Investigations on Strategies for Profit Maximization in Networked Microgrids

Submitted in partial fulfilment of the requirements
for the award of the degree of

Doctor of Philosophy

in

Electrical Engineering

By

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December 2023

APPROVAL SHEET

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CERTIFICATE

This is to certify that the thesis entitled "**Investigations on Strategies for Profit Maximization in Networked Microgrids**" being submitted by **V. Lokesh (718126)** is a bonafide research work carried out under my supervision and guidance in fulfillment of the requirement for the award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering, National Institute of Technology Warangal-506004, Telangana, India. The matter embodied in this thesis is original and has not been submitted to any other University or Institute for the award of any other degree.

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DECLARATION

This is to certify that the work presented in the thesis entitled "**Investigations on Strategies for Profit Maximization in Networked Microgrids** " is a bonafide work done by me under the supervision of **Dr. Altaf Q. H. Badar**, Assistant Professor, Department of Electrical Engineering, National Institute of Technology Warangal, and was not submitted elsewhere for the award of any degree.

I declare that this written submission represents my ideas in my own words and where others ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea / data / fact / source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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ACKNOWLEDGEMENTS

The fruition of my research work and the completion of this thesis have been made possible through the unwavering inspiration and support of those around me. I extend my deepest gratitude to all who have contributed in various capacities.

First and foremost, I extend heartfelt thanks to my esteemed research supervisor, **Dr. Altaf Q. H. Badar**, Assistant Professor in the Department of Electrical Engineering at the National Institute of Technology Warangal. His guidance, scholarly insights, and consistent encouragement have been instrumental in the realization of this work. The unconditional moral support provided by him allowed me the freedom to plan and execute my research ideas without any undue pressure, enabling me to discern my strengths and weaknesses and bolstering my self-confidence.

I would like to express my utmost gratitude to **Prof. S. Srinivasa Rao**, Chairman of DSC, Department of Electrical Engineering, for his continuous technical suggestions, encouragement, and collaborative support.

I take this opportunity to express gratitude to all members of my DSC Committee, **Prof. M. Sailaja Kumari**, Professor, Department of Electrical Engineering, **Dr. B. Nagu**, Associate Professor, Department of Electrical Engineering, and **Dr. T. Ramakrishnudu**, Associate Professor, Department of Computer Science and Engineering, for their detailed technical review, constructive suggestions, and excellent advice during the progress of this research work.

A special thanks to **Prof. Narasimharaju B. L**, Head, Department of Electrical Engineering, for his consistent encouragement, support, and cooperation.

I extend my sincere appreciation to **Prof. Bidyadhar Subudhi**, the Director of NIT Warangal, for his official support and encouragement.

I also wish to acknowledge the encouragement received from the teaching and non-teaching members, as well as the entire Department of Electrical Engineering community at NIT Warangal. Their ongoing encouragement and support have been pivotal.

Finally, I would like to express profound gratitude to my family members for all they have undergone to bring me up to this stage. I express gratitude to my parents, **Sh. V. Govindu** and **Smt. Jyothi**, for their kind support, the confidence, and the love they have shown to me. You are my greatest strength, and I am blessed to be your son. I extend my heartfelt appreciation to my younger brother, **Sh. V. Saikrishna**, for his unwavering support and understanding throughout the process of completing this thesis. His enthusiasm, encouragement, and genuine interest in my academic pursuits have been a constant source of motivation.

V. Lokesh

ABSTRACT

Microgrids, acknowledged as small-scale power distribution systems integrating loads, energy storage systems, and distributed generation, represent a key component in the evolution of future power systems. With a dual operating capability, namely islanded and grid-connected modes, microgrids play a crucial role in managing the intermittent nature of renewable energy sources and addressing associated uncertainties. However, the intrinsic complexities related to generation and load patterns necessitate the formation of networked microgrids, allowing for enhanced resource sharing, minimized transmission losses, and improved overall system reliability. The concept of networked microgrids has emerged as a response to the challenges posed by individual microgrids, emphasizing coordinated energy management, bidirectional energy trading, and optimized resource scheduling. This framework facilitates energy exchange not only between the grid and microgrids but also among interconnected microgrids, thereby fostering an efficient, collaborative energy ecosystem. In this regard, diverse strategies such as hour block-based demand response programs are proposed in comparison to hour-to-hour demand response to optimize energy trading and minimize operational costs. Each hour block is formed based on generation and load imbalance, the role of microgrids and the Time-of-Use tariff system. Both techniques are evaluated in terms of time and complexity using the Particle Swarm Optimization method. Optimal capacity sizing of renewable energy sources and battery energy storage systems with the objective of cost reduction and the enhancement of overall reliability within the networked microgrid framework is proposed. To facilitate energy trading within the networked microgrids, both peer-to-peer and peer-to-grid approaches are employed, with the former utilizing a proposed "proportional trading method"; managed by a networked microgrid manager or aggregator. This study addresses these concerns through the development of a multi-objective optimization problem. Multi-Objective Particle Swarm Optimization is applied to solve the formulated optimization problem. Different strategies for scheduling the individual energy storage system in networked microgrid environment is proposed to emphasize the dynamic nature of energy trading within microgrids with the objective to maximize the individual profits of each microgrid while ensuring collective benefits for the entire networked microgrid. Moreover, the integration of shared energy storage systems within networked microgrids is identified as a cost-effective solution to mitigate space constraints and minimize deployment expenses compared to individual energy storage system. Economic analyses further affirm the feasibility and financial

advantages of implementing such strategies, highlighting the potential of networked microgrids in shaping sustainable and resilient energy solutions for the future.

Contents

List of Symbols

t	Hour block
B	Set of buyer MGs
S	Set of seller MGs
N	Total number of MGs
b	Buyer MG
s	Seller MG
v	Velocity of Particle
x	Particle position
p_{best}	Particle best position
$p_g best$	Global best position
$L_{d_i}^t$	Load in MG_i during t
$L_{d_{i,al}}^t$	Actual total load in MG_i for whole day
E_i^t	Excess energy generated in MG_i during t
D_i^t	Deficit energy in MG_i during t
$P_{grid,s}^t$	Grid selling tariff during t
$P_{grid,b}^t$	Grid buying tariff during t
$P_{NMG,s}^t$	NMG energy selling tariff during t
$P_{NMG,b}^t$	NMG energy buying tariff during t
G_i^{NE}	Energy generated in MG_i during t in NE-zone
$L_{d_i}^{NE}$	Load demand in MG_i during t in NE-zone
$E_{MG_i,s}^t$	Energy sold by seller MG_i to NMG during t
$E_{MG_i,b}^t$	Energy bought by buyer MG_i from NMG during t
$E_{MG_i,b}^{g,NE}$	Total Energy bought by MG_i from grid during NE zone.
$E_{\mathrm{NMG},b}^{g,\mathrm{NE}}$	Total Energy bought by NMG from grid during NE zone
$E_{\mathrm{MG}_i,s}^{g,t}$	Energy sold by seller MG_i to grid during t.
$E_{\mathrm{MG}_i,b}^{g,t}$	Energy bought by buyer MG_i from grid during t
$C_{\mathrm{MG}_i,b}^t$	Cost incurred to buyer MG_i during t
$C_{\mathrm{MG}_i,s}^t$	Profit earned by seller MG_i during t
$C_{\mathrm{MG}_i,b}^{\mathrm{NE}}$	Total cost incurred to MG_i during NE zone
$TC_{\mathrm{NMG,b}}^{\mathrm{NE}}$	Total cost incurred to NMG during NE zone
$TC_{\mathrm{MG}_b}^t$	Total cost incurred to all buyer MG_i during t
$TC_{\mathrm{MG}_s}^t$	Total profit earned by all seller MG_i during t
$TC_{MG,i}$	Total cost for MG_i during whole day

TC_{NMG}	Total cost for NMG during whole day
i	Index of MGs
w	Index of Week
d	Index of Day
N	Total number of Microgrids
ld_i^t	Load in MG_i at time t
$ld_i^{w,t}$	% Load available in MG_i at time t during week w
$ld_i^{d,t}$	% Load available in MG_i at time t during day d
$ld_{cy,i}^t$	Load capacity in MG_i
PV_i^t	Load capacity in MG_i
$PV_{al,i}^t$	% PV generation available in MG_i at time t
$PV_{cy,i}^t$	PV capacity in MG_i
W_i^t	Wind generation in MG_i at time t
$W_{al,i}^t$	% Wind generation available in MG_i at time t
$W_{cy,i}^t$	Wind capacity in MG_i
PV_i^t	PV generation in MG_i at time t
$PV_{al,i}^t$	% PV generation available in MG_i at time t
$PV_{min,i}$	Minimum PV capacity in MG_i
$PV_{max,i}$	Maximum PV capacity in MG_i
$W_{min,i}$	Minimum wind capacity in MG_i
$W_{max,i}$	Maximum wind capacity in MG_i
BE_i^t	Battery Energy in MG_i at time t
BE_i^{max}	Maximum BESS Energy allowable in MG_i
BE_i^{min}	Minimum BESS Energy allowable in MG_i
$BP_{i,c}^t$	BESS charging power in MG_i at time t
$BP_{i,c}^{min}$	Minimum BESS charging power allowable in MG_i
$BP_{i,c}^{max}$	Maximum BESS charging power allowable in MG_i
$BP_{i,d}^t$	BESS discharging power in MG_i at time t
$BP_{i,d}^{min}$	Minimum BESS discharging power allowable in MG_i
$BP_{i,d}^{max}$	Maximum BESS discharging power allowable in MG_i
$MG_{i,sur}^t$	Surplus energy in MG_i during t
$E_{T,ex}^t$	Total excess energy with seller $MG's$ during t
$E_{T,rq}^t$	Total deficit energy with buyer $MG's$ during t
$PMG_{s,i}^t$	Energy sold by seller MG_i during t
$PMG_{b,i}^t$	Energy bought by buyer MG_i during t
$PG_{s,b,i}^t$	Energy bought/sold by MG_i during t from/to grid

AEC_i	Annual Energy Cost of MG_i
C_i^{INV}	Investment cost of MG_i
$C_i^{O\&M}$	Operation & Maintenance cost of MG_i
C_i^{PC}	Power purchase cost of MG_i from grid/NMG
$I_i^{U,RE}$	Income of MG_i from utilization of RE
$I_i^{U,B}$	Income of MG_i from utilization of BESS
I_i^{SL}	Salvage Income of MG_i
$P_i^{G,RE,t}$	Renewable energy generated in MG_i during t
$P_i^{U,RE,t}$	Renewable energy utilized in MG_i during t
$E_{p,b}^t$	Grid to Peer energy trading price during t
$P_i^{G,cy}$	Power generation capacity of each source in MG_i
L_i	Life time of RES/BESS in MG_i
E_i^{SI}	Salvage Cost of RES/BESS in MG_i
E_i^{IC}	Investment Cost of RES/BESS in MG_i
$E_i^{O\&M}$	Operation & Maintenance Cost of RES/BESS in MG_i
$C_i^{PG,t}$	Cost for power purchased/sold by MG_i from grid during t
$E_{p,s}^t$	Peer to Grid energy trading price during t
$C_i^{PMG,t}$	Cost for power purchased/sold by MG_i from NMG during t
$LPSP_{MG_i}$	LPSP of individual MG_i
$LPSP_{NMG}$	LPSP of NMG framework
C	Total operation cost of NMG
C_{OM}^i	Operation and Maintenance (O&M) cost of RES in MG_i
$C_{G,TD}^i$	Cost of energy trading with the grid by MG_i
$C_{N,TD}^i$	Cost of energy traded within NMG by MG_i
C_{ESS}^i	Cost of energy exchanged with ESS by MG_i
MG	Total number of MGs in NMG
$\rho_{PV}^{i,t}$	O&M cost of PV
$P_{PV}^{i,t}$	Power generated by PV in MG_i at time t
$\rho_{WT}^{i,t}$	O&M cost of WT
$P_{WT}^{i,t}$	Power generated by WT in MG_i at time t
T	Total number of operated hours
$\rho_{b,G}^{i,t}$	Electricity price at which MG_i buy electricity from the grid
$P_{b,G}^{i,t}$	Amount of energy bought by MG_i from the grid at time t
$\rho_{s,G}^{i,t}$	Electricity price at which MG_i sell electricity to the grid
$P_{s,G}^{i,t}$	Amount of energy sold by MG_i to the grid at time t.
$\rho_{b,N}^{i,t}$	Electricity price at which MG_i buy electricity from the NMG

$P_{b,N}^{i,t}$	Amount of energy bought by MG_i from the NMG at time t
$\rho_{s,N}^{i,t}$	Electricity price at which MG_i sell electricity to the NMG
$P_{s,N}^{i,t}$	Amount of energy sold by MG_i to the NMG at time t
$\rho_{b,ESS}^{i,t}$	Electricity price at which MG_i buy electricity from ESS
$P_{b,ESS}^{i,t}$	Amount of energy bought by MG_i from ESS at time t
$\rho_{s,ESS}^{i,t}$	Electricity price at which MG_i sell electricity to ESS
$P_{s,ESS}^{i,t}$	Amount of energy sold to MG_i from ESS at time t
$P_L^{i,t}$	Load in MG_i at time t
η_c	Charging and discharging efficiency of the ESS
η_d	Discharging efficiency of the ESS
$\Delta(t)$	Period for which ESS is charging or discharging.
$P_L^{N,t}$	Total load in NMG at hour 't'
$P_L^{G,t}$	Total generation in NMG at hour 't'
TOU^t	TOU price for hour 't'

List of Abbreviations

MG	Microgrid
DER	Distributed Energy Resources
DG	Distributed Generation
ESS	Energy Storage System
IESS	Individual Energy Storage System
SESS	Shared Energy Storage System
BESS	Battery Energy Storage System
DG	Distributed Generators
CHP	Combined Heat and Power
RES	Renewable Energy Sources
NMG	Networked Microgrid
EMS	Energy Management System
DR	Demand Response
D	Discount Rate
DMS	Distributed Management System
DSO	Distribution System Operator
DNO	Distribution Network Operator
MGO	Microgrid Operator
EMO	Energy Market Operator
P2P	Peer-to-Peer
P2G	Peer-to-Grid
PLC	Power Line Communication
QoS	Quality of Service
PV	Photo-Voltaic
DSM	Demand Side Management
FERC	Federal Energy Regulatory Commission
NSGA	Non-dominated Sorting Genetic Algorithm
CP	Compromised Programming
MMG	Multiple Microgrid
DA	Day Ahead
PSO	Particle Swarm Optimization
TOU	Time-of-Use
MILP	Mixed Integer Linear Programming

MAS	Multi Agent System
MIQP	Mixed-Integer Quadratic Programming
AEP	Annual Energy Profit
ESP	Energy Service Provider
MOPSO	Multi-Objective Particle Swarm Optimization
PCC	Point of Common Coupling
MGO	Microgrid Operator
E-zone	Excessive Zone
NE-zone	Non-Excessive Zone
WT	Wind Turbine
LPSP	Loss of Power Supply Probability
AEC	Annual Energy Cost
MOO	Multi-Objective Optimization
REP	Repository
MGCC	Microgrid Central Controller
FIT	Feed-In Tariff
MV	Medium Voltage
LV	Low Voltage

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Chapter 1
Introduction

1.1 Microgrid

An MG is a self-sustained power system that can operate independently or in parallel with the conventional, centralized electrical grid. MGs incorporate DERs such as DG, ESS, and CHP systems with defined electrical boundaries [1]. DGs consist of both conventional DGs such as diesel generators, natural gas generators, microturbines, etc and RES. An MG can power a single building or campus, a small community, or a specific industrial facility. An MG can operate in two operational modes: grid-connected mode and islanded mode. When operating in grid-connected mode it is connected to the main grid and can export or import power as required. They operate in "islanded mode" during grid failures or system fluctuations.

