamic approach based FPA with adaptive switch probability is very efficient. Twofold reasons viz., long-distance pollinators and flower consistency accomplish such higher efficiency. Pollinators such as insects travel long distances, hence introduce the ability (into the algorithm) to escape local landscape, also explore larger search space. On the other hand, flower consistency ensures that same species of flowers (thus similar solutions) are chosen more frequently hence guarantee the convergence more quickly i.e., exploitation step [306]. The interplay and interaction of these key components as well as inclusion of adaptive switch probability (discussed in Section 4.4) promotes higher efficiency.

Comparison of obtained results from Table 5.22 illustrates that total emissions decrease by 13.3% utilizing meta-dynamic approach based FPA with adaptive switch probability in case neglecting demand response compared to PSO. Emissions decrease by 13.6% utilizing meta-dynamic approach based FPA with adaptive switch probability in case considering demand response compared to PSO.

Comparison of obtained results from Table 5.22 illustrates that total emissions decrease by 1.8% utilizing meta-dynamic approach based FPA with adaptive switch probability in case neglecting demand response compared to meta-dynamic approach based TVAC-PSO. Emissions decrease by 1.98% utilizing meta-dynamic approach based FPA with adaptive switch probability in case considering demand response compared to meta-dynamic approach based TVAC-PSO.

5.1.4. Multi-objective energy management in microgrid system for cost and emission minimization using MMOFPA with adaptive switch probability

24-hours energy scheduling with optimal operational cost and emission (without DR) are provided as follows:

Firstly, performing single objective optimization for cost minimization utilizing meta-dynamic approach based Flower Pollination Algorithm with adaptive switch probability where 24 hours scheduling provided in Table 5.17.

Secondly, performing single objective optimization for emission minimization utilizing meta-dynamic approach based Flower Pollination Algorithm with adaptive switch probability where 24 hours scheduling provided in Table 5.20.

Thirdly, multi-objective optimization for cost and emission minimization utilizing meta-dynamic approach based multi-objective Flower Pollination Algorithm (MMOFPA) with adaptive switch probability carried out and 24 hr scheduling provided in Table 5.23.

Concept of multi-objective optimization and dominated, non-dominated solves explained in Section 3.2.3.2.

5.1.4.2.: Case 9. Operation costs as well as emissions without DR utilizing MMOFPA with adaptive switch probability

Subsequent Table 5.23, presents achieved outcomes of minimizing dual inconsistent functions viz., operating costs as well as pollutant emissions without responsive loads. System data is taken from Section 5.1.1.1. Problem formulation obtained from equations (3.4) and (3.15), neglecting DR term.Optimization technique utilized is MMOFPA with adaptive switch probability; MMOFPA described in Section (4.6), FPA illustrated in Section (4.3), and meta-dynamic approach described in Section 5.1.1. Optimization technique parameters are as follows: initial population of solutions are 20, number of iterations for multi-objective optimization is 200, and adaptive switch probability which is utilized has been illustrated in equation (4.12). 24 hours scheduling for this case is provided in Table 5.23.

Case 9: Grid linked microgrid generation schedule without demand response using meta-dynamic approach based multi-objective flower pollination algorithm with adaptive switch probability

In Table 5.23 unit's optimal power generation allocation is presented considering both objectives viz., operating costs as well as pollutant emissions without responsive loads and fulfilling each to some extent.

Table 5.23. Grid linked microgrid generation schedule without demand response using meta-dynamic approach based multi objective flower pollination algorithm with adaptive switch probability

Hours.	Units					
	MT (kW).	FC. (kW).	PV. (kW).	WT (kW)	Battery(kW)	Utility(kW)
1	21.1745	14.7449	0.0000	0.9542	1.3212	14.7552
2	19.9606	13.5812	0.0000	1.1786	0.7590	14.3706
3	19.8508	13.4760	0.0000	0.5857	1.2725	15.1650
4	19.9051	13.5280	0.0000	0.6815	1.6117	15.6437
5	22.7746	16.2788	0.0000	2.0640	1.4905	14.4221
6	25.8719	19.2479	0.0000	0.4494	2.2293	14.3815
7	29.4568	22.6845	0.0000	0.2871	3.3124	14.6693
8	30.0000	23.7537	1.9104	0.0713	4.1977	16.1368
9	30.0000	24.5356	0.4363	0.1826	4.0122	16.3833
10	30.0000	26.9234	1.4154	1.4022	3.8050	17.6640
11	30.0000	30.0000	1.3014	0.6858	-2.4763	18.5890
12	30.0000	18.6717	0.4524	1.3612	3.1676	20.8370
13	30.0000	25.4899	0.6318	0.2801	1.4212	14.0769
14	30.0000	30.0000	0.7185	0.1133	13.0602	-2.0021
15	30.0000	30.0000	0.3233	0.6476	9.6029	6.4562
16	30.0000	30.0000	0.6922	0.3442	1.3968	18.1967
17	30.0000	30.0000	0.0931	2.1025	-1.8487	24.9131
18	30.0000	30.0000	0.0000	1.4686	7.4774	18.8848
19	30.0000	30.0000	0.0000	0.2910	10.3106	19.2784
20	30.0000	30.0000	0.0000	0.3422	-1.0014	27.9492
21	30.0000	30.0000	0.0000	0.4616	-5.4679	23.0063
22	27.1029	29.9955	0.0000	0.3647	5.5575	8.7894
23	30.0000	29.9764	0.0000	0.1873	11.9205	-6.9942
24	30.0000	30.0000	0.0000	0.3792	1.0865	-5.6657
Total cost=311 €ct				Total emission=324 kg		

Responsive loads are not considered in Table 5.23. Multi objective optimization for cost and emission minimization utilizing meta-dynamic approach based multi objective Flower Pollination Algorithm (MMOFPA) with adaptive switch probability is carried out.

5.1.4.3. Case 10: Operational costs as well as emissions with DR utilizing MMOFPA with adaptive switch probability.

System data is taken from Section 5.1.1.1.

When considering DR, in multiobjective optimization here, fitness function formulation obtained from equation (3.4) and equation (3.15), whereby DR term is considered. Optimization technique parameters are as follows: initial population of solutions are 20, number of iterations for multiobjective optimization is 200, and adaptive switch probability which is utilized has been illustrated in equation (4.12).

24-hours energy scheduling with optimal operational cost and emission (with DR) are provided as follows:

Firstly, performing single objective optimization for cost minimization utilizing meta-dynamic approach based Flower Pollination Algorithm with adaptive switch probability where 24 hours scheduling provided in Table 5.18.

Secondly, performing single objective optimization for emission minimization utilizing meta-dynamic approach based Flower Pollination Algorithm with adaptive switch probability where 24 hours scheduling provided in Table 5.21.
Thirdly, multi objective optimization for cost and emission minimization utilizing meta-dynamic approach based multi objective Flower Pollination Algorithm (MMOFPA) with adaptive switch probability carried out. 24 hours scheduling for this case is provided in Table 5.24. Concept of multiobjective optimization and dominated, non-dominated solves explained in Section 3.2.3.2.

Case 10: Grid linked microgrid generation schedule with demand response using meta-dynamic approach based multi objective FPA with adaptive switch probability

Subsequent Table 5.24, presents achieved outcomes of minimizing dual inconsistent functions viz., operating costs as well as pollutant emissions with responsive loads. When demand response programs are implemented, location of optimal operating point is improved.

Table 5.24: Grid linked microgrid generation schedule with demand response using meta-dynamic approach based multi objective FPA with adaptive switch probability

Hours.	Units					
	MT.(kW).	FC. (kW).	PV. (kW)	WT(kW).	Battery (kW).	Utility (kW).
1	20.8871	14.5473	0.0000	1.9766	1.5860	15.1130
2	21.5409	15.1775	0.0000	0.2766	1.0197	14.0552
3	20.6108	14.2810	0.0000	0.1773	1.7743	15.4866
4	23.5463	17.1106	0.0000	0.8125	2.6487	15.6619
5	24.7750	18.2950	0.0000	0.7120	2.8377	15.4803
6	25.9833	19.4597	0.0000	0.1865	2.4769	14.5137
7	30.0000	24.3506	0.0000	0.3250	3.7311	15.5034
8	30.0000	23.9348	0.9732	0.1344	2.7542	13.8235
9	29.4284	22.7805	1.7023	0.5621	3.3778	14.5390
10	30.0000	23.5961	1.0225	0.0804	3.7269	15.0040
11	30.0000	28.5247	0.5575	1.6821	7.3590	6.0867
12	30.0000	30.0000	0.3626	0.5682	7.9555	2.7738
13	29.2449	30.0000	0.3232	1.2996	-2.3340	10.0564
14	30.0000	30.0000	1.4289	1.8807	11.9716	-8.4812
15	30.0000	30.0000	2.9312	0.2069	-4.5788	12.8707
16	30.0000	30.0000	1.2969	0.7061	6.7534	7.8135
17	30.0000	30.0000	0.1094	0.1640	-7.5309	27.9374
18	30.0000	30.0000	0.0000	0.7232	2.3122	19.7046
19	30.0000	30.0000	0.0000	0.1739	12.1386	13.2575
20	22.2014	30.0000	0.0000	0.7842	10.3660	20.6984
21	30.0000	28.8759	0.0000	1.3144	1.8084	23.5913
22	24.6668	12.7500	0.0000	0.9192	11.8631	26.9409
23	29.5285	30.0000	0.0000	0.8684	1.5351	13.6780
24	30.0000	30.0000	0.0000	1.2263	9.8427	-3.1390
Total cost= 230.1 €ct				Total emission=243.5 kg		

Optimal results are shown in Table 5.24, where multi objective optimization for cost and emission minimization utilizing meta-dynamic approach based multi objective Flower Pollination Algorithm (MMOFPA) with adaptive switch probability carried out where effect of responsive loads are considered.

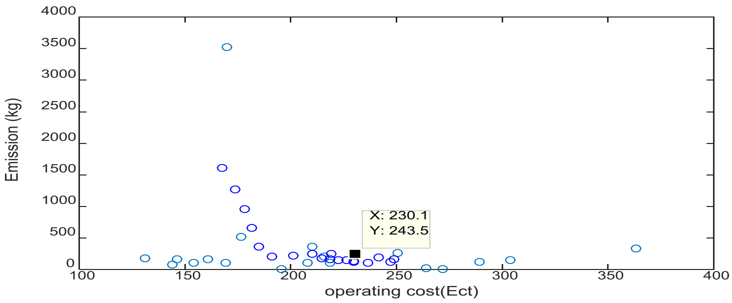


Figure 5.7. Convergence characteristics of MMOFPA with adaptive switch probability with DR

Figure 5.7 shows convergence characteristics of MMOFPA with adaptive switch probability considering DR. Cost and emission which is obtained from above figure presents trade-off solution, between objective of minimum cost and objective of minimum emission. The total cost achieved is 230.1 €ct and total emission achieved is 243.5 kg, which is not so unacceptable in real operation.

5.2. TEST SYSTEM 2: Modified IEEE 33 bus system

This research focuses on multi-layered energy managements (MEMS) in multi-microgrid (MMG) smart distributions networks (SDNs).