An MG is not connected to the main grid when it is operating in islanded mode, thus it must rely on its resources to meet the power demand. The DERs work together to meet the power demand of the MG and ensure an equilibrium between demand and supply in island mode. Also, MG is exclusively responsible for the system's reliability, power quality, and security in island mode. The island mode, allows MGs to deliver reliable power and enhance the system's overall resilience. An MG is considered a single entity from a grid point of view in both cases because it is a self-sufficient system that can generate, distribute, and manage its power supply regardless of its connection with the grid.

In comparison to centralized power, the following are the advantages and disadvantages of MGs when operating in islanded mode and grid-connected mode:

1.1.1 Advantages

:

- **Reliability**: MGs can provide a reliable power supply by using a combination of DGs and ESS. In case of grid failures, MGs can function in "islanded mode" and supply power to the connected loads.

- **Resilience**: Overall power system resilience is improved, where MGs provide an alternate power source in the event of a grid failure.
- **Sustainable power practices**: MGs can maximize the use of DGs and reduce reliance on fossil fuels, which can lead to enhanced sustainability and decreased greenhouse gas emissions.
- **Cost savings**: MGs can reduce energy costs by using DGs, reducing transmission and distribution losses, and providing ancillary services to grid.
- **Flexibility**: MGs can adapt to different types of loads and energy sources, and can be easily expanded or contracted as needed
- **Reduced dependence on conventional power**: MGs can provide energy independence for remote or rural communities and critical infrastructure such as hospitals and emergency services.
- **Grid support**: MGs can provide ancillary services to the grid, like load balancing and voltage control, which will help enhance the overall power system's stability and reliability.
- **Better integration of RES**: MGs can aid in the integration of RES like solar and wind power into the grid.
- **Increased control over energy supply**: When operating in islanded mode, the MG has full control over the energy it generates and distributes.

1.1.2 Disadvantages

:

- **High initial cost**: The cost of building and integrating an MG into grid or its operation in islanded mode can be high.
- **Dependence on the main grid**: MGs connected to grid are dependent on grid for power during normal operation and may not have the ability to function in island mode.

- **Energy Constraints**: Islanded MGs operate contingent on local energy resources, shouldering sole responsibility for system reliability, power quality, and security. Energy availability in islanded MGs is inherently restricted by local energy sources and storage capacity, exposing these MGs to risks of output power fluctuations, frequency and voltage variations, and potential blackouts.

- **Limited scalability**: MGs operating in islanded mode may be limited in terms of scalability and may not be able to handle large loads or energy demands.

In addition to the mentioned drawbacks, the MG system itself faces security concerns when one or more DG units become unavailable or fail during islanded mode. In such scenarios, the MGs resort to load shedding to maintain the supply-demand balance, which is both economically undesirable and inconvenient.

1.2 Networked Microgrids

NMGs take the concept of MGs further by interconnecting MGs having different characteristics. The enhancement of system performance is significantly achieved by modelling large power grids through a network of interconnected MGs, as stated in IEEE standard 1547.4 [2]. The NMG also operates in two modes similar to individual MGs, i.e., grid-connected and islanded mode. The MGs, forming the NMG, are characterized to be geographically close to each other. The MGs operation structure, in literature, is studied through a layer-based approach. The authors consider three-layer, five-layer, and six-layer structures to distinctly assess the function of each layer in the MGs [3]. The infrastructure/physical layer, control layer, and communication layer are the most important layers among these architectures. In the MG, the infrastructure/physical layer integrates the DERs, communication sources, protection devices, and so on. Various control methods, such as V/f control, PQ control, and droop control, are employed at the control layer through the EMS to ensure reliable performance in different operational modes, depending on the operating conditions of the DERs. The communication layer serves as an intermediary between the control layer and the physical layer and communicates the status of equipment. The interconnection of MGs can be performed at the physical layer or control layer, or both layers [4].

1.2.1 Benefits of NMGs over individual MGs

- **Increased reliability**: NMGs can provide a more reliable power supply by pooling resources and sharing energy. If one MG fails, the other MGs can offer backup power. This allows for better management of supply and demand and can prevent blackouts.

- **Increased resilience**: By providing various alternative power sources in the event of a grid failure, NMGs can improve power system resilience. This can lessen the impact of power outages and increase power availability to customers.
- **Increased energy efficiency**: NMGs can enhance energy efficiency and minimize greenhouse gas emissions by optimizing the use of DERs and reducing reliance on fossil fuels.
- **Cost savings**: NMGs can reduce energy costs by using local energy sources, participating in energy sharing/energy trading, reducing transmission and distribution losses, and providing ancillary services to the grid.
- **Flexibility and scalability**: NMGs can be easily expanded or contracted to accommodate different types of loads and energy sources.
- **Ancillary services**: NMGs help in improving the power system stability and reliability by providing ancillary services to the grid, like load balancing and voltage regulation.
- **Improved DR**: NMGs allow for better coordination of DR, which can help to balance supply and demand and reduce peak load.

1.2.2 Challenges for NMGs

- **Technical challenges**: It can be technically difficult to coordinate the energy flow between the MGs, integrate various loads, and energy resources. This includes ensuring the compatibility of different technologies, dealing with communication and data transfer issues, and ensuring the security of the system.
- **Economic challenges**: Building and maintaining an NMG can be costly, and there may be challenges in developing an economically viable business model. Additionally, the cost of integrating RES and ESS can be high.
- **Regulatory challenges**: There may be challenges in navigating the regulatory environment and meeting the necessary standards and requirements for connecting an NMG to the main grid.

- **Interoperability challenges**: Ensuring interoperability between MGs and grid can be a challenge. This includes dealing with different communication protocols, data formats, and control systems.
- **Cybersecurity challenges**: NMGs are prone to cyber-attacks, and guaranteeing system security can be difficult.
- **Socio-technical challenges**: NMGs involve the integration of various technical and non-technical aspects, such as social acceptance, community engagement, and stakeholder participation. This can be a challenge to ensure that the system meets the needs and expectations of all stakeholders.

1.3 NMG Architectures

In NMG framework MGs can be interconnected both among themselves and with distribution network in various ways. The architectures of NMGs are categorized considering both the interconnection among MGs and distribution network, as well as the control mechanisms governing NMGs. This section explores different architectures derived from the interconnection of MGs and distribution network. In references such as [5, 6], the NMG architecture is elucidated with a focus on its connection to the feeder. The authors describe three different architectures:

1. Series-Connected MGs on a Single Feeder:
   (a) In this architecture, different MGs can connect to each other, and only a single MG is connected directly to the grid.
   (b) This arrangement allows for communication between MGs, but only the MG connected to the grid is responsible for communicating with the DMS.
2. Parallel-Connected MGs on a Single Feeder:
   (a) In this architecture, various MGs are connected directly to the grid without interconnection among them.
   (b) An optional tie-line is provided in this architecture for interconnection among MGs.
3. Interconnected MGs on Different Feeders:

(a) In interconnected MGs on different feeders architecture, the MGs are connected to different feeders with a possible tie-line to interconnect the MGs.

(b) The interconnected MGs and the parallel connected MGs on a single feeder allow communication between the MGs and the DMS.

In these architectures, as shown in Fig. 1.1, DMS has DSO/ DNO, as the decision-making authority, which is considered to communicate with each MG for control and operation of NMG.

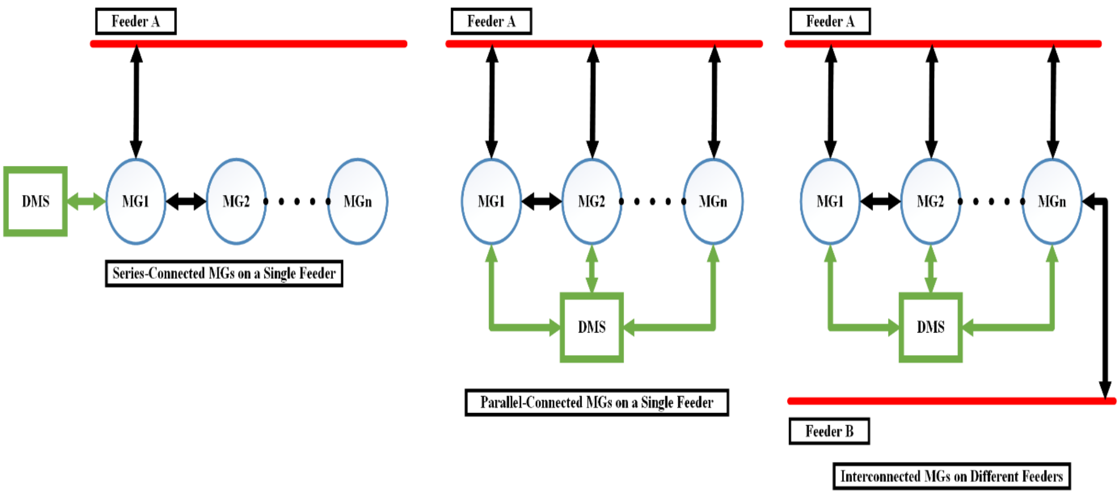


Figure 1.1: NMG Topology based on connection with Feeder.

In [7], NMG architecture is classified based on the type of interconnection with the grid and among the MGs. The architectures are elaborated below and shown in Fig. 1.2:

1. Parallel-Connected MGs with External Grid:

   (a) The parallel-connected MGs with an external grid architecture are similar to the parallel-connected MGs on a single feeder architecture, but the tie-line is absent.

   (b) In this topology, each MG has a single point of connection with the external grid.

2. Grid-Series Connected MGs:

   (a) In grid-series connected architecture, different MGs interconnect among them, forming a grid with no external connection to the grid.

3. Mixed Parallel-Series Connected MGs:

    (a) In mixed parallel-series connected MG architecture, the MGs can form clusters of parallel connection or series-connected clusters, but each cluster must at least have a single point of coupling with the external grid.

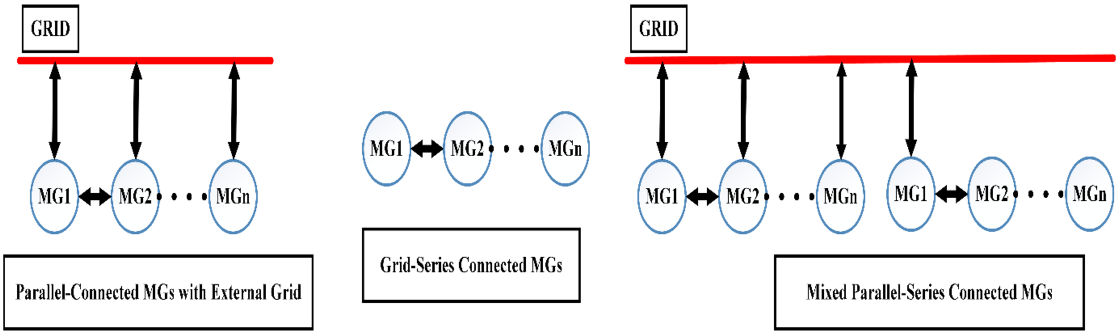


Figure 1.2: NMG Topology based on the type of interconnection with Grid and among MGs.

In [8], based on the interconnection among MGs and with the grid, three different topologies are presented as represented in Fig. 1.3:

1. Radial or Star Topology:

    (a) The radial or star topology is similar to the parallel connected MGs, with each MG individually connected to the grid.

    (b) Energy sharing among the MGs in this topology is only possible through the line dedicated by the grid.

    (c) This topology does not allow energy sharing and communication among MGs directly. The MGs only communicate with DNO directly.

2. Daisy-Chain Topology:

    (a) In the daisy-chain topology, the MGs adjacent to each other are connected, and MGs are also connected to the grid. This allows energy sharing between neighbouring MGs and the grid.

3. Mesh Topology:

    (a) In a mesh topology, each MG is interlinked with other MG, and also each MG is connected to the main grid.

(b) This allows the exchange of energy among any MGs, but the structure is more complicated.

In mesh topology and daisy-chain topology, communication among MGs and with DNO is allowed.

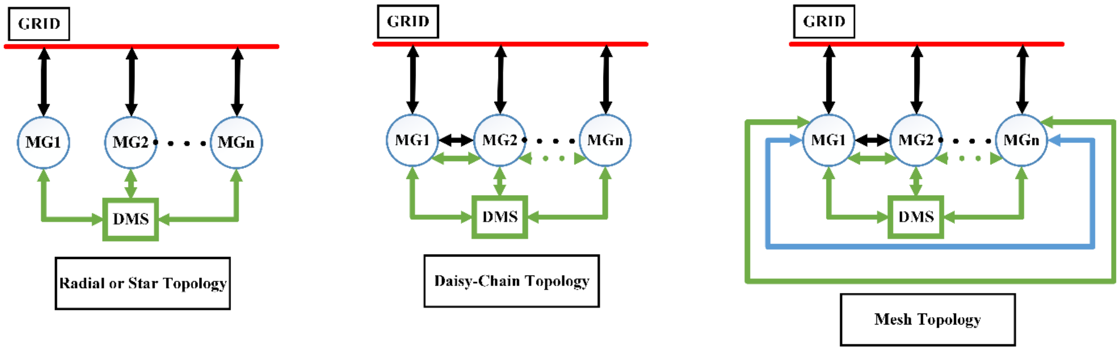


Figure 1.3: NMG Topology based on the type of interconnection with Grid and among MGs.