5.2.1 Energy-management for multi-MG smart distribution network

Concept of Smart Distribution Network (SDN) is illustrated as follows: Smart grids (SGs), is a contemporary utility-upgrading idea, and spread in different researching domains aiming to revolutionize electrical networks. SGs upgradation can be significantly noticed within distribution networks (DNs). Futuristic distribution systems possess interconnecting operating strategy [331]. Smart DNs (SDNs) should efficiently work along with advanced techniques whereby accommodating diverse distributed generator (DG) categories as well as related-components; such as DGs with renewable sources, different storage-methods, Demand Response (DR) etc.
In Test System 2, DR is included. Emissions in schedulable generators are considered. Here, each MG execute energy management (EM) also scheduling unit and determines shortage and surplus power. After that from obtained data, SDN operators (SDNOs) prepare priority lists (PL) within entities devised upon average cost and capacity. Priority list (PL) encourages investors for utilizing renewable generators. Then global EM is executed. Meta-heuristic optimization viz., multi objective modified personal best particle swarm optimization algorithm has been utilized and simulations on altered IEEE 33-bus system which show that the suggested approach encourage individual microgrid operators for implementing renewable generators for clean production. Figure 3.3(a) presents MMG system structure along with distribution network utilized in this research in Test system 2.

System components: System consists of distribution network (DN) comprising MGs, DG, WT, PV networks, energy storage systems (ESSs), and loads shown in Figure 3.3 (a) [278].

System data: The operating system has T=24 hours horizon where the presumed time interval (t) is of 1 hour. Value of parameters ξ=0.2 in equation (3.57) and ψ=0.2 in equation (3.58). Table 5.25 presents net thermal value of fuel (NthV(KJ/kg)), emission factor (EmF(tCO_2/TJ)), oxidation factor (OxF (%)), emission coefficients (EmCoef(tCO_2/m^3))and Table 5.26 illustrates cost coefficient, start-up costs, ramp rate for diesel generators within every MG as well as DN [278]. IEEE 33 bus original test system is described in Appendix.

Table 5.25: Emission coefficients

Fuel's Types	**NthV(KJ/kg)**	**EmF(tCO_2/TJ)**	**OxF (%)**	**EmCoef(tCO_2/m^3)**
Oil.	48000	74.00	99.00	3.51
Coal.	27000	95.50	99.00	2.58
Gas.	43000	53.10	99.00	2.25

Table 5.26: Cost coefficient, starting costs, ramp rate for diesel generators within every MG as well as DN

Parameters	**MG-1**	**MG-2**	**DN.**
α_1	15	20	12
α_2	80	85	75
α_3	0	0	0
Start-up costs ($)	15	13	15
Ramp up rates	0.30	0.20	0.20

Parameters linked with ESS in microgrids as well as DN are presented in Table-5.27.

Table 5.27: Parameters linked with ESS in microgrids as well as DN

Parameters	**MG1.**	**MG2.**	**MG3.**	**DN.**
Capacities (MWh)	3.00	6.00	5.00	5.00
Initial-Energies (MWh)	1.50	1.20	1.00	1.50
Final-Energies (MWh)	1.00	1.00	1.00	1.00

5.2.2 Multilayer Energy Management System (MEMS)

MEMS system within MMG-SDN with losses as well as Demand Response program is illustrated. In first layer of MEMS respective microgrid units or microgrid operators, perform local optimizations (LO). Within secondary layer's, smart distribution network operator execute EMS depending upon obtained informations of several units, so smart distribution network (SDN) optimization is carried out in this layer [278].

5.2.3. Layer 1: MGs Optimization

Microgrid operators aim into optimize operating costs described in equations (3.69), (3.70), and (3.71). Within this first layer, MG operator attempts to minimize its total operating costs. All MGs try to sell power to upstream network during instances of higher energy prices. Also, MGs buy power from upstream network during times of low energy prices.

5.2.4. Layer 2: SDN Optimization

Subsequent to local optimization in each MG, SDN operator makes priority list (PL) whereby decides which units to be committed to supply SDN demands as well as to supply MGs with shortage power. Within this layer, SDN operator (SDNO) accumulates information about shortage/surplus power as well as generating costs of distributed generators. Finally, SDNO performs global energy management, also informs all entities regarding their commitments as well as scheduling.

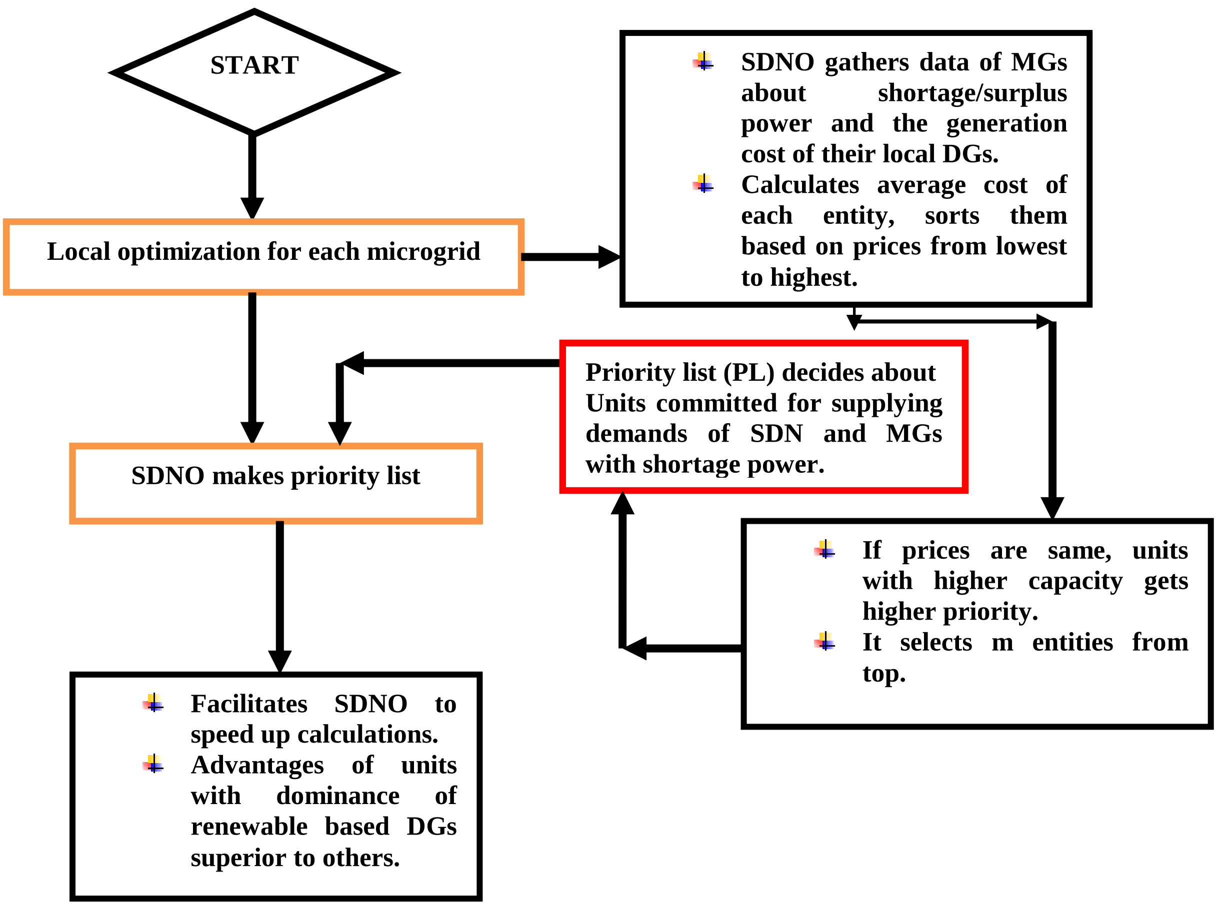


Figure 5.8. Flowchart of SDN Optimization

Figure 5.8 represents flowchart of SDN optimization and described in equations (3.72), (3.73), and (3.74). Figure 5.9 presents flowchart of priority list [278].

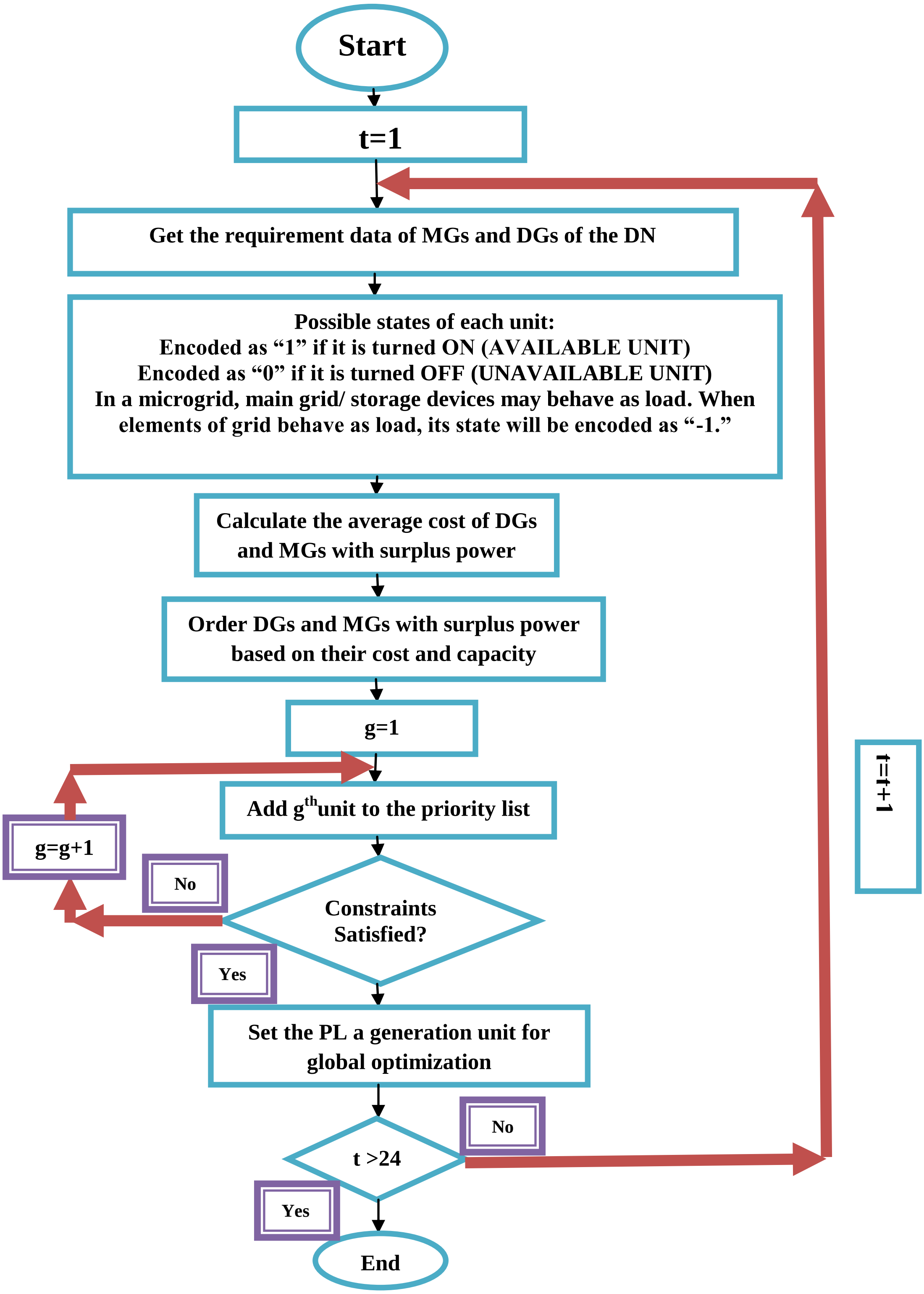


Figure 5.9. Flowchart of priority list (PL)