Table 1.1. compares the different topologies given in the literature. These topologies are classified as radial or star topology or parallel connected MGs, Daisy-chain topology, series-connected MGs, mesh topology, and mixed series-parallel connected MGs.

Based on the control of NMGs, several different architectures of NMGs are proposed, including Centralized architecture, Distributed architecture, Hybrid architecture, Peer-to-peer architecture, and Hierarchical architecture. These architectures are explained in brief below:

1. Centralized architecture:

   (a) In this architecture, a central controller manages and coordinates the energy flow between different MGs.

   (b) It is responsible for monitoring the energy resources and loads and for making decisions about how to best use the resources.

2. Distributed architecture:

   (a) In this architecture, each MG has its controller that is responsible for managing and coordinating the energy flow within that MG.

Table 1.1: Comparison of Different Topologies

Topology	**Description**	**Comment**
Radial topology or Star topology or Parallel connected MGs	All MGs are directly linked to the main grid.	1. Energy path through the main grid only. 2. No exchange of energy between MGs. 3. Trading of energy only with the main grid. 4. Each MG must be self-sufficient in the case of an islanding mode.
Daisy-chain topology	The MGs are linked to the neighboring MGs and to the central grid.	1. Possible flow of energy/information between MGs and the main grid. 2. Based upon interaction with linked MGs, the corresponding MG-EMS defines an operating schedule of its own. 3. Need communication technology to exchange information between MGs.
Series connected MGs	Point-to-point connection between adjacent MGs without connection to the main grid.	1. Connection to an external grid is missing. 2. Energy and information flows between MGs. 3. The integrated MGs must control the voltage, frequency, and maintain power balance. 4. For islanding, the system may be divided into smaller clusters supporting each other.
Mesh topology	All the MGs are interlinked and connected to the main grid.	1. Energy and information flow among all the NMGs. 2. Efficient cooperation between MGs reduces operational costs. 3. Interconnected MGs affect the scheduling. 4. Rigid communication between MGs is required.
Mixed series-parallel connected MGs	The MGs can connect directly to the grid or form series clusters beforehand and connect to the main grid.	1. Allows supporting other MGs during islanding or any disturbance in the main grid. 2. Incorporates the advantages and disadvantages of series-connected and parallel-connected MGs.

(b) The controllers can communicate with each other to share information and coordinate energy flow between the MGs.

3. Hybrid architecture:

   (a) This architecture combines elements of both centralized and distributed architectures.

   (b) A central controller manages and coordinates the energy flow between MGs, but each MG also has its controller to manage the energy flow within the MG.

4. P2P architecture:

   (a) This architecture allows MGs to communicate and transact energy and ancillary services directly with each other without the need for a central controller.

   (b) However, different models instead of complete P2P are also studied. Where MGs trade among their peers with the mediator i.e. energy sharing coordinator. Here, the mediator participates on behalf of the participant and performs energy trade. In another model, the combination of P2P and mediator is performed.

5. Hierarchical architecture:

   (a) This architecture divides the MGs into different levels, such as primary, secondary, and tertiary MGs.

   (b) Primary MGs are connected to the grid, while the secondary and tertiary MGs are linked to the primary MGs.

The choice of architecture depends on the requirements of the NMGs, such as size, location, type of energy resources, loads, and the main grid connection. Centralized architectures are commonly used for smaller systems, while distributed or hybrid architectures are used for larger systems. Peer-to-peer and hierarchical architectures are becoming more popular in recent times.

For the above-presented architectures based on the control of NMGs, the communication network is vital for transferring measurements and control signals. In a power system, PLCs are utilized because of low costs and the transfer of information through

Table 1.2: Comparative Analysis of Wired and Wireless Technologies

Type	Technology	Advantages	Disadvantages
Wired	Optic Fiber	High Speed Low interference Low latency	Expensive Complex scalability
	Twisted Pairs	Easy access Easy configuration	Complex scalability
	PLC	Low implementation cost	Fixed topology Complex scalability
Wireless	Wi-fi	Cheaper technology Easy scalability	Low security Susceptible to interference
	ZigBee	Cheaper technology Low power consumption	Low speed
	Bluetooth	Cheaper technology Low power consumption	Low penetration Security issues
	Cellular	Low latency	Expensive

power lines, whereas this cannot be utilized in individual MGs or NMGs because of the presence of fast response inverter-based DERs. For MGs and NMGs, wired or wireless technology can be used for communication. The selection of appropriate communication depends on factors such as scale of MG, latency, reliability, bandwidth, QoS, scalability, interoperability, security, data losses, operation and maintenance cost, etc [9, 10]. Table 1.2, presents a comprehensive analysis of wired and wireless technologies, encompassing their appropriateness, benefits, and drawbacks [9, 10].

1.4 Motivation of Research

The motivation behind this research stems from the growing need for sustainable and efficient energy solutions in the face of increasing demand, and enviromental concerns within centralized power systems. The limitations of individual MGs, such as their reliance on local resources and potential failure scenarios, underscore the necessity of developing advanced NMG frameworks that can overcome these challenges.

The aim is to leverage the interrelation of MGs within NMGs to maximize energy efficiency, optimize resource utilization, and facilitate seamless energy trading. By addressing technical, economic, and regulatory challenges, this research endeavors to unlock the potential of NMGs, paving the way for a resilient, secure, and cost-effective energy ecosystem.

1.5 Aim and Objectives

The primary objective of this thesis is to comprehensively investigate the potential of NMGs and develop strategies to maximize their efficiency and profitability. The specific research objectives are outlined as follows:

- To implement an hour block-based demand response program in NMGs, minimizing operating costs of individual MGs and NMG, and optimizing load profiles while simplifying the complexity of the DR problem.
- To conduct an optimal sizing analysis of RES and BESS in NMGs based on proportional P2P and P2G energy trading, to reduce annual energy costs, and enhancing system reliability.
- To perform an economic analysis of energy scheduling and trading within a multiple-microgrid environment, aiming to develop innovative energy management and scheduling strategies within the NMG system, optimize resource dispatch, maximize individual MG profits, and enhance the overall performance of the entire NMG.
- To develop and analyze scheduling strategies for utilizing a SESS in NMG, addressing the integration of SESS to overcome cost and space limitations of IESS for each MG, thereby minimizing the overall operating cost of NMGs.

1.6 Significance of the Study

The significance of this research lies in its potential to address critical challenges in the energy sector and pave the way for a more sustainable and efficient energy future. By focusing on the development and optimization of NMGs, this study aims to make the following contributions:

- **Enhanced Efficiency and Reliability**: The proposed strategies and frameworks for NMGs have the potential to significantly enhance the overall efficiency and reliability of the energy distribution system. By leveraging advanced demand response programs and optimal resource sizing, NMGs can effectively balance energy demand and supply, ensuring a consistent and reliable power supply for communities and industries.

- **Cost Reduction and Profit Maximization**: The economic analyses and scheduling strategies introduced in this study aim to reduce operational costs and maximize profits for individual MGs within the network. By optimizing energy trading and resource utilization, NMGs can minimize energy costs, leading to potential savings for both MG operators and end consumers.
- **Resilient and Sustainable Energy Infrastructure**: The integration of SESS and advanced energy management techniques can significantly enhance the resilience and sustainability of NMGs. By overcoming the limitations of IESS and fostering seamless energy sharing, NMGs can ensure a more stable and sustainable energy infrastructure, reducing the impact of grid failures and fluctuations.
- **Advancement of Energy Trading Techniques**: The study's focus on proportional P2P energy trading and innovative energy scheduling strategies not only contributes to the advancement of energy trading techniques within NMGs but also sets the stage for more efficient and transparent energy markets. These advancements can foster a more collaborative and competitive energy trading environment, promoting fair pricing and effective resource utilization.
- **Practical Implementation and Industry Adoption**: The practical implications of the research findings are significant for industry stakeholders, policymakers, and energy regulators. The findings obtained from this research have the potential to guide the creation of stronger regulatory frameworks, encouraging the uptake of next-generation technologies and facilitating the incorporation of sustainable energy solutions into current energy infrastructures.

By addressing these key areas, the study aims to contribute to the broader discourse on sustainable energy management and advance the practical implementation of NMGs, thereby fostering a more resilient, reliable, and sustainable energy ecosystem for present and future generations.

1.7 Organisation of the thesis

This thesis is organised into six chapters. The work presented in each chapter is outlined as follows:

Chapter 1: Introduction - highlights individual MGs' advantages over centralized networks, but notes their limitations, leading to the emergence of the NMG framework.

It briefly examines different NMG architectures, delving into their advantages and disadvantages in terms of connectivity and trading. Also outlines the research goals, contributions, and thesis structure.

Chapter 2: Literature Review - A comprehensive analysis of existing literature relevant to the NMG framework, identifying key findings and research gaps.

Chapter 3: Hour Block-Based Demand Response Optimization - Exploration of the implementation of an hour block-based DR strategy in NMGs, with a particular focus on load optimization and reduction of operational costs.

Chapter 4: Optimal Sizing of RES and BESS in NMGs - Investigating the optimal sizing of RES and BESS in NMGs through proportional P2P and P2G energy trading to enhance reliability and minimize annual energy costs.

Chapter 5: Economic Analysis of Energy Scheduling in Multiple-Microgrid Environments - Analysis of energy scheduling and trading strategies in an NMG setting to maximize individual MG profits and benefit the entire NMG system.

Chapter 6: Strategies for Utilizing Shared Energy Storage Systems in NMGs - Discussion on the development and analysis of scheduling strategies for utilizing SESS in NMGs, with the aim of minimizing the overall operating cost of the network.

Chapter 7: Conclusion - A comprehensive summary of the research findings and contributions of the thesis, along with recommendations for future research directions and practical implications.

Chapter 2
Literature Review

2.1 Introduction

The concept of NMGs as an alternative framework, its advantages, and different architectures are studied in the previous chapter. In the pursuit of advancing into NMGs, this dissertation embarks on a comprehensive exploration of relevant literature, synthesizing existing knowledge and identifying gaps that warrant further investigation. The literature survey serves as the foundational chapter, offering a panoramic view of the current state of research in NMGs, their operational strategies, and their role in the evolving energy landscape. The literature review chapter is organized into distinct sections, each focusing on key dimensions of NMG research. The chapter delves into specific aspects, including demand response strategies, optimal sizing of renewable resources and energy storage, economic analysis of energy scheduling, and innovative approaches involving SESS.

2.2 Arrangement of Sections

- Demand Response in NMGs: This section explores existing research on DR strategies within NMGs, considering how these strategies contribute to load optimization and cost reduction.
- Optimal Sizing of RES and BESS: In this section literature related to the optimal sizing of RES and BESS provides insights into maximizing reliability and minimizing operational costs in NMGs.
- Economic Analysis of Energy Scheduling: The economic analysis of energy scheduling within NMGs is a focal point, examining various strategies for profit maximization and efficient energy trading.
- Utilization of SESS: The last section delves into innovative models involving SESS, exploring the economic and operational benefits of collaborative energy storage initiatives.

In this thesis, the notations NMG and MMG are used interchangeably to denote the same concept of interconnected MGs.

2.3 Hour Block-Based Demand Response Optimization

NMGs are typically installed at the MV level, with several LV MGs and DERs connected to the nearby distribution network [11]. This arrangement improves the operational efficiency of the system by optimizing the use of RES, thereby promoting environmental sustainability. It also helps in minimizing energy losses, enhancing system protection and reliability, and facilitating energy trading between MGs to increase overall profitability [12].

The variability of RES, such as PV and Wind, often leads to a mismatch between supply and demand within an MG. This variability contributes to scenarios where generation exceeds demand, while at other times, demand surpasses generation. In response to this energy imbalance, MGs contemplate the incorporation of backup generation, including diesel generators, utilization of ESS, and adoption of DSM strategies [13, 14]. However, the integration of diesel generators has been observed to exacerbate environmental issues. ESS integration in MGs is hindered by its limited power capacity, high maintenance costs, and energy losses during charging and discharging. In the context of NMGs, various DSM strategies are employed to bridge the gap between supply and demand. DSM allows consumers to adjust and curtail their peak load in response to the fluctuating generation [15]. Among the different DSM methods, DR programs facilitate load shifting corresponding to generation, incentivizing consumers accordingly. This capability enables the rearrangement of load profiles within an MG, particularly in an NMG configuration. The FERC classifies DR programs into two categories: time-based and incentive-based initiatives [16].

In [17], the impact of the DR program in MMG-based ADN is explored by considering DR transaction costs in the objective. The problem is formulated as a multi-objective optimization problem and solved using an NSGA-II and backward forward load flow technique. Additionally, a collaborative multi-objective EMS is proposed for the MMG environment [18]. The strategy involves using CP to minimize MMG costs while reducing its dependence on the power grid. The implementation of the DR framework is based on grid prices. Moreover, an EMS based on a cooperative market framework is proposed for MMGs operating in both grid-connected and isolated modes in [19]. The approach utilizes nodal marginal prices to optimize market clearing, thereby maximizing NMG's social welfare. Real-time pricing-based incentive DR programs are considered in this model. Additionally, [11] highlights the maximization of profits for DNOs within the MMG framework using multi-follower bi-level programming. This involves the implementation of energy trading among MGs and the DR program. At the top level, the DNO aims to reduce operational costs by considering grid power purchasing costs, electricity exchange costs, and DER operating costs. At the lower stage, MGs aim to optimize benefits while complying with DR requirements. Furthermore, a hierarchical bi-level optimization approach is suggested in [20], with the upper-level network operator and the lower-level MG operator collaborating for the efficient operation of MMGs. The DR program is applied based on TOU pricing. The optimization problem with DR is resolved using PSO. Considering isolated NMGs, [21], proposes a bi-level EMS with the outer level focusing on energy and information exchange among interconnected MGs. The inner-level EMS is responsible for the scheduling of isolated MGs during faults, along with the introduction of a novel power exchange pricing scheme and step-by-step DR program implementation.

In [22], a hierarchical optimization algorithm, based on the MAS, is introduced to minimize operational costs and enhance the reliability of NMGs. The proposed EMS incorporates adjustable control and DR programs and utilizes the MILP model for problem optimization. In [23], an intelligent EMS is presented, catering to both local and global energy markets. The local market facilitates energy trade wit hin MGs, while the global market handles energy transactions between MGs and the grid. MAS-based energy trading among smart MGs with DR is introduced in [24], employing an innovative incentive strategy that prioritizes energy generation preference during deficit periods. Following the execution of energy contracts, a novel method is used to distribute energy losses among the DGs and loads. A priority-driven DR program, akin to [23], is implemented, considering load size and frequency of participation. The simulation of trading and power management is facilitated using agent theory. In [25], a two-stage energy management system for NMG based on MIQP and game theory, integrating distribution feeder reconfiguration in the presence of shiftable load-based DR programs is proposed. A two-level framework for optimizing the operation cost of interconnected islanded NMGs, incorporating a price-based DR approach is proposed in [26]. Furthermore, in [27], the influence of DR intensity and BESS size on MG costs, intra-MG trading, power transfer to loads in MGs, and BESS charging is investigated. The study examines both price-based and incentive-based DR methods within the NMG framework. The proposed methodology increases internal trading among MGs while reducing external energy trading with the grid and operational costs.