5.2.5. Simulation and Results

Here, simulation within system is performed for demonstrating MMG optimal EM. In this proposed approach meta-heuristic optimization viz., MMPBPSO is utilized described in Section 4.8. MATLAB software utilized for simulations performed on multi-microgrid based modified IEEE 33 bus system. Priority list also produced using MATLAB. The system comprise PVs, Wind turbine, schedulable DG and Energy Storage System as shown in Figure 3.3(b). No schedulable generating unit within 3rd microgrid so the productions remain clean.
Three MGs are connected to modified-IEEE-33-bus-DN [278] shown in Figure 3.3(b). MG-1, MG-2 and MG-3 are connected to modified-IEEE-33-bus-DN at nodes 22, 14 and 33 respectively.
MG-1 as well as MG-2 comprise of PV's generating units, WT, dispatchable distributed units such as diesel generator and ESSs. MG-3 possess no diesel units; its generating units being WTs, PVs and ESSs.
From Figure 5.10, it can be observed that MG-1 consists of battery connected at node 11; WT connected to node 7; diesel generator at nodes 1 and 15; PV connected at node 10.
MG-2 consists of battery connected at node 7; WT connected to node 13; diesel generator at node-1; PV connected at node 1.
MG-3 consists of battery connected at nodes 5 and 8; WT connected to nodes 1 and 12; PV connected at nodes 1 and 13.
IEEE 33 bus test system is described in Appendix. 24 hours forecasted wind power and PV power in kW [278] is provided in Table 5.28. Table 5.29 shows priority list for selecting committed units in distribution network; wherein '1' indicate units operating as well as '0' indicates non operating units within network.

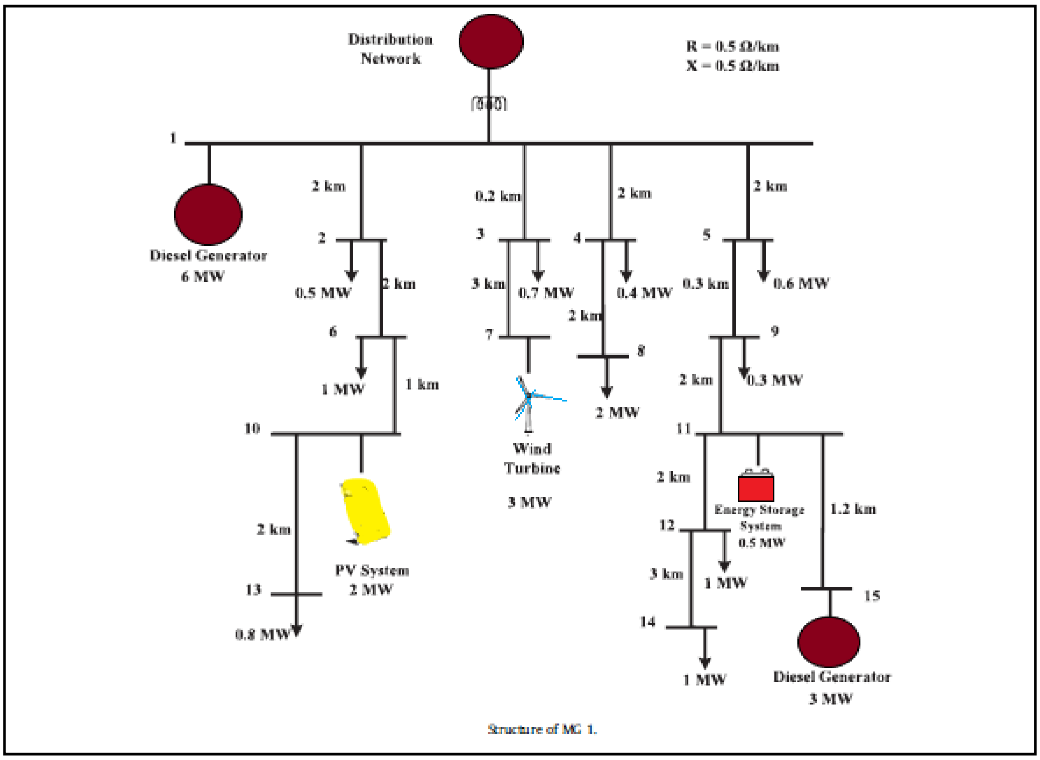
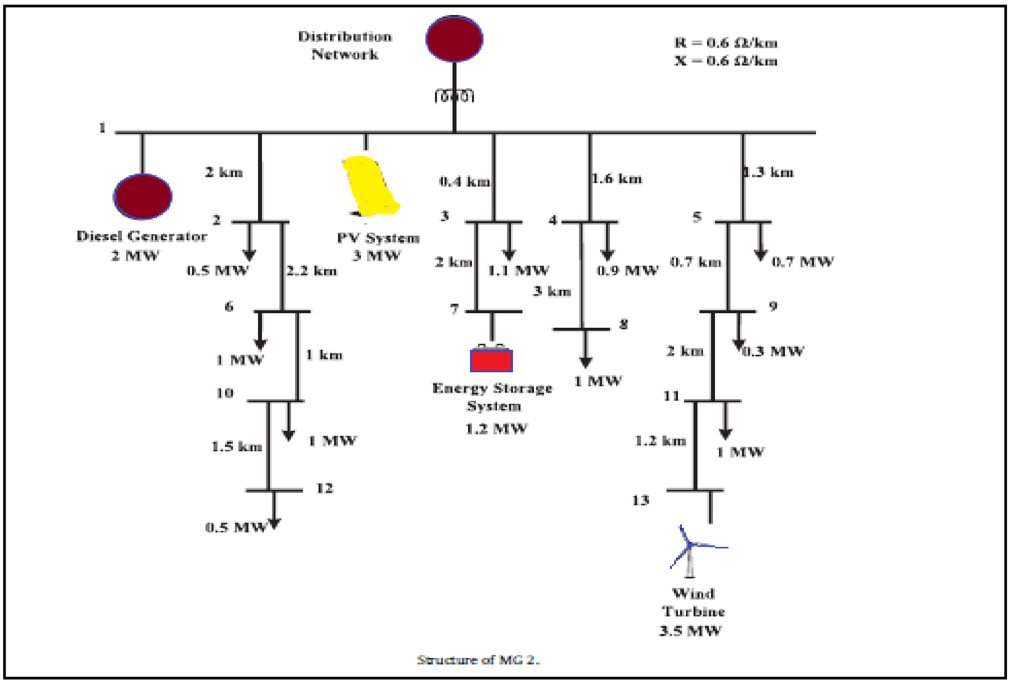
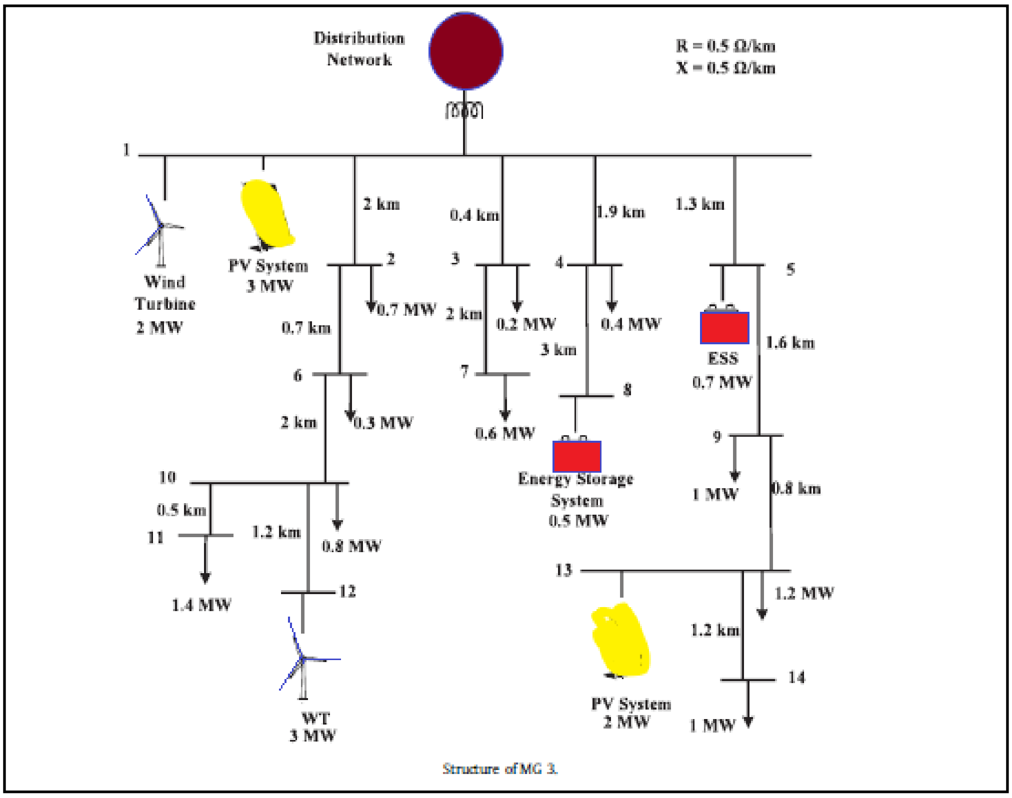


Figure 5.10. (a) Structure of MG1



Structure of MG 2.

(b)



Structure of MG 3.

(c)

Figure 5.10. Structures of (a) MG-1, (b) MG-2 and (c) MG-3

5.2.5.1 Test System 2 specifications

24 hours forecasted wind power as well as photovoltaic power in kW provided in Table 5.28 and considered load from [278]. Values of penalty factors in equation (3.75) are $\lambda_p = \lambda_{ESS} = \lambda_{def-load} = \lambda_{shedded_{load}} =$10^5.

Table 5.28: 24 hours forecasted wind power and PV power

Time in hrs	PV Power in kW	Wind power in kW
1	0.0000	6.6000
2	0.0000	10.5000
3	0.0000	11.4000
4	0.0000	12.3000
5	0.0000	12.6000
6	0.0000	12.6000
7	0.0000	15.0000
8	20.4540	5.0000
9	54.5450	11.7000
10	84.7400	9.6000
11	110.0640	15.0000
12	128.5710	13.8000
13	134.4150	12.6000
14	123.7010	12.0000
15	95.4540	11.7000
16	59.4150	4.8000
17	35.0640	0.6000
18	8.8620	1.2000
19	0.0000	1.5000
20	0.0000	0.7500
21	0.0000	0.9000
22	0.0000	8.4000
23	0.0000	12.3000
24	0.0000	7.8000

Case A: Multi-objective optimization taking prices & losses utilizing MMPBPSO with demand response for microgrid 1.

Considering loss, fitness function is illustrated in equation (3.69) wherein including DR term and incorporating loss term, cost obtained in this case is 9003$. Figure 5.11 presents convergence characteristics of operational prices vs. benefit utilizing MMPBPSO with demand response in microgrid 1.