In [28], an EMS for optimal MG scheduling is proposed, utilizing time-based DR techniques. The time-based DR approach is based on microeconomics, where load-shifting depends on differentiated pricing models, including single-price and multi-sensitivity models. The optimization problem is formulated as an MILP problem. For the DA scheduling of MMGs, a time-based DR solution is recommended in [29]. The proposed EMS accounts for load priority, voltage profiles, and the number of loads in MGs to mitigate operating costs and environmental impacts. Time-based DR is also adopted in NMGs for reconfiguration purposes within the distribution network, determining the states of interconnecting switches between MGs and the grid [30]. A price-based DR is proposed along with adjustable power for NMG [18], to minimize the cost for MGs. Time-based and incentive-based DR programs are proposed for networked multi-carrier networked microgrids to improve flexibility and minimize costs [31].

2.3.1 Summary

From the literature review on DSM in NMGs, the implementation of DR in NMGs considering an hour-to-hour DR approach which depend on the generation of DGs, BESS, load, and price signals from the grid is observed. However, the review does not delve into strategies for reducing the time required to implement DR within the NMG framework.

2.4 Optimal Sizing of RES and BESS in NMGs

Several research studies have delved into the optimal sizing of RES and BESS in NMGs with a focus on minimizing operational costs and losses, maximizing reliability, resilience, and profit. In [32], a three-level approach is established to determine the ideal size for NMGs, considering resilience, and cost. This strategy integrated the adaptive genetic algorithm, NSGA-II, and time-coupled AC optimal power flow. In the pursuit of increased resilience and reliability, [33] delves into the optimal sizing of the ESS within NMG. Here, a bi-level problem is reduced to a single-level problem and solved using MILP. In [34], proposed determination of boundaries, optimum size, and placement of DGs for different MGs utilizing the imperialist competitive algorithm, aiming to optimize the operating costs of MMG. The borders of the MGs based on geographical and electrical constraints, it does not account for power exchange among MMGs. In [35], the optimal siting, sizing, type, and dispatch of DERs, incorporating the allocation of section switches. The problem is formulated as MILP and tackled using MOPSO. In [36], suitable placement and size of components in various buildings serving as smart MGs for a pilot project in Iran is proposed. Sizing and siting are optimized using PSO to reduce MG costs and losses, without addressing inter-MG trading. In [37], a two-stage

NMG planning strategy is outlined, with the initial stage concentrating on minimizing yearly investment costs and the subsequent stage on reducing daily operating expenses in both grid-connected and islanded modes.

In [38], a case study in Adelaide aimed at minimizing the total yearly cost to meet the annual load demand is proposed. The study illustrated how individual homes in the area operate as an MG, collectively forming an MMG framework. It demonstrated that MMG reduces the required capacity for DG installation and enhances grid interaction. In [39], RE generation planning, considering long-term investment and short-term operating costs is examined. This work employed Nash bargaining mechanism to distribute costs among the MGs, without factoring in energy exchange between MG and the grid. Additionally, [40] achieved the optimal sizing of DG, ES, and the market clearing price for energy trading, taking into account the interaction between the MMG and the real-time electricity market to lower the MMG's overall cost. The Cournot equilibrium is utilized to determine the market-clearing price, and quantum-PSO is employed to establish the optimal decision variables. In a bid to minimize operational expenses, [41] addressed the optimal planning of both single and multi-carrier MGs, considering all technical, environmental, and mechanical constraints, and tailoring the sizing accordingly to the seasonal load changes.

Furthermore, [42] determined the optimal capacity allocation of RES and BESS to maximize the AEP by treating the problem as a cooperative game and solving it for the Nash bargaining solution using PSO. In [43, 44], a Nash equilibrium and cooperative game is proposed for the multi-objective game-theoretic challenge in allocating capacities for RES and BESS. This approach utilizes PSO with the objective to maximize AEP and enhancing system reliability.

2.4.1 Summary

From the literature review on optimal sizing of RES and BESS considering energy trading, different objectives like cost minimization, improving reliability, and resilience and profit maximization are considered. However, the literature lacks consideration of trading energy through the NMG manager/aggregator among seller and buyer MGs for determining the ideal sizes of RES and BESS.

2.5 Economic Analysis of Energy Scheduling in Multiple-Microgrid Environments

Numerous studies have focused on strategies to maximize profits in NMGs by incorporating various scheduling techniques and enabling energy trading among MGs within the NMG framework. In [45], a naive auction algorithm is introduced for energy trading among MGs in NMG. This strategy is tested for two scenarios, proving effective only when the market consists of an equal number of buyers and sellers. To facilitate energy trading within an MMG setup, a cooperative model providing additional flexibility in energy trading through the community EMS [46] is proposed. In [47], proposed energy trading based on agents, integrates ESS at both the local and global levels. Considering the interaction between ESPs and the energy market, [48] designed a Stackelberg game for EM of MMGs using a bi-level programming technique.

In [49], a contribution-based energy trading mechanism is proposed, confirming the existence of Nash equilibrium among consumers for fair energy allocation. Furthermore, in [14, 50, 51] a similar approach is proposed, focusing on energy allocation based on a priority index for different MGs. A coalition operation model aimed at minimizing total operation costs is presented in [52], while [53] formulated an intra-MG trading problem as a non-cooperative game and proposes a multi-leader multi-follower Stackelberg game model for inter-MG trading. Utilizing rolling optimization in the first stage to schedule ESS and the Stackelberg game to optimize internal prices in the second stage, [54] introduced PSO-based energy scheduling for MMGs, minimizing distribution losses and maximizing MG profits.

In [55], a probabilistic optimization approach for scheduling NMGs is proposed, under conditions of uncertainty. In the proposed EMS, the BESS is charged/discharged for utilization within the MGs and does not participate in energy trading. The EMS efficiently manages the charging and discharging of BESS, ensuring a balanced generation and load in NMGs and reducing costs for customers. In [56], a three-stage approach is proposed for resilience-constrained scheduling of NMGs, with the BESS utilized for addressing load imbalance and contingency scenarios. In [57], a two-stage robust optimization model addresses uncertainties and outages in the scheduling of DERs, involving BESS operation based on energy balance or during outages. In [58] and [59], the emphasis is on utilizing BESS to enhance the resilience of NMGs, providing backup power during sudden failures, enabling load shifting, integrating renewable energy, and regulating voltage. In [60], the facilitation of distributed P2P trading among MGs within an ADN using ESS, to enhance energy supply and demand management is demonstrated. Additionally, a hybrid ESS is employed to optimize the economic schedule for NMGs in [61], utilizing BESS for long-term energy storage and super-capacitors for short-term energy storage and rapid load response. In [62], a centralized dispatch algorithm, where ESS in each MG of the NMG framework are optimized based on current load imbalance in MG and predicted energy demand and RES generation, is proposed.

2.5.1 Summary

The literature review delves into strategies for profit maximization in NMGs, focusing on energy trading and scheduling of IESS. The explored literature presents various applications of IESS, showcasing its role in improving NMG performance. However, a noticeable gap in the existing research is evident, specifically, in studies that directly compare the utilization and scheduling of IESS under different conditions.

2.6 Strategies for Utilizing Shared Energy Storage Systems in NMGs

The integration of ESS requires significant space and comes at a high cost. The high costs associated with ESS installation and replacement restrict its integration in different frameworks. Also, ESS such as BESS have a limited life span and need to be replaced after a certain number of charging-discharging cycles or after a specified lifespan. To overcome these disadvantages and bring new economic opportunities, the concept of shared economy has been introduced for ESS, known as SESS. In SESS, multiple users invest in or combine, to operate the ESS, allowing them to charge and discharge the ESS according to their needs [63]. This reduces the initial investment burden for users and allows for efficient usage of ESS for users with different generation and load patterns. SESS has a large capacity that enables users to often charge and discharge while also utilizing energy stored by other users as an additional energy source, in turn reducing the electricity price [64]. According to [65], SESS can be implemented through both direct and indirect approaches. In the direct approach, external ESS is implemented or the IESS are interconnected with each other. In an indirect approach, IESS shares only the stored energy, and capacity sharing of ESS cannot be adopted. In [65], SESS is classified as: a) community ES b) cloud ES c) virtual ES.

Furthermore, [66] proposed a DA economic optimal dispatch model for a cluster of

MGs incorporating SESS, considering factors such as MG energy demand and supply, SESS capacity, P2P transaction prices, and electricity grid constraints. In [67], an optimal dispatch model for NMG with an SESS is proposed while considering uncertainties in RES and load forecasting. In [68], a DA bidding strategy for a cloud ESS, facilitating long-term and short-term agreements between MGs and the electricity market is proposed. References [69] and [70] propose bi-level optimization problems, with cloud ESS coordination among MGs and the grid, enabling efficient energy exchange among the stakeholders.

2.6.1 Summary

Literature on the utilization of SESS in various forms for different households, buildings, apartments, and communities is abundant. However, research on the application of SESS for NMGs is limited.

2.7 Conclusion

The literature review on NMGs reveals several noteworthy findings and research gaps. The implementation of DR in NMGs is explored with a focus on an hour-to-hour approach, relying on DGs, ESS, load, and grid prices. However, strategies to expedite DR implementation within the NMG framework remain underexplored. Therefore, in Chapter 3, a novel hour block approach is proposed for DR application in NMGs, aiming at load optimization and operational cost reduction. The optimal sizing of RES and BESS in NMGs have been investigated considering objectives such as cost minimization, reliability improvement, resilience, and profit maximization. While the literature explores energy trading, it overlooks the potential of trading energy through the NMG manager/aggregator among seller and buyer MGs to determine ideal RES and BESS sizes. Chapter 4 addresses this gap by studying optimal sizing, incorporating proportional P2P and P2G energy trading through the NMG manager/aggregator. Profit maximization in NMGs, centered on energy trading and IESS scheduling, showcases various applications with a positive impact on NMG performance. Nevertheless, a gap exists in studies directly comparing IESS utilization under different conditions. Chapter 5 addresses this gap by exploring various strategies for energy scheduling and trading, aiming to maximize the profits of individual MGs and the entire NMG. While SESS finds extensive use in diverse settings, research specifically focusing on their application in NMGs is limited. This points to a critical research gap, highlighting the need for further exploration to enhance the understanding and utilization of SESS in the context of NMGs. Considering this different scheduling strategies are studied and developed for utilizing SESS with the objective to minimize operating cost of network.

Chapter 3

Hour Block based Demand Response for Optimal Energy Trading Profits in Networked Microgrids

3.1 Introduction

This chapter pioneers an hour-block-based DR method tailored for NMGs. This approach strategically employs generation and load imbalances, TOU pricing, and dynamic MG roles within NMG environments. This study crucially analyzes and compares hour-to-hour and hour-block-based energy trading with DR in NMGs. Unlike the typical 24-hour optimization, the hour-block model proposed in this chapter simplifies DR challenges. Operating under grid-connected NMG assumptions, we aim to reduce MG and total NMG operational costs. Compared to prevalent hour-to-hour DR approaches, the proposed novel hour-block methodology streamlines DR applications within the NMG framework. The interconnectedness of MGs and the grid, along with a deterministic approach, forms the optimization basis. The application of PSO refines the proposed approach, ensuring satisfaction for customers and MGs in the NMG ecosystem.

3.2 System Description

NMGs are a cluster of MGs i.e. having physical interconnection among two or more MGs and exchange energy among MGs. In addition to the exchange of energy among MGs, they can also trade with the grid. An MG can be AC or DC type based on the DER generation or use of type of power for distribution. The NMG framework allows both types of MGs to be connected and also interchange energy. A benchmark framework for NMGs is proposed in [71]. This benchmark system is modified to facilitate energy trading amongst the MGs, as shown in Fig. 3.1. The NMG system under consideration comprises of four distinct MGs of varying sizes, each interlinked with one another and connected to the distribution network. The total NMG system consists of 40 Buses and 44 transmission lines. Each MG is considered to consist of PV and wind generation along with controllable loads. The details of each MG are presented in Table 3.1. The first bus of each MG i.e., bus numbers 101, 201, 301, 401 are considered as a slack

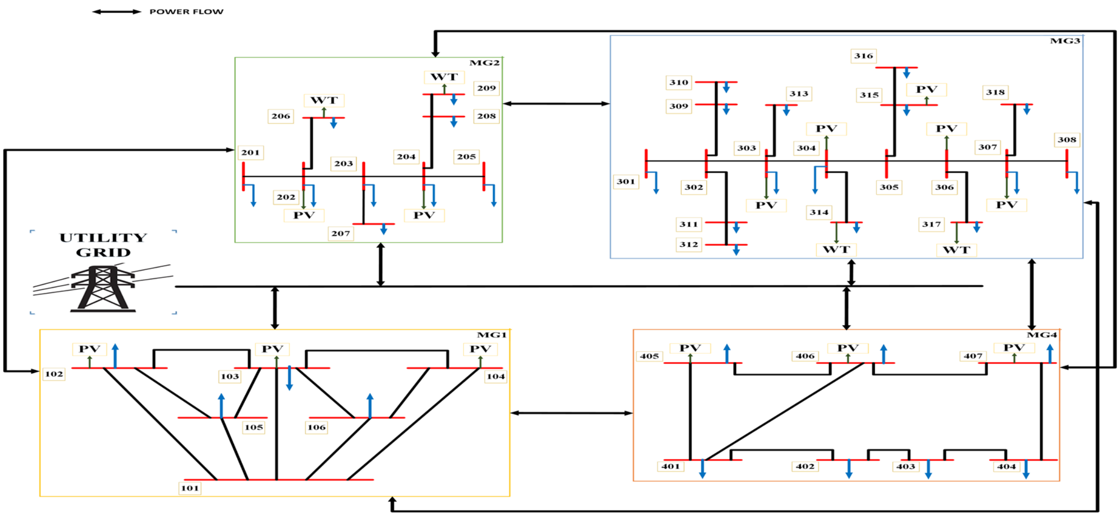


Figure 3.1: Modified Single Line Diagram of NMG.

bus for corresponding MG. The MGs are interconnected to each other through the PCC. The MGs within the NMG environment can exchange energy with each other and the grid through dedicated lines. Also, a different framework where each MG shares the information about excess / deficit energy in the MG with NMG manager / aggregator as shown in Fig. 3.2. The MGs with excess energy are defined as sellers and the MGs with deficit energy as buyers. The NMG manager / aggregator is responsible for collecting this information and allocating the energy from seller MGs to buyer MGs. Here, the NMG manager or aggregator is also responsible for determining prices for energy trading among MGs.

Table 3.1: Details of MGs in NMG system

Quantity of Components	**MG_1**	**MG_2**	**MG_3**	**MG_4**	**Total**
Buses	6	9	18	7	40
Feeders	11	8	17	8	44
PV Systems	3	3	6	3	15
Wind Energy Systems	0	2	2	0	4
Slack bus	101	201	301	401	4

At a particular hour 't', each MG in the NMG framework will generate power G_i^t based on the sources in MG to supply a load $L_{d_i}^t$. Depending on the environmental condition and the number of sources available in MG, sometimes $G_i^t \geq L_{d_i}^t$, then the respective MG acts as a seller for the corresponding hour 't'. The seller MGs are assigned as set 'S' as in [Eq 3.1]. When, $L_{d_i}^t \geq G_i^t$ for an MG, then the respective MG functions as a buyer for the same corresponding hour 't'. The buyer MGs are assigned to a set 'B' as in [Eq

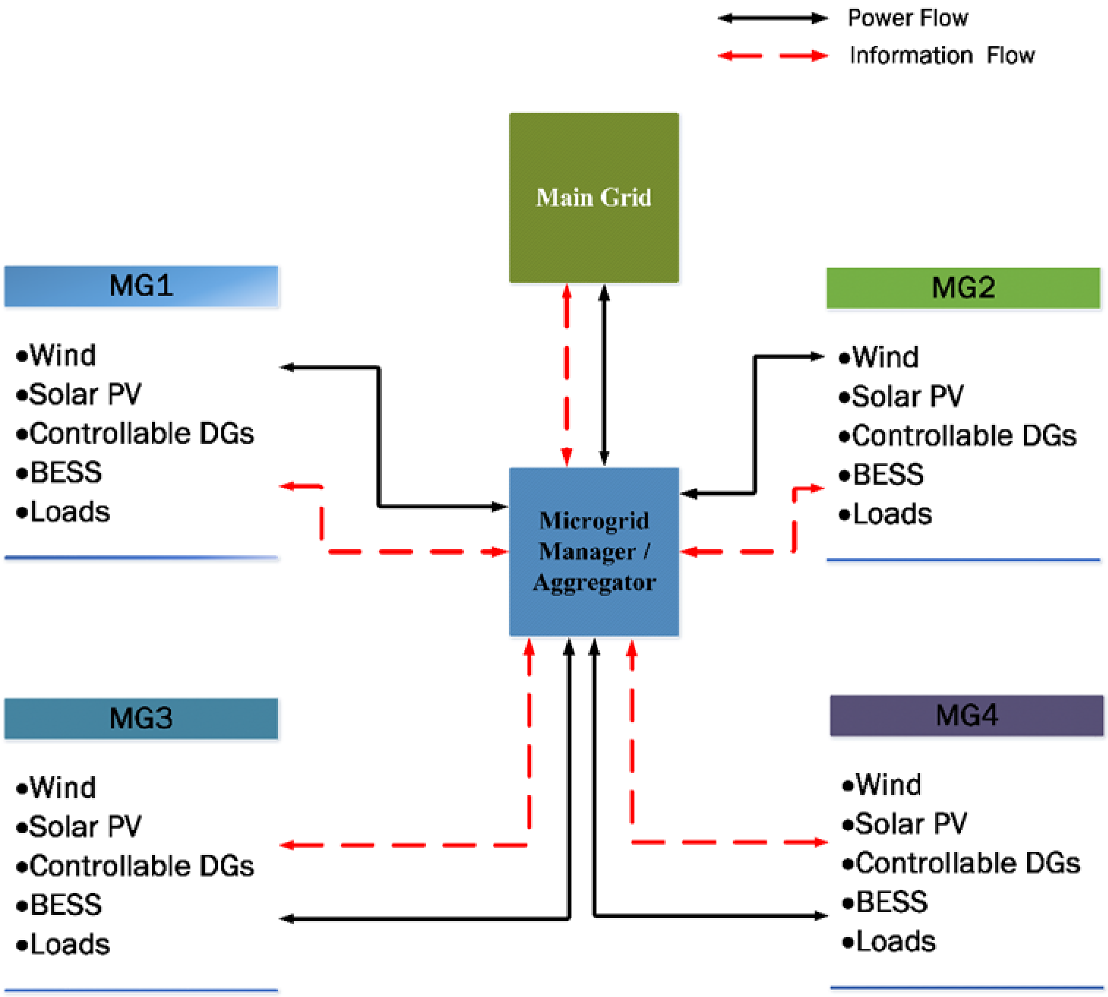


Figure 3.2: NMG Framework with NMG Manager / Aggregator.

3.2]. After meeting their corresponding load, each seller MG has excess energy as given in [Eq 3.3]. The buyer MG, after receiving energy from its corresponding generation requires an additional energy given as [Eq 3.4]. The surplus energy with seller MGs in 'S' is exchanged with buyers MGs in 'B'. At the corresponding hour 't', if the excess energy with seller MGs is more than the energy required by buyer MGs, it is sold to the grid. Also if the energy required by buyer MGs is more than the energy with seller MGs, it is bought from the grid.

$$S = \{\forall i \in N \mid G_i^t \geq L_{d_i}^t\} \tag{3.1}$$

$$B = \{\forall i \in N \mid G_i^t < L_{d_i}^t\} \tag{3.2}$$

$$E_i^t = G_i^t - L_{d_i}^t \quad \forall i \in S \tag{3.3}$$

$$D_i^t = L_{d_i}^t - G_i^t \quad \forall i \in B \tag{3.4}$$

At hour 't', the TOU prices given by the grid are $P_{\text{grid},s}^t$ and $P_{\text{grid},b}^t$, where, $P_{\text{grid},s}^t$ is the price at which the grid sells energy to the MG and $P_{\text{grid},b}^t$ is the price that the grid pays for the energy supplied by the MG. While, trading energy among the MGs in the NMG framework, the price is in between the range of $P_{\text{grid},s}^t$ and $P_{\text{grid},b}^t$. This influences the MGs to trade among them rather than with grid, because the price at which energy bought from MGs i.e., $P_{\text{grid},b}^t$ is lesser than grid selling price i.e. price at which energy sold to MGs $P_{\text{grid},s}^t$ as shown in [Eq 3.5]. This allows MGs to optimize their profits. In case, this constraint is not satisfied, the MGs shall trade energy with the grid rather than other MGs and the objective of forming NMG for energy trading shall cease to exist.

$$P_{\text{grid},b}^t \leq P_{\text{NMG},s}^t = P_{\text{NMG},b}^t \leq P_{\text{grid},s}^t \tag{3.5}$$

3.3 Problem Formulation

Each MG is equipped with either PV or wind generation in the NMG framework to supply power to the corresponding loads. But, the variable and intermittent nature of

RES creates power imbalance in the MGs. This necessitates energy trading among the MGs or with grid. The energy trading is performed based on the hour-to-hour approach in literature. Here, we propose the hour-block based approach to reduce the complexity and time required.

3.3.1 Hour-to-Hour Trading Approach

Among MGs, based on the energy imbalance they are classified as buyers and sellers respectively as discussed in section 3.2. In each hour 't', the amount of energy generated is calculated for each MG, and the power imbalance is calculated to determine the buyers and sellers as given in [Eqs 3.3 and 3.4]. Subsequently, the NMG manager gathers information regarding excess and deficit energy from MGs. Additionally, NMGs supervise the distribution of energy among the MGs using the proportional approach. The NMG is also responsible for determining the trading prices among the MGs in accordance with the conditions specified in [Eq 3.5]. In addition to energy trading, the MGs can derive benefits from load shifting between hours. The extent of load shift is constrained to 20%, as indicated in [Eq 3.6], while ensuring that the total daily load is met, as specified in [Eq 3.7] [72].

$$0.8 \cdot L_{d_i}^t \leq L_{d_i}^t \leq 1.2 \cdot L_{d_i}^t \tag{3.6}$$

$$\sum_{t=1}^{24} L_{d_i}^t = L_{d_{i,\mathrm{al}}} \tag{3.7}$$

While trading energy among MGs two conditions can arise in the NMGs,

- The condition of excess generation occurs when the total amount of generated energy is greater than or equal to the load/demand.
- The condition of excess demand arises when the total amount of generated energy is less than the load/demand.

3.3.1.1 Excess Generation

In this scenario, the excess energy generated by seller MGs is either greater than or equal to the demand of buyer MGs within the NMG framework. The energy sold by the NMG manager from seller MGs to buyer MGs follows a proportional approach, as shown in [Eq 3.8].

$$E^t_{\mathrm{MG}_{i,s}} = \frac{E^t_i}{\sum_{j=1}^{S} E^t_j} \cdot \sum_{k=1}^{B} D^t_k \tag{3.8}$$

Any remaining excess energy with seller MGs after proportional trading is exchanged with the grid, as described in [Eq 3.9].

$$E^{g,t}_{\mathrm{MG}_{i,s}} = E^t_i - E^t_{\mathrm{MG}_{i,s}} \tag{3.9}$$

The amount that each buyer MG is required to pay is determined by [Eq 3.10], and the total cost for all buyer MGs collectively is calculated according to [Eq 3.11].

$$C^t_{\mathrm{MG}_{i,b}} = D^t_i \cdot P^t_{\mathrm{NMG},s} \tag{3.10}$$

$$\mathrm{TC}^t_{\mathrm{MG}_b} = \sum_{i=1}^{B} C^t_{\mathrm{MG}_{i,b}} \tag{3.11}$$

The amount gained by each seller MG is specified in [Eq 3.12], and the total amount gained by all seller MGs collectively is given by [Eq 3.13].

$$C^t_{\mathrm{MG}_{i,s}} = E^t_{\mathrm{MG}_{i,s}} \cdot P^t_{\mathrm{NMG},s} + E^{g,t}_{\mathrm{MG}_{i,s}} \cdot P^t_{\mathrm{grid},b} \tag{3.12}$$

$$\mathrm{TC}^t_{\mathrm{MG}_s} = \sum_{i=1}^{S} C^t_{\mathrm{MG}_{i,s}} \tag{3.13}$$

3.3.1.2 Excess Demand

In this scenario, the energy demand of buyer MGs is more than excess energy generated by seller MGs. A portion of the demand of buyer MGs is fulfilled from the energy generated by the seller MGs i.e. from proportional trading. The remaining energy needed by buyer MGs is then obtained from the grid. The energy traded in the NMG framework is shown in [Eq. 3.14] and the remaining deficit energy is purchased from the grid [Eq. 3.15].

$$E^t_{\mathrm{MG}_i,b} = \frac{D^t_i}{\sum_{k=1}^{B} D^t_k} \cdot \sum_{j=1}^{S} E^t_j \tag{3.14}$$

$$E^{g,t}_{\mathrm{MG}_i,b} = D^t_i - E^t_{\mathrm{MG}_i,b} \tag{3.15}$$

The amount to be paid by individual buyer MG and the aggregated amount are given in [Eqs 3.16 and 3.17], respectively.

$$C^t_{\mathrm{MG}_i,b} = E^t_{\mathrm{MG}_i,b} \cdot P^t_{\mathrm{NMG},s} + E^{g,t}_{\mathrm{MG}_i,b} \cdot P^t_{\mathrm{grid},s} \tag{3.16}$$

$$\mathrm{TC}^t_{\mathrm{MG}_b} = \sum_{i=1}^{B} C^t_{\mathrm{MG}_i,b} \tag{3.17}$$

The amount earned by individual seller MG and aggregated amount is given by [Eqs 3.18 and 3.19], respectively.

$$C^t_{\mathrm{MG}_i,s} = E^t_i \cdot P^t_{\mathrm{NMG},s} \tag{3.18}$$

$$\mathrm{TC}^t_{\mathrm{MG}_s} = \sum_{i=1}^{S} C^t_{\mathrm{MG}_i,s} \tag{3.19}$$

The total cost incurred to individual MGs and the NMG system for a whole day is given by [Eqs 3.20 and 3.21], respectively.

$$\mathrm{TC}_{\mathrm{MG},i} = \sum C^t_{\mathrm{MG}_i,b} + \sum C^t_{\mathrm{MG}_i,s} \tag{3.20}$$

$$\mathrm{TC}_{\mathrm{NMG}} = \sum \mathrm{TC}^t_{\mathrm{MG}_b} + \sum \mathrm{TC}^t_{\mathrm{MG}_s} \tag{3.21}$$

During some hours, all the MGs could be acting as buyers and buy this energy from the grid as shown in [Eq 3.22]. The total cost incurred by NMG for buying this energy is given in [Eq 3.23]. [Eqs 3.24 and 3.25] represent the power purchased and cost incurred by individual MGs, respectively.

$$E^{g,t}_{\text{NMG},b} = \sum_{i=1}^{N} \left(L^t_{d_i} - \sum_{i=1}^{N} G^t_i \right) \tag{3.22}$$

$$\text{TC}^t_{\text{NMG},b} = E^{g,t}_{\text{NMG},b} \cdot P^t_{\text{grid},s} \tag{3.23}$$

$$E^{g,t}_{\text{MG}_i,b} = L^t_{d_i} - G^t_i \tag{3.24}$$

$$C^t_{\text{MG}_i,b} = E^{g,t}_{\text{MG}_i,b} \cdot P^t_{\text{grid},s} \tag{3.25}$$

Similarly, during some hours, all the MGs could be acting as sellers and sell this energy from the grid as shown in [Eq 3.26]. The total price gained by NMG from selling this energy is given in [Eq 3.27]. [Eqs 3.28 and 3.29] represent the power purchased and cost incurred by individual MGs, respectively.

$$E^{g,t}_{\text{NMG},s} = \sum_{i=1}^{N} \left(\sum_{i=1}^{N} G^t_i \right) - L^t_{d_i}) \tag{3.26}$$

$$\text{TC}^t_{\text{NMG},s} = E^{g,t}_{\text{NMG},s} \cdot P^t_{\text{grid},b} \tag{3.27}$$

$$E^{g,t}_{\text{MG}_i,s} = G^t_i - L^t_{d_i} \tag{3.28}$$

$$C^t_{\text{MG}_i,s} = E^{g,t}_{\text{MG}_i,s} \cdot P^t_{\text{grid},b} \tag{3.29}$$

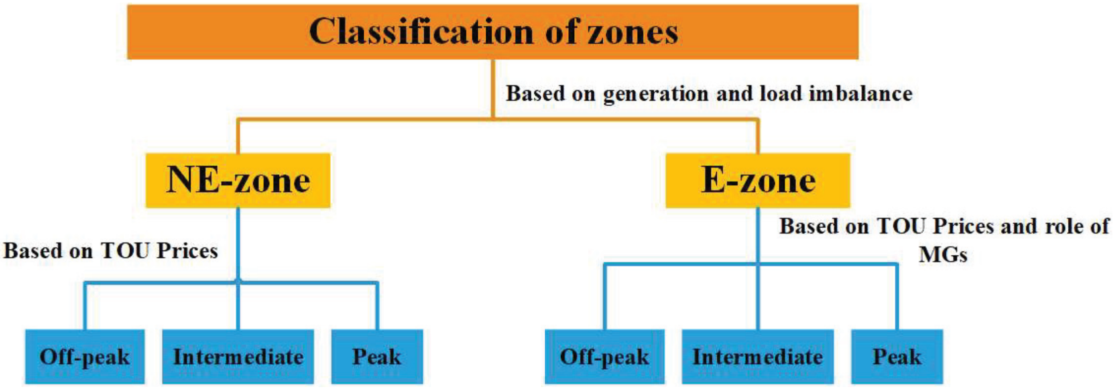


Figure 3.3: Classification of hour blocks.