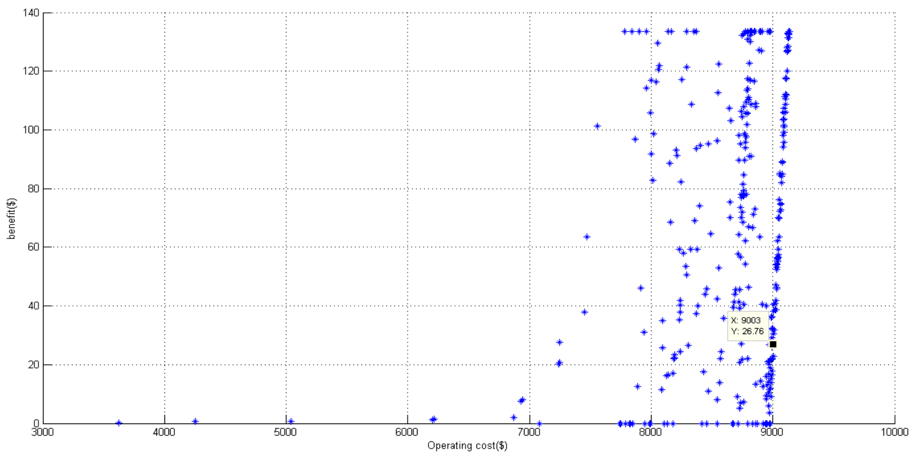


Figure 5.11. Convergence characteristics of operational prices vs. benefit utilizing MMPBPSO considering demand response in microgrid 1

Multi-objective optimization where a function to be minimized ("cost") on the x−axis and a second function ("benefit"), to be maximized, on the y−axis. Each blue dot represents a possible solution. Multi-objective approaches are always an enhancement over single-objective approaches and the solution chosen provides trade-off between cost and benefit.

Case B: Multi-objective optimization with costs as well as losses utilizing MMPBPSO with demand response for microgrid 2.

When loss is considered, fitness function is illustrated in equation (3.69) wherein including loss term and incorporating, DR term, cost is 7019$. Figure 5.12 presents convergence characteristics of operating cost and benefit utilizing MMPBPSO with demand response in microgrid 2.

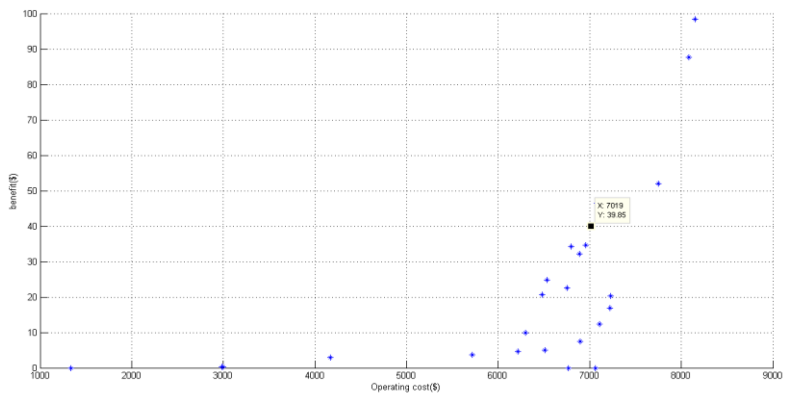


Figure 5.12. Convergence characteristics of operational prices vs. benefit utilizing MMPBPSO considering demand response in microgrid 2

Case C: Multi-objective optimization taking cost as well as loss utilizing MMPBPSO considering demand response in microgrid 3.

When-ever loss is included, fitness function is illustrated in equation (3.69) incorporating loss term and considering DR term, price is −886.6$ (negative sign presents total benefits). Figure 5.13 presents convergence characteristics of operating cost and loss utilizing MMPBPSO considering demand response in microgrid 3. The generation scheduling for microgrid 3 in this case is provided in Table 5.30.

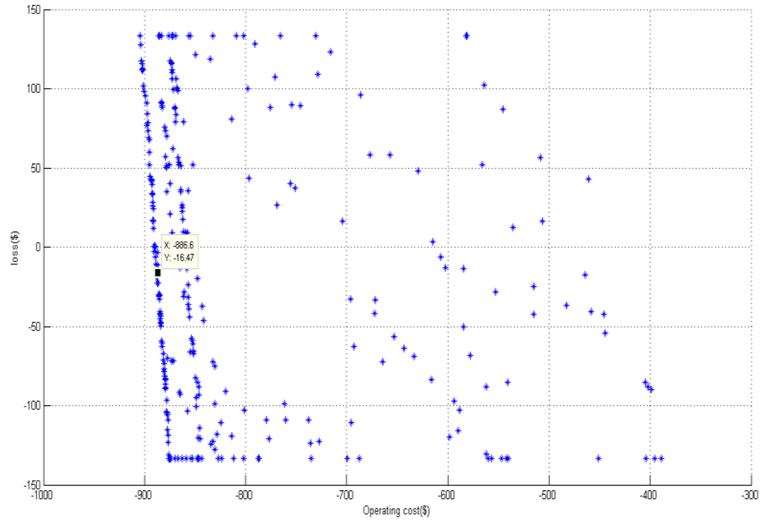


Figure 5.13. Convergence characteristics of operational prices vs. losses utilizing MMPBPSO considering demand response in microgrid 3

Case D: Multi-objective optimization including cost as well as benefit utilizing MMPBPSO considering demand response in smart distribution network.

When loss is considered, fitness function illustrated in equation (3.72) including loss term and incorporating DR term, cost is 9046$. Figure 5.14 illustrates convergence characteristics for cost as well as benefit utilizing MMPBPSO with demand response in smart distribution network.

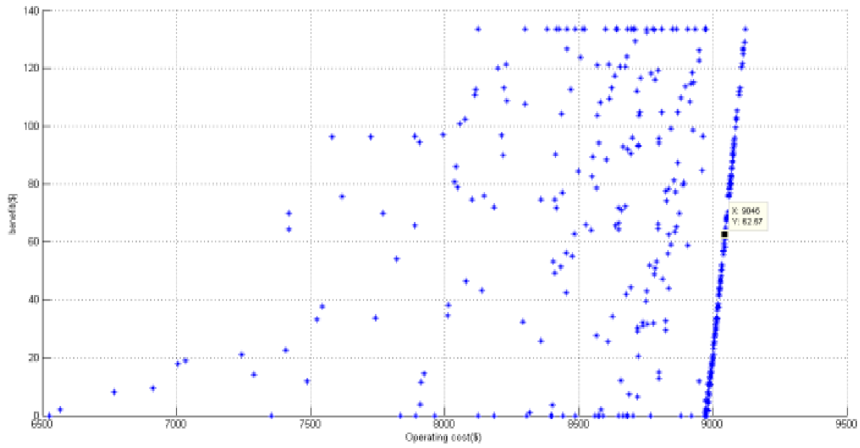


Figure 5.14. Converging characteristics including prices as well as benefits utilizing MMPBPSO considering demand response in smart distribution network

Table 5.29: PL to select committed units within DN

Time-duration	Units in PL					
	WT	**PV**	**MG3**	**Diesel**	**MG2**	**MG1**
T-0	1	0	1	1	1	0
T-1	1	0	0	1	0	1
T-2	1	0	0	1	0	0
T-3	1	0	0	1	0	1
T-4	1	0	0	1	0	0
T-5	1	0	0	1	0	1
T-6	1	1	0	1	0	1
T-7	1	1	1	1	0	0
T-8	1	1	1	1	1	1
T-9	1	1	1	1	1	0
T-10	1	1	1	1	1	1
T-11	1	1	0	1	1	0
T-12	1	1	0	1	0	0
T-13	1	1	1	1	0	1
T-14	1	1	1	1	1	1
T-15	1	1	1	1	1	1
T-16	1	1	0	1	1	1
T-17	1	0	1	1	1	0
T-18	1	0	1	1	0	1
T-19	1	0	0	1	1	0
T-20	1	0	0	1	0	0
T-21	1	0	0	1	0	1
T-22	1	0	0	1	0	0
T-23	1	0	1	1	1	0

PL to select committed units within DN is shown in Table 5.29. The uncertain behavior of renewable energy sources like wind and solar energy occurs due to their dependence upon environmental conditions; hence, it is not possible for only renewables to meet energy demand. In this context, diesel generator can be integrated with the renewable energy sources for maintaining balance between load-demand and generation.

Table 5.30: Test System 2: Generation Scheduling for MG 3

Hours	MG 3					
	PV at bus 1 (kW)	**PV at bus 13 (kW)**	**WT at bus 1 (kW)**	**WT at bus 12 (kW)**	**ESS at bus 5 (kW)**	**ESS at bus 8 (kW)**
1	0.0000	0.0000	0.6600	1.2267	0.6999	-0.4999
2	0.0000	0.0000	1.0500	1.5755	0.6999	-0.4999
3	0.0000	0.0000	1.1400	1.5714	0.6997	-0.4998
4	0.0000	0.0000	1.2300	1.6274	0.6997	-0.4998
5	0.0000	0.0000	1.2600	1.6190	0.6995	-0.4997
6	0.0000	0.0000	1.2600	1.7567	0.6996	-0.4997
7	0.0000	0.0000	1.5000	2.5665	0.6995	-0.4996
8	0.9268	0.2045	0.5000	2.8308	0.6998	-0.4999
9	1.0353	0.5455	1.1700	2.5448	0.6997	-0.4998
10	1.2510	0.8474	0.9600	2.2968	0.6994	-0.4996
11	1.7206	1.1006	1.5000	2.8308	0.6994	-0.4996
12	1.8041	1.2857	1.3800	2.8308	0.6999	-0.4999
13	1.8706	1.3442	1.2600	2.8308	0.6994	-0.4996
14	1.7777	1.2370	1.2000	2.8308	0.6999	-0.5000
15	1.6536	0.9545	1.1700	2.8308	0.6996	-0.4997
16	1.1532	0.5942	0.4800	2.6635	0.6995	-0.4997
17	0.8739	0.3506	0.0600	0.6000	2.3809	-0.4999
18	0.5641	0.0886	0.1200	1.2000	1.4778	-0.4996
19	0.0000	0.0000	0.1500	1.5000	1.5652	-0.4999
20	0.0000	0.0000	0.0750	0.7500	1.7601	-0.4997
21	0.0000	0.0000	0.0900	0.9000	1.9894	-0.4998
22	0.0000	0.0000	0.8400	2.9958	0.7000	-0.5000
23	0.0000	0.0000	1.2300	2.9474	0.6995	-0.4996
24	0.0000	0.0000	0.7800	2.1839	0.6996	-0.4997
TOTAL COST=−886.6$						

It can be observed from the above Table 5.30 that there are no dispatchable generators within the system. But renewable energy resources are present. Hence clean power production is obtained. Total operating cost is −886.6$ (negative sign presents benefits). Conventional units use fossil fuels where procurement costs are high. But renewable resources use sun's irradiance and wind from nature which is obtained free of costs. Hence renewable resources have negligible operating costs compared to conventional generators. Thus MG 3 provides higher profits compared to other microgrids.

Table-5.31 presents operating prices for entities using multi-objective modified personal best particle swarm optimization (MMPBPSO).