3.3.2 Hour-Block Energy Trading Approach

In contrast to the hour-to-hour energy trade mentioned earlier, a different approach is taken to diminish reliance on the utility network through hour-block energy trading. This method is based on the generation and load profiles of MGs, and it involves the categorization of two zones: E-zone and the NE-zone. The E-zone is established when the energy generated by seller MGs surpasses the load requirements of the buyer MGs within the NMG environment. In contrast, the NE-zone is defined when the energy generation from all MGs in the NMG system falls short of meeting the corresponding load demand. In the proposed method, it is possible to have multiple E-zones and NE-zones in a day. The NE-zone is further classified based on TOU prices i.e. during off-peak, intermediate, and peak tariff periods, whereas the E-zone is divided based on TOU prices and the role of MGs as shown in Fig. 3.3. The blocks cannot be merged or further split once created. In the NE-zone, there are only buyer MGs whereas, in E-zone, the MGs in the NMG environment may act as sellers or buyers. The consumers in the MGs can benefit by shifting their loads between these demarcated zones, according to the DR program.

3.3.2.1 NE-zone

The energy generated by individual MGs is inadequate to meet their corresponding loads in the NE-zone. So the entire deficit of energy in the NMG framework is purchased from the grid as in [Eq 3.30]. The overall cost borne by the NMG system for acquiring this energy is specified in [Eq 3.31]. [Eqs 3.32 and 3.33] provide the corresponding power purchased and the cost incurred by individual MGs during the NE zones.

$$E^{g,NE}_{\mathrm{NMG},b} = \sum_{i=1}^{N} \left(L^{NE}_{d_i} - \sum_{i=1}^{N} G^{NE}_{i} \right) \tag{3.30}$$

$$\mathrm{TC}^{NE}_{\mathrm{NMG},b} = E^{\mathrm{grid},t}_{\mathrm{NMG},b} \cdot T^{t}_{\mathrm{grid},s} \tag{3.31}$$

$$E^{g,NE}_{\mathrm{MG}_i,b} = L^{NE}_{d_i} - G^{NE}_{i} \tag{3.32}$$

$$C^{NE}_{\mathrm{MG}_i,b} = E^{g,NE}_{\mathrm{MG}_i,b} \cdot T^{t}_{\mathrm{grid},s} \tag{3.33}$$

3.3.2.2 E-zone

In the E-zone, the energy generated exceeds the load requirements in certain MGs. Within a given E-zone, two conditions may arise based on excess generation in MGs, similar to those discussed in section 3.3.1 above: excess energy and excess demand. The NMG aggregator will employ the proportional approach for trading energy among the MGs, as outlined in sections 3.3.1.1 and 3.3.1.2. The total costs incurred for the MGs and the NMG system for an entire day are provided by [Eqs 3.34 and 3.35], respectively.

$$\mathrm{TC}_{\mathrm{MG},i} = C^{NE}_{\mathrm{MG}_i,b} + \sum C^{t}_{\mathrm{MG}_i,b} + \sum C^{t}_{\mathrm{MG}_i,s} \quad \forall t \in \{NE, E\} \tag{3.34}$$

$$\mathrm{TC}_{\mathrm{NMG}} = \mathrm{TC}^{NE}_{\mathrm{NMG},b} + \sum \mathrm{TC}^{t}_{\mathrm{MG}_b} + \sum \mathrm{TC}^{t}_{\mathrm{MG}_s} \quad \forall t \in \{NE, E\} \tag{3.35}$$

Both approaches, hour-to-hour and hour-block based energy trading, are implemented using PSO and subsequently compared.

3.4 Particle Swarm Optimization

PSO is a population-based evolutionary technique developed for solving continuous non-linear equations [73]. The PSO algorithm is inspired by the social behavior observed in animals such as birds flocking and fish schooling. It mimics the collective movement of individuals in a group seeking an optimal solution point [74]. PSO navigates through the search space based on the best position found individually and also the best position found by other particles. In PSO, particles are simple entities positioned within the search space of a problem. Their primary task is to explore and identify the objective function at their respective positions. The next iteration commences after all particles have moved from their initial positions, with each particle adjusting its position based on the collective knowledge gained from the swarm. PSO have three D-dimensional vectors, current position x_i, previous best position p_{besti} and velocity v_i. The current position, denoted as x_i, is considered the solution in every iteration, representing a point in space. If the position found is superior to positions in previous iterations, it is stored as the previous best position p_{besti}. The current position is updated by adding the velocity to current position. As previously mentioned, PSO operates by facilitating interactions among particles, where the position of each particle is influenced by the best position found among all particles in its neighborhood, referred to as the global best position p_{gbesti}. The velocity of each particle is updated in every iteration, as expressed in [Eq 3.36].

$$v_i = \omega \cdot v_i + c_1 \cdot \text{Rand} \cdot (p_{\text{best}_i} - x_i) + c_2 \cdot \text{rand} \cdot (p_{\text{gbest}_i} - x_i) \tag{3.36}$$

As stated in [Eq 3.37], the position of the particle changes its location from one position to another position based on the velocity.

$$x_i = x_i + v_i \tag{3.37}$$

The inertia constant (ω), balances the global and local search for optimal solution by maintaining its value constant or adjusting dynamically. A higher inertia value assist global search, while a lower value assists local search [75]. A constant inertia value is considered in this study. c_1 represents the exploration coefficient, and c_2 serves as the exploitation coefficient; both are instrumental in guiding the algorithm towards finding the global optimal solution. c_1 and c_2 are considered to be 2.05. Rand and rand are random functions generating a random value between 0 to 1.

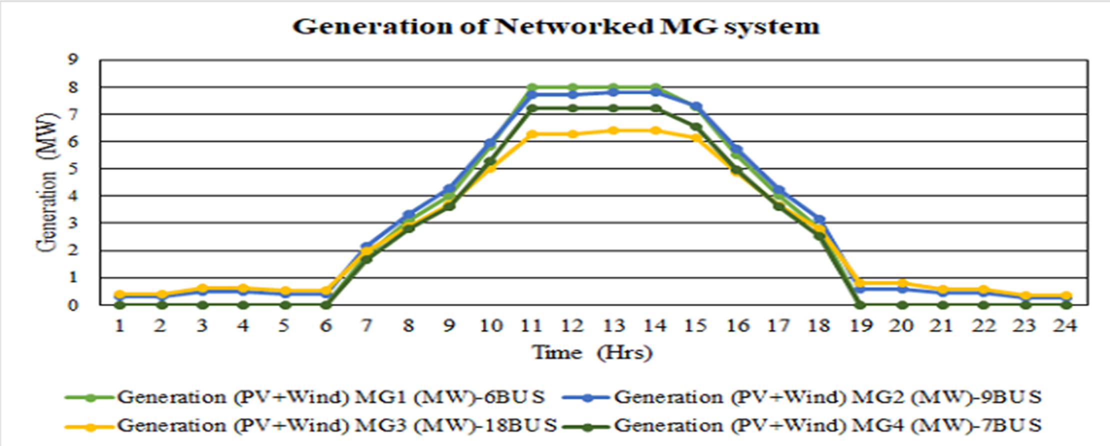


Figure 3.4: PV and wind generation in NMGs.

3.5 Results

For this study, a modified NMG framework given in [71] is considered. This system consists of 4 MGs. Each MG is interconnected to each other and enables trading among MGs through the NMG manager. MG_1 is a 6-bus system, MG_2 is a 9-bus system, MG_3 is an 18-bus system and MG_4 is a 7-bus system, respectively. Each MG is equipped with either PV systems, wind energy systems, or a combination of both, along with schedulable loads. The combined RES generation for MGs for the 12th of February is shown in Fig. 3.4. The load of all MGs for 24 hours of the same day is shown in Fig. 3.5. In the system, the grid purchasing price, i.e., the price at which the grid buys energy from the NMG, is maintained at one-third of the grid selling price given by $1/3 * P^t_{\text{grid},s}$. The TOU prices for all hours of the day are shown in Fig. 3.6. The TOU prices for the day are taken from [72]. The price of the whole day is classified into 3 categories off-peak, intermediate, and peak periods as summarized in Table. 3.2.

Table 3.2: TOU prices for the day and its classification

Period	**Time (Hrs)**	**Grid Selling Price (USD/MWh)**	**Grid Buying Price (USD/MWh)**
Off-peak	1 - 7, 11 - 12, 22 - 24	93.6	31.2
Intermediate	8 - 10, 13 - 18, 21	124.8	41.6
Peak	19 - 20	156	52

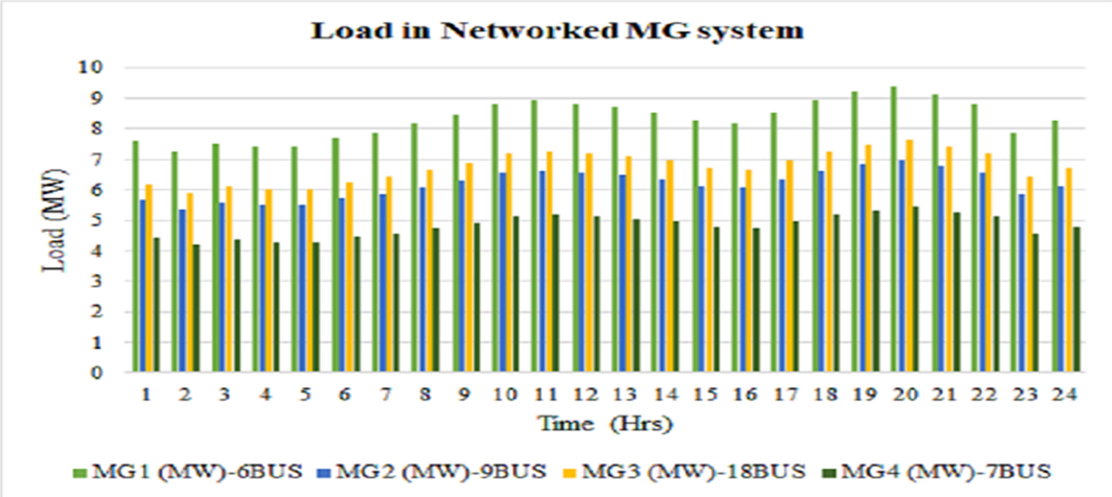


Figure 3.5: Load in NMGs.

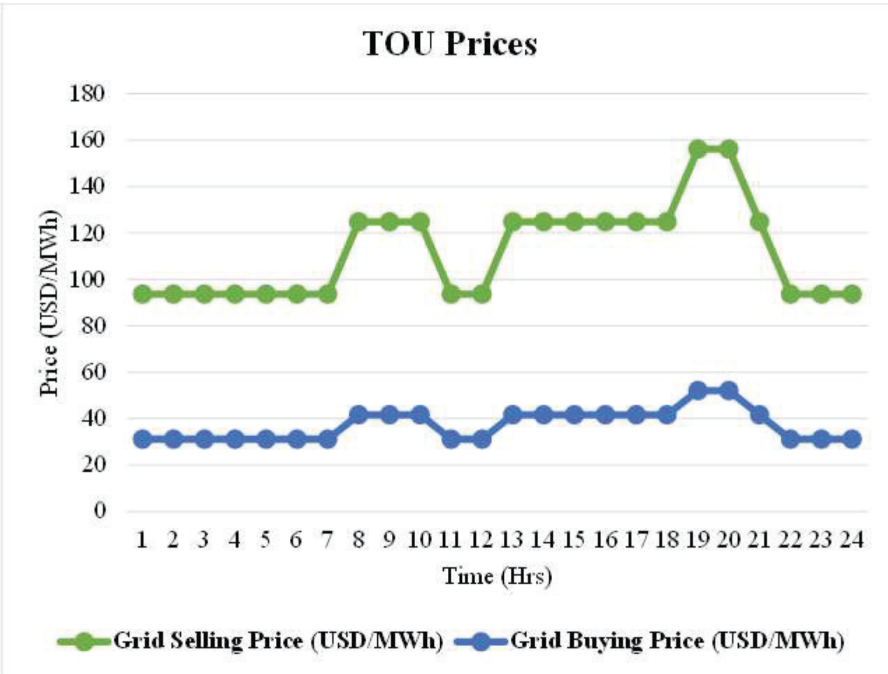


Figure 3.6: TOU Prices for NMGs.

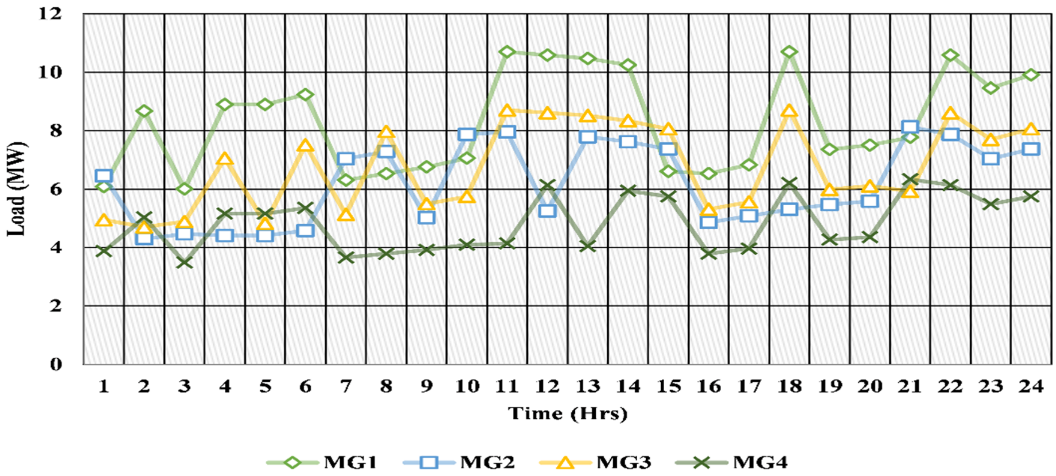


Figure 3.7: Load in NMGs for Hour-to-Hour based Trading

3.5.1 Hour-to-Hour Trading

For the considered system, the load is shifted through the implementation of hour-to-hour energy trading based DR, as discussed in section 3.3. The load shifting is illustrated in Fig. 3.7. For the entire 24-hour duration, the roles of MGs are outlined in Table 3.3. The energy trading price obtained for 24 hours between MGs is shown in Fig. 3.8. The total combined cost of each MG for the whole day is MG_1: 14054.61 (USD/MWh), MG_2: 8339.865 (USD/MWh), MG_3: 10942.53 (USD/MWh) and MG_4: 6159.603 (USD/MWh), respectively. The total operating cost of the whole NMG system is 39410.07 (USD/MWh).

PSO is executed for 40 times and the average amount of time taken for each iteration is 4.578602 seconds. The average and minimum values for the objective function are 39674.19 (USD/MWh) and 39410.07 (USD/MWh). The standard deviation for 40 runs is 139.3305.

3.5.2 Hour Block Trading

The whole day is divided into 6 blocks based on their classification as E-zone or NE-zone. Zone-wise distribution of generation and load is shown in Figs. 3.9 and 3.10. The 6 zones obtained, consists 3 NE-zones and 3 E-zones. During 1-7, 8-9, 17-18, 19-20, 21, and 22-24 hrs, all MGs require energy, so these hour blocks are assigned as NE-zones. MG_4 has excess energy at 10 and 16 hrs, MG_2 and MG_4 generate excess energy at 11-12 and 13-15 and these hour blocks are considered as E-zones.

Table 3.3: Buyer-Seller Matrix for MGs

Hour	TOU Grid Selling Price (USD/MWh)	MG_1	MG_2	MG_3	MG_4
1	93.6	Buyer	Buyer	Buyer	Buyer
2	93.6	Buyer	Buyer	Buyer	Buyer
3	93.6	Buyer	Buyer	Buyer	Buyer
4	93.6	Buyer	Buyer	Buyer	Buyer
5	93.6	Buyer	Buyer	Buyer	Buyer
6	93.6	Buyer	Buyer	Buyer	Buyer
7	93.6	Buyer	Buyer	Buyer	Buyer
8	124.8	Buyer	Buyer	Buyer	Buyer
9	124.8	Buyer	Buyer	Buyer	Buyer
10	124.8	Buyer	Buyer	Buyer	Seller
11	93.6	Buyer	Buyer	Buyer	Seller
12	93.6	Buyer	Seller	Buyer	Seller
13	124.8	Buyer	Seller	Buyer	Seller
14	124.8	Buyer	Seller	Buyer	Seller
15	124.8	Seller	Buyer	Buyer	Seller
16	124.8	Buyer	Seller	Buyer	Seller
17	124.8	Buyer	Buyer	Buyer	Buyer
18	124.8	Buyer	Buyer	Buyer	Buyer
19	156	Buyer	Buyer	Buyer	Buyer
20	156	Buyer	Buyer	Buyer	Buyer
21	124.8	Buyer	Buyer	Buyer	Buyer
22	93.6	Buyer	Buyer	Buyer	Buyer
23	93.6	Buyer	Buyer	Buyer	Buyer
24	93.6	Buyer	Buyer	Buyer	Buyer

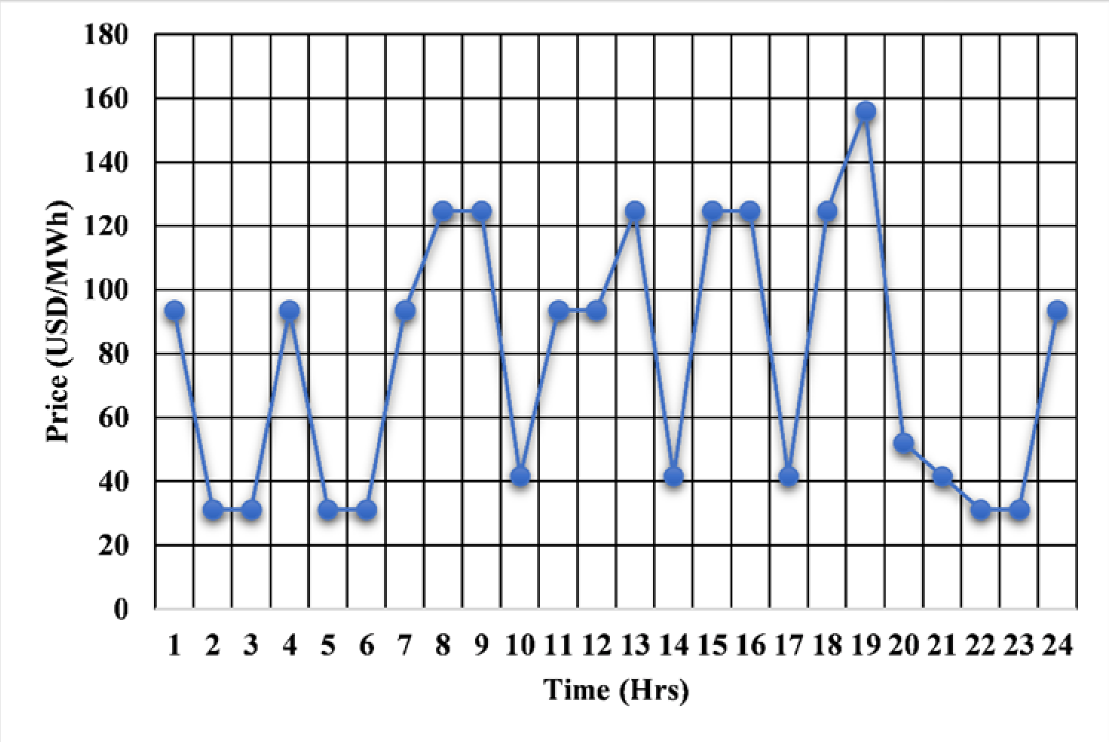


Figure 3.8: Energy Trading Prices among MGs in Hour-to-Hour Trading

3.5.2.1 Hour Blocks without DR

In this case, the generation and load for different zones is considered to be the same as shown in Figs. 3.9 and 3.10 and TOU prices as shown in Fig 3.6. This case verifies the cost in each MG and NMG based on TOU prices in each zone without applying DR programs. The operating cost of each MG for each zone is shown in Figure 3.11.

The total combined cost of each MG for the whole day is MG_1: 14784.26 (USD/MWh), MG_2: 8816.86 (USD/MWh), MG_3: 11021 (USD/MWh) and MG_4: 6903.59 (USD/MWh), respectively. The total operating cost of the whole NMG system is 41525.71(USD/MWh).

3.5.2.2 Hour Blocks with DR

In this case, the DR program and hour blocks are applied for the minimization of costs for each MG as well as the overall NMG system. PSO is applied for the implementation of the DR program in the NMG framework. The results are compiled after executing PSO 40 times. The zone-wise loads of MGs in NMG based on the proposed method is shown in Fig. 3.12. The comparison of zone-wise actual load and the load distribution

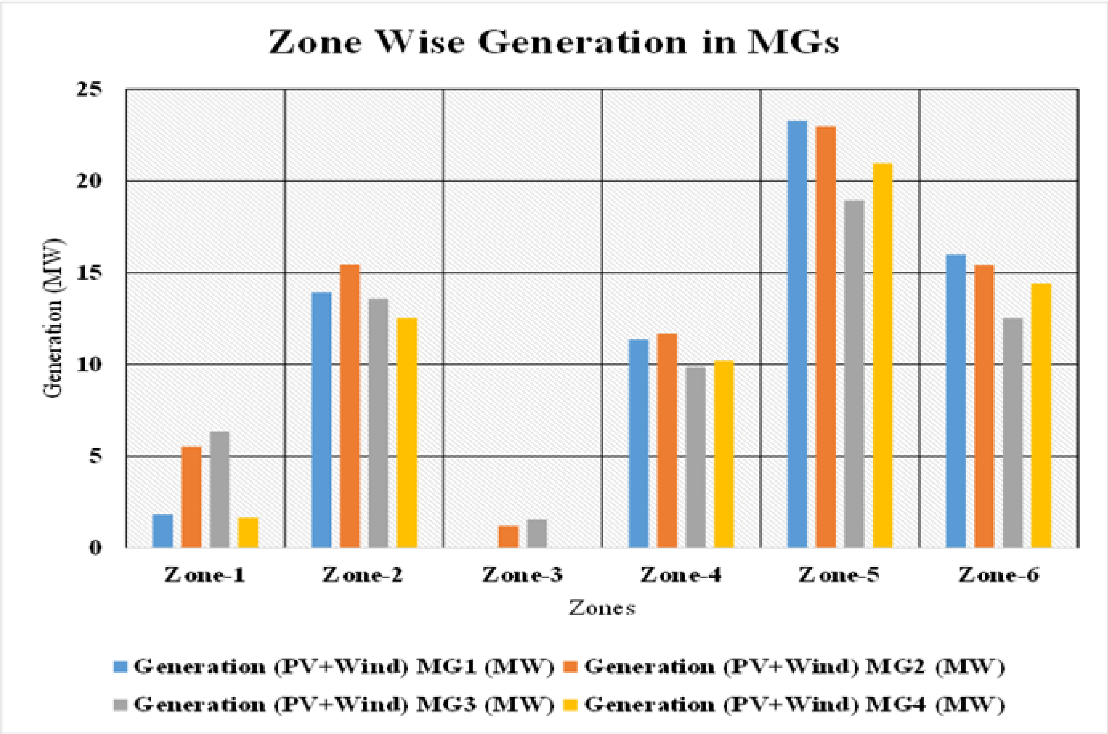


Figure 3.9: Zone Wise Generation in NMG

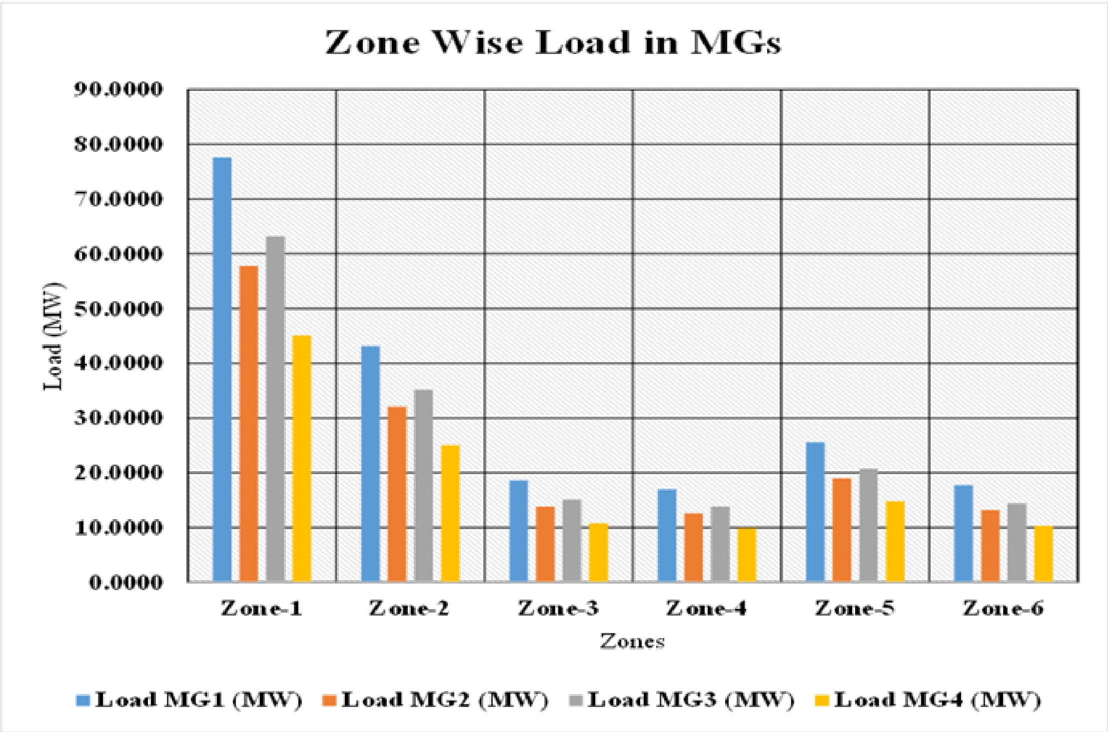


Figure 3.10: Zone Wise Load in NMG

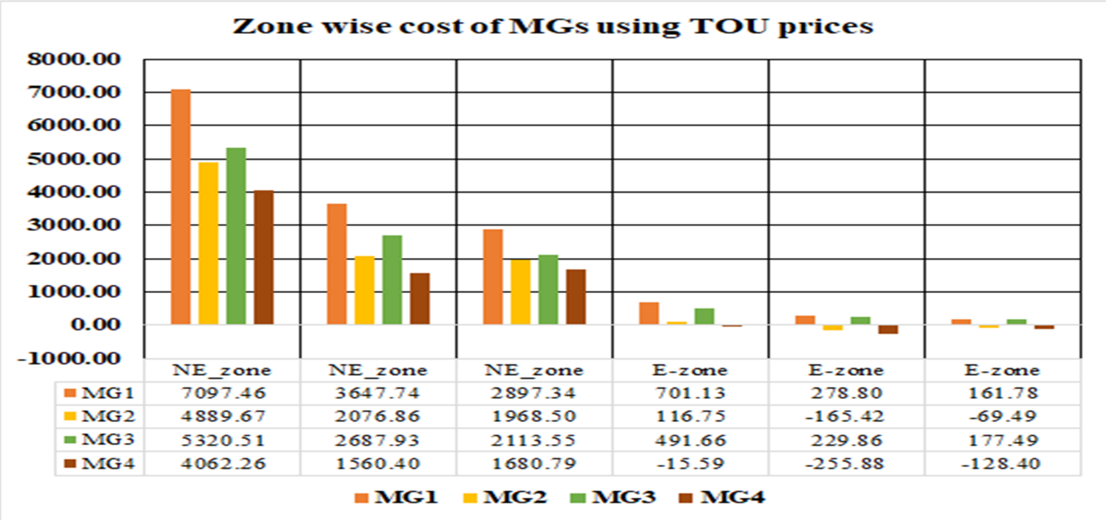


Figure 3.11: Cost of Individual MGs for Hour Blocks without DR

according to PSO is shown in Fig. 3.13. The role of each MG as a buyer or seller is dependent on the optimal load schedule obtained through PSO which is displayed in Table 3.4. The mean of energy trading price of MGs, $P^{t}_{\mathrm{NMG},s}$ in NMG framework for three E-zones after multiple executions of PSO are obtained as 74.88 (USD/MWh), 83.2 (USD/MWh) and 56.41 (USD/MWh) respectively. The optimal costs for energy trading in E zones are obtained as 41.6 (USD/MWh), 41.6 (USD/MWh) and 31.2 (USD/MWh) respectively. The standard deviation for load in each zone and the trading prices for the E-zones as compared to the case of Hour Blocks without DR are shown in Table 3.5. In Table 3.6, the results obtained through PSO show an improvement in costs compared to the Hour-to-Hour case. There is a 7.03% reduction in total operating costs of NMG for optimal PSO results respectively as compared to Hour Blocks without DR. The implementation of the DR program also adds to the minimization of operation costs in individual MGs. PSO is needed for DR to achieve these optimal results.