Table-5.31: Test System-2: Operating prices

Entities	Operating prices incorporating losses considering DR utilizing presented method ($)	Operating prices without losses considering DR utilizing presented method ($)
MG-1	9003	9022
MG-2	7019	7175
MG-3	−886.6	−786
SDN	9046	9277

Cost in MG 3 has negative value which indicates that it possess pure benefit that is capable of selling electrical power to its customers and also make higher profits. MG 3 possess only renewable energy resources where operating costs are negligible. But other microgrids comprise of diesel units which increase their operating costs.

5.3. TEST SYSTEM 3: Energy Management System of Multi-Microgrid based Smart Distribution network considering power flow constraints using Improved Flower Pollination Algorithm (IFPA)

This research develops a Multiple Layered Energy Management System (MEMS) [289] within Multi-Micro-Grid (MMG) and Smart Distribution Network (SDN).
In Test System 2, MG-1, MG-2 and MG-3 are connected to modified-IEEE-33-bus-DN at nodes 22, 14 and 33 respectively. But in Test System 3, MG-1, MG-2 and MG-3 are connected to altered-IEEE-33-bus-DN at nodes 2, 26 and 22 respectively.

5.3.1. Overview:

In Test System 3, pre-congestion analysis is carried out in case 1; whereas case 2 illustrates post-congestion condition of the system thus emphasizing necessity of incorporating security constraints; again case 3 elaborates an effective solution i.e., inclusion of tie-lines and establishing microgrid central controller to overcome the excessive increment in costs occurred due to consideration of security constraints.
The main difference between Test System 2 and Test System 3 is that in Test System 2, microgrid and distribution network optimization is carried out only whereas in Test System 3, case 1, case 2 and case 3 are included. Concept of SDN is illustrated in Section 5.2.1.
Here, during detailed analysis within security constrained energy management system (SC-EMS) the multiple layered energy management system (MEMS) is performed. Initially, security constraints are not included and microgrids are able to buy/sell power from/to distribution network. After that the security constraints are considered in DN optimization problem [289].
High load increment coupled with higher amount of Distributed Generators (DG) and Energy Storage Systems (ESSs) causes obstacles in DN like congestion within lines. Present research analyzes influence of congestion upon operating costs for MMGs. Security-Constrained

Energy Management system (SC-EMS), is proposed and meta-heuristic optimization viz. Improved Flower Pollination Algorithm (IFPA) is employed for cost analysis in multiple case-scenarios within altered IEEE 33 buses system.
Figure 3.5(a) illustrates MMG system and distribution network structure in Test System 3. Table 5.32 illustrates diesel generator data wherein price co-efficient parameters, starting prices ($), ramp rates (MW/hr) and maximum capacity in MW is illustrated [289]. Table 5.33 depicts energy storage system parameters wherein storage system capacity, initial energy and final energy values in MWhr, converter capacity in KW as well as converter efficiency (%) are illustrated [289]. Table 5.34 and Figure 5.15 presents forecast values of PV and WT. Figure 5.16 [289] presents centralized MMG schematic where MGs 1, 2 and 3 linked via tie-lines with each other; where MGs have both data as well as power transactions within themselves and also linked to the MG controller who performs energy management optimization of MGs.

Table 5.32: Diesel generator data

Parameters	MG-1	MG-2	SDN
A_1	18	15	12
A_2	90	85	75
A_3	0	0	0
Starting price ($)	200	200	150
Ramp up/ down rate (MW/hr)	1.3	1.2	1.2
Maximum Capacity (MW)	1.6	2	3

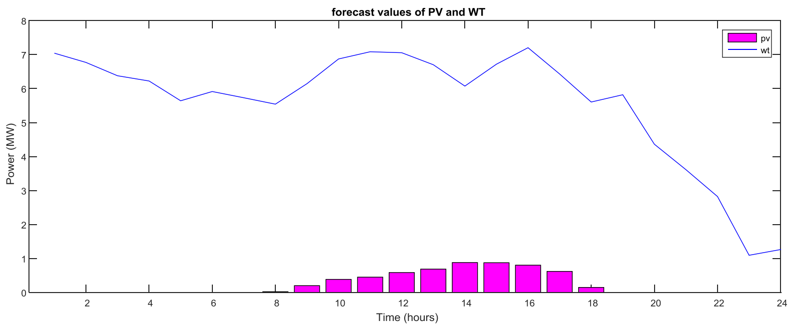


Figure 5.15. Forecast values of PV and WT

Table 5.33: Energy storage system parameters

Parameter	MG-1	MG-2	MG-3	SDN
Capacities (MWh)	1	1	1	3
Initial Energies (MWh)	0.2	0.2	0.2	1.2
Final Energies (MWh)	0.5	0.5	0.5	1
Converter Capacity (KW)	500	500	500	750
Converter Efficiency (%)	98	98	98	99

Table 5.34: Forecast values of PV and WT

Time in hours	Forecast PV power in MW	Forecast WT power in MW
1	0.0000	7.0424
2	0.0000	6.7701
3	0.0000	6.3778
4	0.0000	6.2233
5	0.0000	5.6413
6	0.0000	5.9135
7	0.0000	5.7300
8	0.0222	5.5418
9	0.2009	6.1445
10	0.3851	6.8718
11	0.4511	7.0837
12	0.5858	7.0554
13	0.6875	6.7021
14	0.8802	6.0734
15	0.8748	6.7181
16	0.8035	7.2030
17	0.6197	6.4298
18	0.1475	5.6045
19	0.0000	5.8187
20	0.0000	4.3632
21	0.0000	3.6137
22	0.0000	2.8229
23	0.0000	1.0944
24	0.0000	1.2634

5.3.2. Day ahead Energy Management Scheduling of Individual entity

The energy management problem comprises of three layers.
In initial stage, individual MG schedules DG units as well as ESSs; subsequently informs DN operator (DNO) regarding shortage/ surplus power within definite time period.
DNO performs energy management and optimizing procedure for DN taking account of achieved results obtained from MGs. Individual MG performs re-scheduling & energy management w.r.t achieved results from DN described in equation (3.96) [289].
In second stage, when DN faces congestion issue, such that it cannot supply individual MG's required power that is computed in first stage for definite time period, which results in increment in price of individual MG due to divergence against optimal schedule. DN optimization is described in equation (3.97).
In third stage, for tackling this problem, it is conceptualized that all MGs are controlled centrally from MG controller (MGC), MGs have both data as well as power pathways among themselves and power trading is possible within them. Proposed methodology illustrated within Figure 5.16 and described in equation (3.98). During this condition, MGC conducts EMS optimization of all MGs as per obtained data from individual MG regarding DG, ESS and loads [289].

After that, MGC notifies DNO regarding excess/deficit power within individual time period. Then, the DN provides power at nodes; MGC disburses achieved power from DN within MGs load requirements utilizing possibilities of interchanging power amidst themselves. Thereby, suggested methodology neutralizes effects of DN congestion problems on EMS of individual MG, henceforth decrease prices for each entity. In equation (3.99), values of penalty factors are $\lambda_p = \lambda_{ESS} = \lambda_v = \lambda_I = 10^5$.

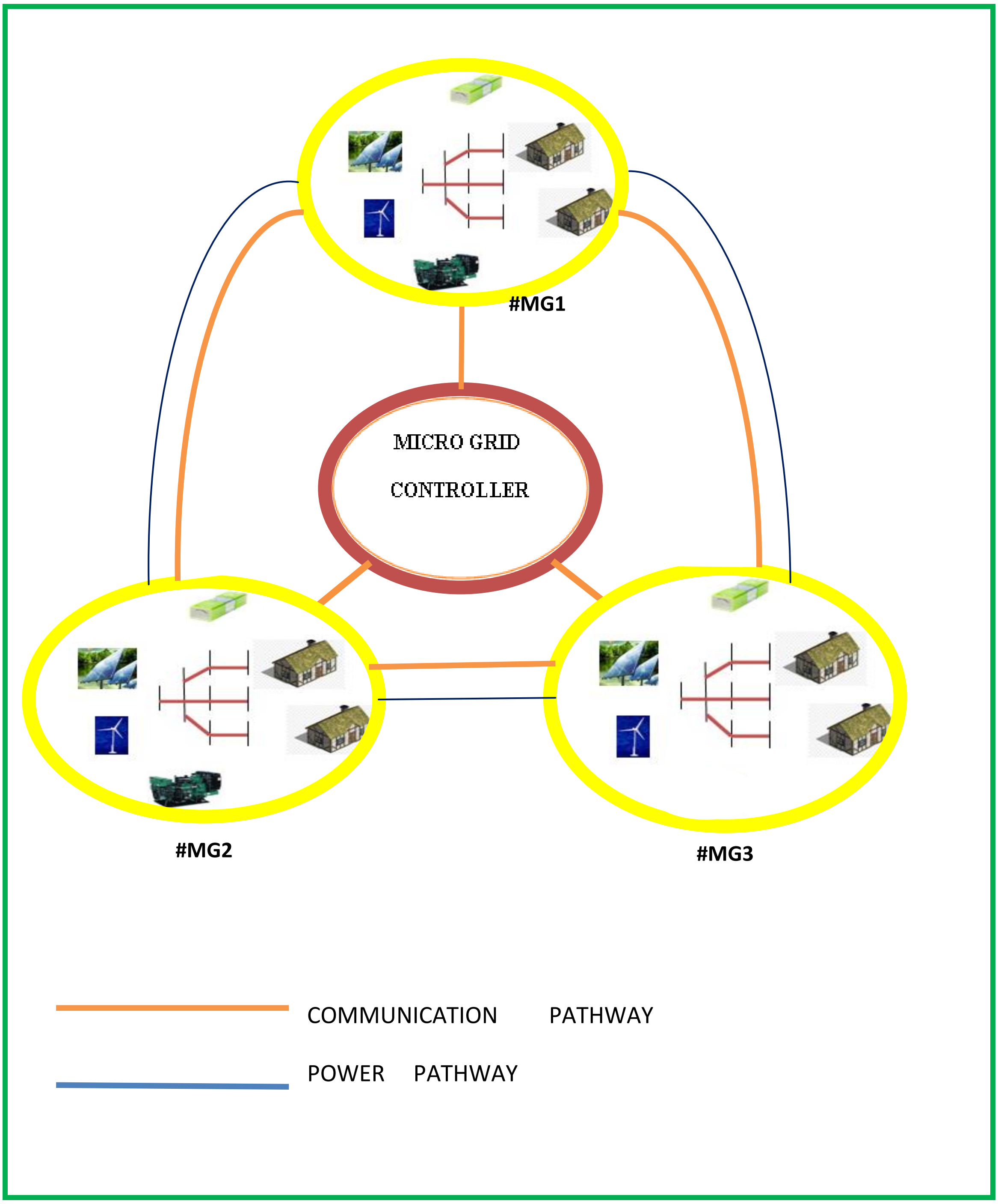


Figure 5.16. Centralized MMG schematic

5.3.3. Define Decision Variables

X, illustrates decision vector comprising unit's out-wattages, amounts for exchanges of wattages between DN, quantities for loads curtailments. P_g denotes real-power vector's of DGs and storage units. $\beta_{i,j}$ denotes l lines exist within node's i, j i.e., $X = [P_g, \beta_{i,j}]$ and $P_g = [P_{DG1}, P_{DG2}, ..., P_{DGN_{DG}}, P_{ESS1}, P_{ESS2}, ..., P_{ESSN_s}, P_{DN}, P_{curt}]$. Energy-Management within Multi-Microgrid and Smart Distribution networks considering power flow constraints utilizing Improved Flower Pollination Algorithm (IFPA) is considered here. IFPA is described in Section 4.4. Optimization technique parameters are as follows: initial population of solutions are 30, number of iterations are 300, dynamic-adaptive probability switch described in Section 4.4.

5.3.4. Simulations and results

Simulations in studied network are conducted & illustrate variations of MGs optimum EM. Here, meta-heuristic viz., IFPA is utilized. Simulations by modifications within IEEE 33 bus system are conducted. System under study is IEEE-33-bus distributing network modified whereby linking three individual MGs, also, PV-arrays, WTs, ESSs. Cumulative loads of IEEE-33-bus network are 3715kW & 2300kVar. Figure 5.17 represents prices of energy trading mechanism (buy/sell).

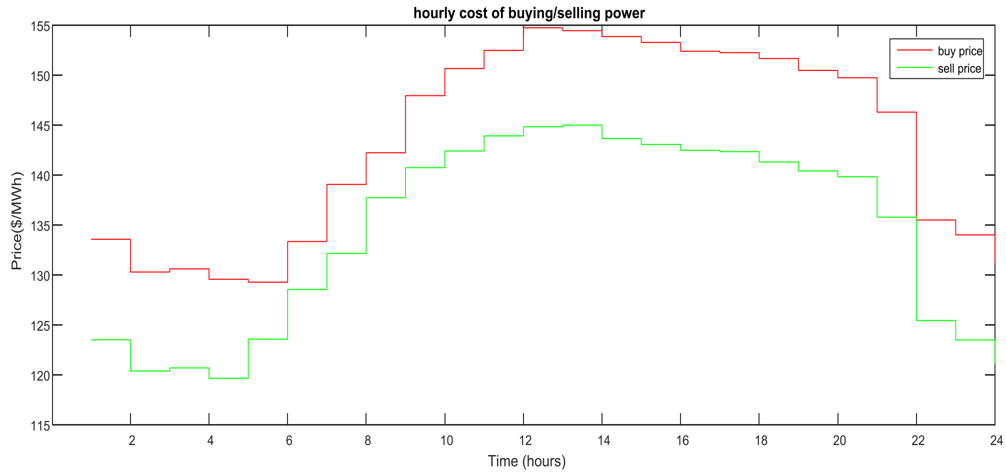


Figure 5.17. Energy trade prices within SDN

In this research, MATLAB simulations are performed for examining efficiency of described technique.

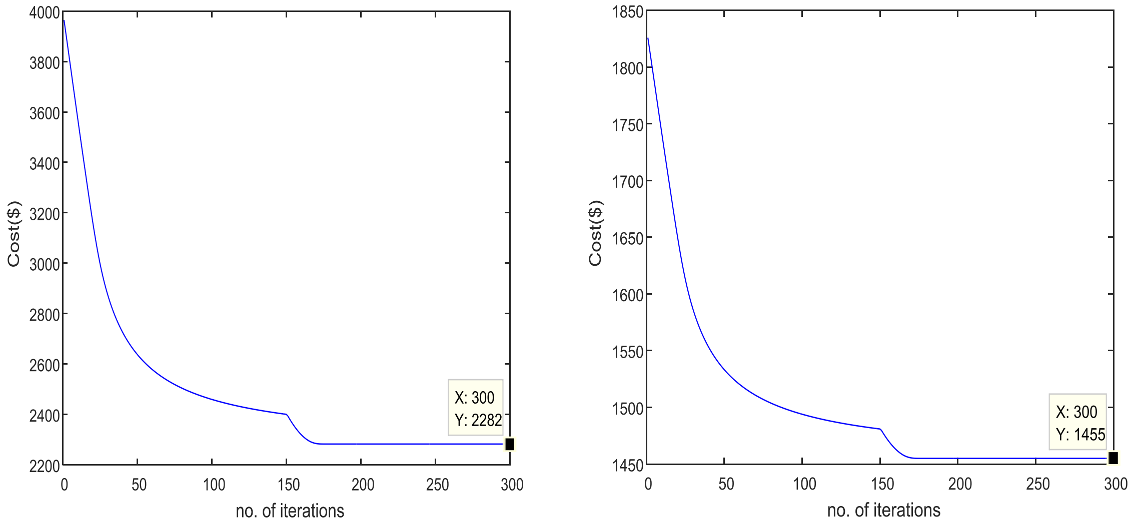
In this research work, three MGs connected to altered-IEEE-33-bus-DN. MG-1, MG-2 and MG-3 are connected to altered-IEEE-33-bus-DN at nodes 2, 26 and 22 respectively shown in Figure 3.6 [289]. IEEE 33 bus test system is described in Appendix.

MG-1 as well as MG-2 comprise of PV's generating units, WT, dispatchable distributed units such as diesel generator and ESSs. MG-3 possess no diesel units; its generating units being WTs, PVs and ESSs.

MG-1 consists of battery connected at nodes 1,4,7 and 9; WT connected to nodes 1,3 and 6; diesel generator at node 1; PV connected at nodes 1,2,5 and 8.

MG-2 consists of battery connected at nodes 1 and 3; WT connected to nodes 1, 2 and 5; diesel generator at node-1; PV connected at nodes 1, 3 and 6.

MG-3 consists of battery connected at nodes 1, 2 and 4; WT connected to nodes 1, 3 and 5; PV connected at node- 1.
Simulations are carried out for three cases.
Case 1 is performed without taking security constraints into consideration.
Case 2 takes security constraints of voltage as well as line's power flow into account considering the DN.
Case 3 presumes the existence of tie lines within MGs and capable of operating in independent way than DN.



(a) **(b)**

Figure 5.18.Convergence characteristics of (a) IFPA in MG1 (b) IFPA in MG2 both in case 1

- Case 1

This case study is performed wherein security constraints are neglected. It is observed that for hours possessing increased electrical prices, EMS tries to enhance power generation for dispatchable entities, starting discharge of ESSs. During higher trade prices, diesel entities in MG-1 and MG-2 operate at the maximum capacities and ESSs of MGs working at discharge mode. This occurs due to reason that EMS attempts for minimizing operating prices. Table 5.35 represents surplus as well as shortage powers of MGs within local optimization for case 1 as well as case 2.
In times possessing lesser trade prices, diesel generators will not function in their highest capacities; battery is in charging state. MGs buy power during hours possessing low energy prices which is economically beneficial. MGs tend to sell excess power into upper network during times possessing high energy prices which fetch profits. Once schedules of MGs are informed to DNO, it initiates global EMS without considering security constraints; MGs freely sell power to DN. Generation scheduling for MG1 (case 1) is shown in Table 5.36. Figure 5.18 shows convergence characteristics of (a) IFPA in MG1 (b) IFPA in MG2 both in case 1.

Table 5.35: Surplus as well as shortage power of MGs within local optimization for case 1, 2

Hrs	24 hour load demand (MW)	MG-1			MG-2			MG-3		
		Gen. (MW)	Shortage (MW)	Surplus (MW)	Gen. (MW)	Shortage (MW)	Surplus (MW)	Gen. (MW)	Shortage (MW)	Surplus (MW)
T0	0.3749	1.7476	0.0000	1.6330	1.0859	0.0000	0.8785	0.0538	0.0000	0.0008
T1	0.3627	0.2421	0.0000	0.2352	0.4338	0.0000	0.1265	0.0486	0.0000	0.0001
T2	0.3545	1.7422	0.0000	1.6433	1.0886	0.0000	0.8840	0.0519	0.0000	0.0008
T3	0.3382	1.0184	0.0000	0.6713	0.3289	0.0000	0.1194	0.0235	0.0000	0.0003
T4	0.3046	1.7517	0.0000	1.6792	1.0863	0.0000	0.9033	0.0500	0.0000	0.0009
T5	0.3016	0.3754	0.0000	0.3477	0.8244	0.0000	0.3284	0.0409	0.0000	0.0003
T6	0.2976	1.7430	0.0000	1.6833	1.0907	0.0000	0.9055	0.0535	0.0000	0.0009
T7	0.3079	1.3359	0.0000	1.0269	0.5441	0.0000	0.1975	0.0077	0.0000	0.0005
T8	0.3469	1.7450	0.0000	1.6546	1.0947	0.0000	0.8901	0.0527	0.0000	0.0008
T9	0.3787	1.2495	0.0000	0.7854	0.2955	0.0000	0.1073	0.0420	0.0000	0.0004
T10	0.4074	1.7723	0.0000	1.6379	1.0765	0.0000	0.8811	0.0784	0.0000	0.0008
T11	0.4443	1.3983	0.0000	0.9410	0.4472	0.0000	0.1624	0.0465	0.0000	0.0005
T12	0.4607	1.7604	0.0000	1.6157	1.1010	0.0000	0.8692	0.0849	0.0000	0.0008
T13	0.4782	0.2625	0.0000	0.1947	0.3600	0.0000	0.1047	0.1551	0.0000	0.0001
T14	0.5091	1.8045	0.0000	1.6950	1.1879	0.0000	0.9118	0.1244	0.0000	0.0009
T15	0.4980	1.4658	0.0000	1.3733	1.0253	0.0000	0.7388	0.1197	0.0000	0.0007
T16	0.4663	1.7440	0.0000	1.2792	0.6416	0.0000	0.2329	0.0489	0.0000	0.0007
T17	0.4531	1.0668	0.0000	0.6486	0.3282	0.0000	0.1191	0.0561	0.0000	0.0003
T18	0.4686	1.7286	0.0000	1.4283	0.9336	0.0000	0.7684	0.0039	0.0000	0.0007
T19	0.4768	0.4939	0.0000	0.4574	0.8190	0.0000	0.3103	0.0513	0.0000	0.0003
T20	0.4923	1.7445	0.0000	1.4227	0.9311	0.0000	0.7653	0.0055	0.0000	0.0007
T21	0.5139	0.5083	0.0000	0.4618	0.6656	0.0000	0.2484	0.0504	0.0000	0.0002
T22	0.4608	1.7378	0.0000	1.4405	0.9317	0.0000	0.7749	0.0075	0.0000	0.0007
T23	0.4302	1.3078	0.0000	1.0638	0.7087	0.0000	0.5723	0.0503	0.0000	0.0005
Cost ($)		2282			1455			-1222		
Total cost ($)		2515								

- Case 2

The study takes security-constraints into account within optimization formulation of DN. MGs are smaller compared to DN; also does not face congestion in lines. It can be stated that in first layer of EMS security constraints do not affect schedule of MGs. But, after that DN faces congestion problem. Compared to case-1, power exchange with upper grid is decreased and occurs due to congestion problem; DN cannot freely sell/buy desired quantity of power. Operating costs are increased as seen from Table 5.37, because of adding security constraints in optimization problem.

Table 5.36: Generation scheduling for MG1 (case 1)

Hours	Diesel (MW)	PV (MW)	WT (MW)	ESS (MW)
1	1.5876	0.0000	0.0698	0.0901
2	0.0987	0.0000	0.0599	0.0835
3	1.5876	0.0000	0.0645	0.0901
4	0.8715	0.0000	0.0693	0.0777
5	1.5876	0.0000	0.0739	0.0901
6	0.2513	0.0000	0.0626	0.0615
7	1.5876	0.0000	0.0652	0.0901
8	1.2748	0.0000	0.0557	0.4936
9	1.5876	0.0000	0.0673	0.0901
10	0.6758	0.0006	0.0736	0.0155
11	1.5876	0.0021	0.0731	0.0901
12	1.2749	0.0047	0.0610	0.0155
13	1.5876	0.0005	0.0773	0.0901
14	0.0925	0.0051	0.0772	0.0419
15	1.5876	0.0042	0.0852	0.0901
16	1.3264	0.0050	0.0743	0.0153
17	1.5876	0.0003	0.0633	0.0901
18	0.9895	0.0000	0.0719	0.0054
19	1.5876	0.0000	0.0509	0.0901
20	0.3547	0.0000	0.0649	0.0742
21	1.5876	0.0000	0.0668	0.0901
22	0.4350	0.0000	0.0668	0.0064
23	1.5876	0.0000	0.0600	0.0901
24	1.2404	0.0000	0.0564	0.0110
TOTAL COST =2282 $				

Table 5.36 represents generation scheduling for MG1 (case 1). Convergence characteristics of above case using IFPA in MG1 is shown in Figure 5.18 (a).

- Case 3

This case tries to find solution to the increase in operating prices as observed in case 2. In case 3, compensation of economic loss is done wherein tie lines within MGs are considered. MGC becomes responsible and determines output scheduling of MGs as one aggregate unit. The aggregate MG unit and deployment of tie lines reduce shortages in power as well as enhanced excess power quantity. Cost of aggregate MGs points out decrease in prices as compared to individual MGs as shown in Table 5.37. Table 5.37 presents comparison of operational costs of each entity. Table 5.38 presents percentage reduction in operational costs of each entity.

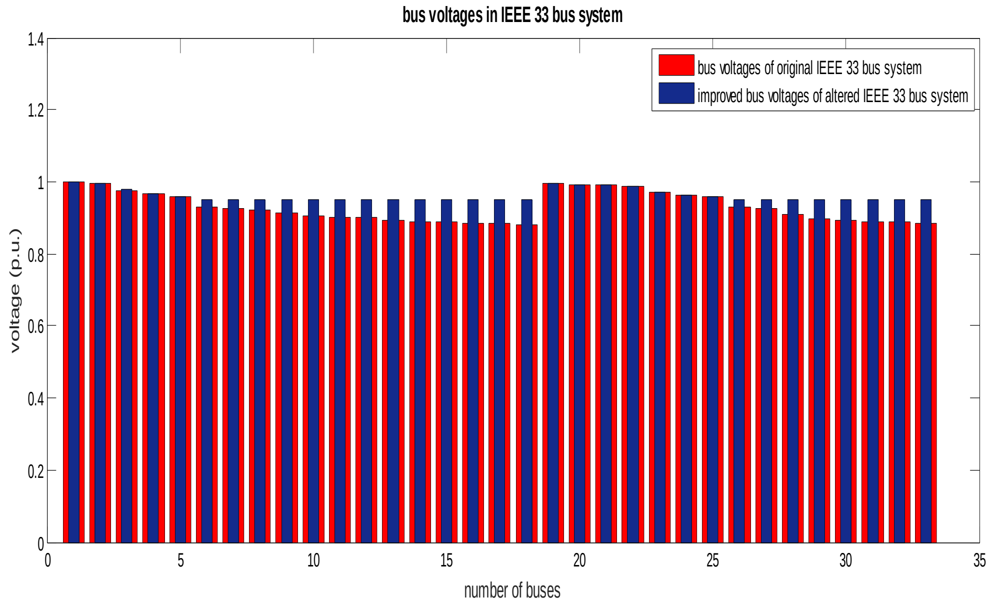


Figure 5.19. Bus voltage in altered IEEE 33 buses distribution network

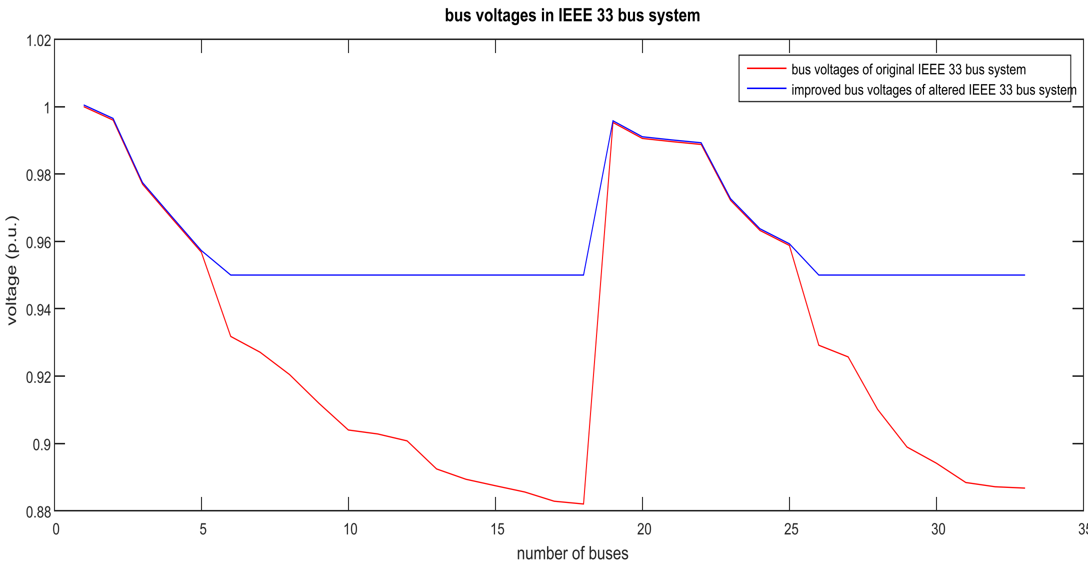


Figure 5.20. Improvement in bus voltage in altered IEEE 33 bus distribution network

Figure 5.19 represents bus voltage in altered 33-bus DN. In Figure 5.20, bus voltages in original 33-bus DN is shown along with improvement of bus voltages in altered 33 bus DN including MGs in the system.

Table 5.37: Comparison of operational costs of each entity

cases	Operating prices ($)											
	MG1			MG2			MG3 (-ve sign denote benefit)			DN		
	GAMS [289]	FPA	IFPA	GAMS [289]	FPA	IFPA	GAMS [289]	FPA	IFPA	GAMS [289]	FPA	IFPA
*WOC	2795	2658	2282	1658	1484	1455	-834	-838	-1222	8200	7775	7355
WC	2976	2973	2897	1924	1820	1746	-546	-551	-606	10980	10070	9867
WTI	2182	1964	1538	1643	1255	1146	-849	-850	-1286	10270	9238	9021

Table 5.38: Percentage reduction in operational costs of each entity

cases	Reduction in Operating prices ($)											
	MG1			MG2			MG3			DN		
	GAMS [289]	IFPA	% reduction	GAMS [289]	IFPA	% reduction	GAMS [289]	IFPA	% reduction	GAMS [289]	IFPA	% reduction
*WOC	2795	2282	18.3%	1658	1455	12.2%	-834	-1222	31%	8200	7355	10.3%
WC	2976	2897	2.65%	1924	1746	9.25%	-546	-606	9.9%	10980	9867	10.1%
WTI	2182	1538	29%	1643	1146	30.2%	-849	-1286	33.9%	10270	9021	12.1%

***WOC= Without Congestion; WC= With congestion; WTI= With tie-lines**

- **Inferences obtained from above study**

Electricity is considered significant component for sustainable development of any country. An essential factor in power system planning is to seek amount of generation required for satisfying given loads. Conceptualization of MMG network being incorporated which facilitates to achieve better economical functioning in SDN.

In this research, an intelligent novel soft computing technique viz., IFPA is utilized to assess the influence of security constraints on EMS of multi-microgrid based DN. The case study comprises of modified IEEE 33 bus DN connected to MGs. EMS consists of three cases. In case 1, neglecting security constraints, individual MG sell/buy specific quantity of power to/from DN. The prices as well as scheduling of MGs indicate local optimization. In case 2, security constraints are considered. Here the DN suffers from congestion problem. MGs in this case cannot sell/buy specific quantity of power to/from DN, thereby their operational costs increases that being highly undesirable by MG owners.

In case 3, above mentioned problem for increase in prices are solved by incorporating tie-lines amidst MGs wherein there are two strategies for functioning. In first strategy, MGs are regarded as isolated entities and can make decision to sell/buy power within tie-lines or from/to upper DN. In second strategy, MGC becomes responsible and determines output scheduling of MGs as one aggregated unit. EMS reduces operating prices by enhancing generation during higher costs as well as increase power purchasing during low prices. Thus, after installation of tie-lines, prices of DN along with MGs are decreased.

It is noteworthy to mention that in Table 5.37 the results of meta-heuristic methods (FPA, IFPA) are compared with General algebraic modeling system (GAMS) [289].

The outcomes achieved in Table 5.38 show reductions in costs: cost reductions are 18.3% in MG1, 12.2% in MG2, 31 % in MG3, and 10.3% in SDN, utilizing IFPA (considering without congestion stage) compared to [289]. Taking account of congestion in the system, cost reductions are 2.65% in MG1, 9.25% in MG2, 9.9% in MG3, and 10.1% in SDN, utilizing IFPA compared to [289]. Considering incorporation of tie-lines within the system, cost reductions are 29% in MG1, 30.2% in MG2, 33.9% in MG3, and 12.1% in SDN, utilizing IFPA compared to [289]. Thus the successful deployment of proposed approach indicates an effective way-out to solve the problem of financial losses occurred by contingencies faced by MMG based DN. This strategy to cater to the problem of economic loss may be well adopted by power network operators that can be extended to formulate MG operating strategy and energy policy in future power systems.

Next chapter presents conclusions obtained from this research studies and scope for future work.

CHAPTER-6

CONCLUSION AND SCOPE FOR FUTURE WORK

6.1 Conclusion & Scope for Future Work

6.1.1. Conclusion

Electricity is the foundation of present society. Electrical networks can be rightfully stated as strong landmark in the process for advancement of mankind. Including renewable sources of energy within present electrical networks is a significant step in this regard. Above mentioned task can be well accomplished by incorporation of microgrid systems into existing networks. In this context, maintaining efficient operation of microgrid, at the same time reducing operating costs, reducing pollutant emissions compared to conventional networks, achieving lower system losses and maximizing benefits, becomes major domains of research and analysis.

Meta-heuristic evolutionary techniques are implemented for the development of generation scheduling in this thesis. All these methods are robust and may be utilized to solve energy management problems within microgrids under environmental uncertainties. These environmental uncertainties are related to the stochastic output power of solar and wind resources.

Briefly, major contributions of the author in present thesis can be compiled as follows:

- Implemented demand response programs (DRPs) which deals with unpredictability occurring due to power-productions via renewable sources like wind turbines (WTs) as well as photovoltaic (PV) panels.

- Evaluated the objective function aimed at economical as well as environmental optimizations while satisfying different technical & operation constraints within MG system.

- Utilized unique meta-dynamic-approach-based multiobjective flower pollination algorithm with adaptive switch probability (MMOFPA) and multiobjective modified personal best particle swarm optimization (MMPBPSO) for generation scheduling whereby Pareto criterion is used.

- Implemented multi-layered energy management system (MEMS) whereby showed that microgrid system with renewable energy sources fetch higher profits because their operating costs are much lower compared to microgrid system having dispatchable units; as operating costs are higher for the latter.

- Investigated influence for congestion problem upon functioning in MGs and DN utilizing meta-heuristic technique like improved flower pollination algorithm (IFPA) applied in MEMS.

- Compared MG operation, working as per independent entities vs. functioning as per integrated system connected by tie-lines for benefit of DN and MGs.

- In Test system 1, a detailed microgrid system structure is analyzed and daily generation scheduling model is obtained. Total operating cost due to operation of each of generating units, storage units and also cost due to connection with grid as well as emission reductions are obtained. Emission reductions certainly provide environmental benefits by reducing green-house gas effects; also beneficial to all living beings as it reduces air pollution.

- In above study different optimization algorithms are investigated. Recent focus of research aims to improve performance of various optimization algorithms by parameter variation techniques. This research work elaborates several such techniques like meta-dynamic approach based Time Varying acceleration coefficients incorporated Particle Swarm Optimization (TVAC-PSO), meta-dynamic approach based non linear decreasing inertia weight particle swarm optimization (NDIW-PSO), meta-dynamic approach based flower pollination algorithm (FPA) with adaptive switch probability.

- A microgrid system of Test system 1 comprising of micro-turbine, fuel cell, solar PV, wind turbine and connected to power grid are considered in this present research work. This work points out some interesting characteristics of demand response programs where all types of residential, commercial and industrial loads are considered. Demand response programs facilitate load reduction and also provide adequate cover for environmental uncertainties caused due to renewable energy resources like wind turbines and solar photovoltaic arrays. This work can be well utilized in other such microgrid networks where service provider wishes to introduce demand response programs.

- In Test system 2, the research focuses on stochastic multi layer energy management for multi-microgrid (MMG) smart distribution network (SDN). Demand Response (DR) programs are considered in optimization process. DR program is not only characteristic feature of SDN but also can be used to manage consumed power of each entity. Here, firstly, each microgrid performs energy management to schedule units and determine shortage and surplus power. After obtaining received data SDN operator (SDNO) prepares priority list (PL) of units on average cost and capacity capable of injecting power to SDN. After that SDNO executes global energy management. In this proposed approach meta-heuristic optimization viz., Multiobjective Modified Personal Best Particle Swarm Optimization (MMPBPSO) algorithm, has been utilized. Simulations on modified IEEE 33 bus test system are performed.

- In Test system 3, Energy Management System of Multi-Microgrid based Smart Distribution network considering power flow constraints using Improved Flower Pollination Algorithm (IFPA) is discussed. Multi-microgrid system is considered, which comprises of several microgrids each consisting of distributed generators (DGs), including renewable energy resources such as wind turbines and PV arrays, is a characteristic feature of this work. The impact of congestion as well as considering security constraints in Multi-Microgrid based Smart Distribution network increases operational costs. Incorporating tie-lines within microgrids enables them to act as an aggregated unit whereby the objective of cost minimization is obtained. This strategy to cater to the problem of economic loss may be well adopted by power network operators that can be extended to formulate MG operating strategy and energy policy in future power systems.

SCOPE FOR FUTURE WORK

6.1.2. Scope for Future Work

- Objective function for energy management in microgrids may be further improved with least efforts via utilization of other different constraint handling techniques; besides penalty factor method used here, for solving constrained power flow formulation. Above modification will immensely be useful for future research in domain of microgrid analysis.

- The penalty factor method considered in this work is not highly adaptive to the ongoing search process. A completely adaptive penalty function method can be formulated including additional adaptive operators which will highly improve effectiveness of penalty function method.

- Energy management with different renewable energy resources considering diverse capacities and various configurations, apart from those utilized here; will assist in future research-work for improvement of voltage-profile.

- Novel techniques like incorporation of demand response programs, inclusion of microgrid central controller as well as tie-lines provides a unique working model which mitigates the problem of economic losses that can be implemented in other modern power networks.

- Optimization technique such as PSO faces hindrance like the premature loss of diversity and the problem dependent performance. Future work may involve development of other hybrid methods which will be more effective for implementing in various engineering problems.

- Above mentioned technologies may be well accepted by the power suppliers which will be a major breakthrough in the field of smart grids and smart distribution networks.

APPENDIX

A1. IEEE 33 bus system data [332]

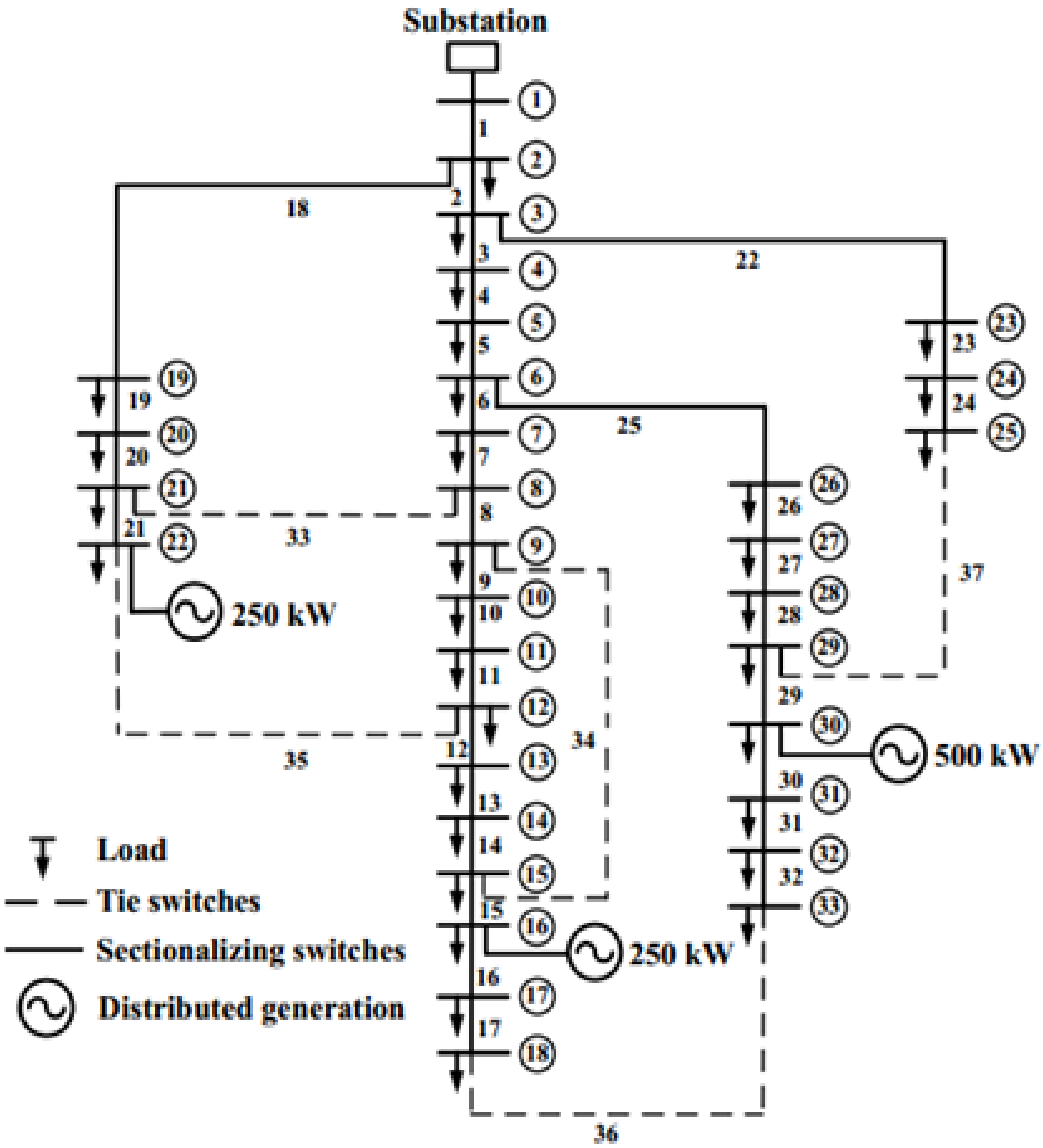


Figure A1: Single line diagram of the IEEE 33 bus radial distribution system

Table A.1. Line data of the IEEE 33-bus radial distribution system [332]

Line Name	From Bus	To Bus	Line Impedance	
			Resistance (Ω)	**Reactance (Ω)**
BRANCH-1	1	2	0.0922	0.0470
BRANCH-2	2	3	0.4930	0.2512
BRANCH-3	3	4	0.3660	0.1864
BRANCH-4	4	5	0.3811	0.1941
BRANCH-5	5	6	0.8190	0.7070
BRANCH-6	6	7	0.1872	0.6188
BRANCH-7	7	8	0.7115	0.2351
BRANCH-8	8	9	1.0299	0.7400
BRANCH-9	9	10	1.0440	0.7400
BRANCH-10	10	11	0.1967	0.0651
BRANCH-11	11	12	0.3744	0.1298
BRANCH-12	12	13	1.4680	1.1549
BRANCH-13	13	14	0.5416	0.7129
BRANCH-14	14	15	0.5909	0.5260
BRANCH-15	15	16	0.7462	0.5449
BRANCH-16	16	17	1.2889	1.7210
BRANCH-17	17	18	0.7320	0.5739
BRANCH-18	2	19	0.1640	0.1565
BRANCH-19	19	20	1.5042	1.3555
BRANCH-20	20	21	0.4095	0.4784
BRANCH-21	21	22	0.7089	0.9373
BRANCH-22	3	23	0.4512	0.3084
BRANCH-23	23	24	0.8980	0.7091
BRANCH-24	24	25	0.8959	0.7071
BRANCH-25	6	26	0.2031	0.1034
BRANCH-26	26	27	0.2842	0.1447
BRANCH-27	27	28	1.0589	0.9338
BRANCH-28	28	29	0.8043	0.7006
BRANCH-29	29	30	0.5074	0.2585
BRANCH-30	30	31	0.9745	0.9629
BRANCH-31	31	32	0.3105	0.3619
BRANCH-32	32	33	0.3411	0.5302
BRANCH-34	8	21	2.0000	2.0000
BRANCH-36	9	15	2.0000	2.0000
BRANCH-35	12	22	2.0000	2.0000
BRANCH-37	18	33	0.5000	0.5000
BRANCH-33	25	29	0.5000	0.5000

Table A.2. Load data of the IEEE 33-bus radial distribution system [332]

Location (Bus no.)	Real Load (kW)	Reactive Load (kVAR)
2	100	60
3	90	40
4	120	80
5	60	30
6	60	20
7	200	100
8	200	100
9	60	20
10	60	20
11	45	30
12	60	35
13	60	35
14	120	80
15	60	10
16	60	20
17	60	20
18	90	40
19	90	40
20	90	40
21	90	40
22	90	40
23	90	50
24	420	200
25	420	200
26	60	25
27	60	25
28	60	20
29	120	70
30	200	100
31	150	70
32	210	100
33	60	40

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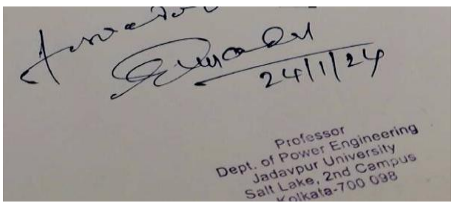

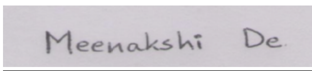

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