Table 3.4: Role of each MG

MG_1	MG_2	MG_3	MG_4	**Zone**
Buyer	Buyer	Buyer	Buyer	NE-zone
Buyer	Buyer	Buyer	Buyer	NE-zone
Buyer	Buyer	Buyer	Buyer	NE-zone
Buyer	Seller	Buyer	Seller	E-zone
Seller	Seller	Buyer	Seller	E-zone
Buyer	Seller	Buyer	Seller	E-zone

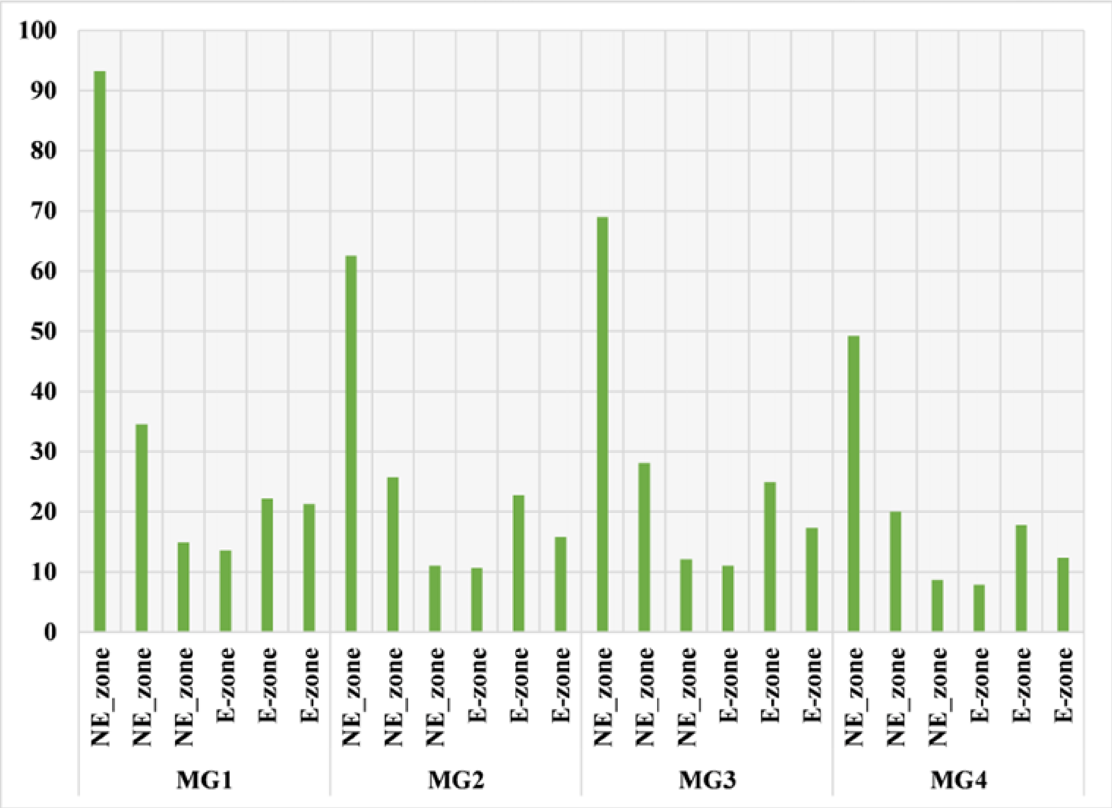


Figure 3.12: Zone Wise Loads for Hour-Block based Energy Trading

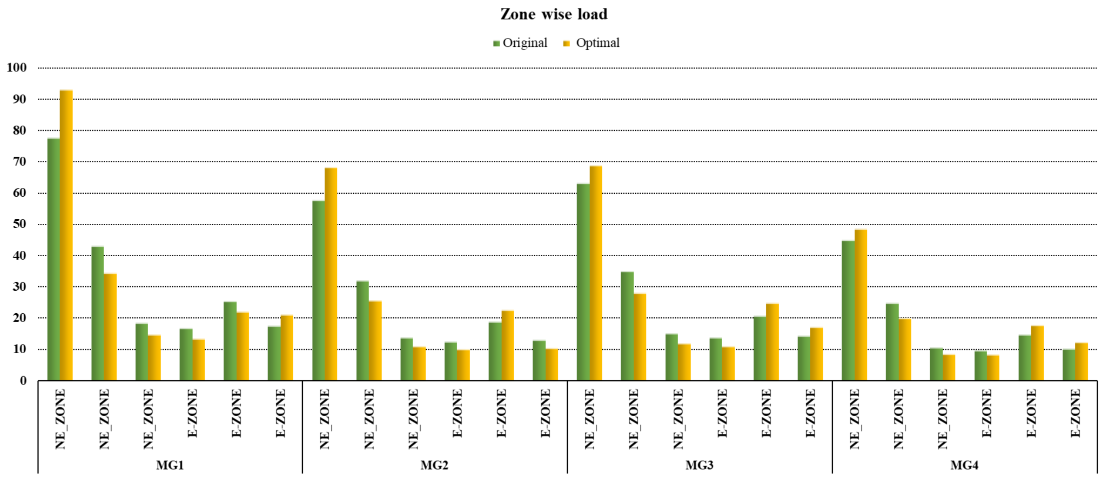


Figure 3.13: Comparison of load for original and optimal case.

Table 3.5: Zone-wise Standard Deviation of Load and Price

Zone	MG_1	MG_2	MG_3	MG_4	Price
NE-zone	5.81	5.42	4.36	3.95	–
NE-zone	0.00	3.33	0.00	3.04	–
NE-zone	1.98	0.87	0.00	1.31	–
E-zone	2.75	2.27	2.32	1.80	41.28
E-zone	3.82	3.19	3.08	2.37	42.13
E-zone	2.23	2.08	2.27	1.69	30.79

Table 3.6: Comparison of MGs' Hour-to-Hour Costs with and without DR

MGs	Hour-to-Hour (USD)	Without DR (USD)	PSO (best) (USD)	Deviation (%)
MG1	14054.61	14784.26	13753.61	-6.97
MG2	8339.865	8816.86	8464.89	-3.99
MG3	10942.53	11021.00	9980.88	-9.44
MG4	6159.603	6903.59	6405.17	-7.22
NMG	39410.07	41525.71	38604.55	-7.03

3.6 Summary

A novel hour-block based DR approach is proposed to reduce the complexity and amount of time taken for application of DR program in comparison to hour-to-hour method. In the proposed method, the objective is to reduce the cost of each MG and the combined NMG framework. In the comparison of hour-to-hour energy trading, the hour-block based energy trading approach involves the formation of zones based on generation and load imbalance. The zones are further classified based on TOU prices and the role of MGs. The comparison of both approaches is presented and results indicate reduction in operating costs of individual MGs and the NMG network except for MG4 for the proposed method.

3.7 Limitations and Applicability in Real World Power System

The study's limitations include a reliance on a deterministic model in the proposed hour-block-based DR approach, assuming predictable generation and load patterns. This might overlook real-world uncertainties, such as weather fluctuations impacting renewable energy generation. Additionally, the NMG framework is simplified with only four MGs, raising questions about the scalability and adaptability of the proposed approach to larger, more diverse systems. The use of static TOU prices in the study, without considering dynamic variations influenced by market conditions and policy changes, adds another limitation. Furthermore, the study lacks an exploration of broader market dynamics, regulatory constraints, and potential fluctuations, which could affect the practicality of the proposed approach in real-world scenarios. Lastly, the idealized settings of the PSO technique, including a constant inertia value and fixed coefficients, may not universally optimize performance, necessitating further investigation into the sensitivity of the proposed approach to PSO parameters.

While the study provides valuable insights into hour-block-based DR for NMGs, its findings should be interpreted within the context of these limitations. Real-world power systems are dynamic, subject to uncertainties, and influenced by numerous external factors. The proposed approach needs adaptation and validation in diverse and more complex settings to ensure its practicality and effectiveness. Addressing these limitations and conducting further empirical studies will enhance the applicability of the findings to real-world power systems.

Chapter 4

Optimal Sizing of RES and BESS in Networked Microgrids Framework based on Proportional Peer-to-Peer Energy Trading

4.1 Introduction

This chapter delves into the detailed exploration of an NMG model, aiming to optimize the capacities of key components such as PV systems, WT, and BESS. The existing literature lacks a comprehensive exploration of energy trading through an NMG manager/aggregator among sellers and buyers for determining optimal sizes of RES and BESS. The key innovation lies in the incorporation of a proportional method for trading energy among sellers and buyers, providing a novel perspective on energy exchange dynamics within the interconnected MG system. The primary contributions encompass multi-objective sizing optimization, emphasizing the simultaneous minimization of the AEC and maximization of reliability measured by LPSP. Additionally, a novel approach to P2P energy trading is presented, facilitated by the NMG manager/aggregator, promoting a balanced and efficient method for energy exchange within the NMG framework. The chapter concludes with a comparative analysis, optimizing individual objectives separately using PSO and comparing results with those achieved through MOPSO, providing insights on the advantages and trade-offs of both P2G and P2P trading approaches.

4.1.1 NMG Topology

The primary goal is to optimize the PV-WT-BESS capacity in an NMG, taking into account proportional P2P trading. To achieve this, we examine a modified version of the standard benchmark system outlined in [71]. The assumption is that each MG is linked to the grid and interconnected via PCC, enabling energy exchange among MGs through the PCC and directly with the grid through the NMG manager or aggregator and DNO. The schematic of the NMGs' trading strategy can be observed in Fig. 4.1. Each MG is composed of PV and WT, either individually or in combination, in addition to loads and BESS. Each MG is overseen by an MGO, responsible for managing the energy within the MG. The NMG manager or aggregator receives information on deficit/excess energy from the individual MGs and coordinates the distribution of energy among peer MGs using proportional approach. The DNO's role in P2G trading is determining the electricity selling and buying prices of the grid. Within the NMG framework, the NMG manager or aggregator determines the prices for energy trading among MGs for P2P transactions.

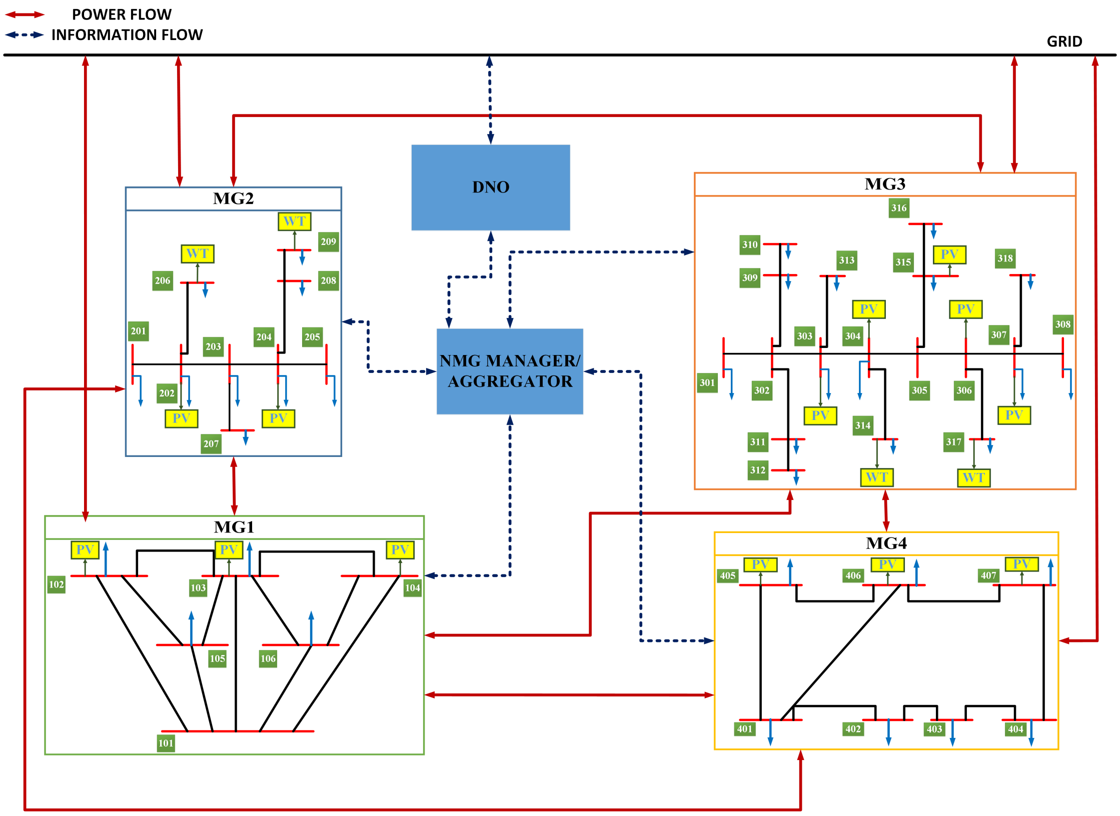


Figure 4.1: Modified Single Line Diagram of NMG.

4.1.2 NMG Modeling

Modeling of PV, WT, load, and BESS for each MG in the NMG framework is discussed in this section.

4.1.2.1 PV, Wind, and Load Modeling

The hour-wise PV and WT generation, along with the load data are statistically modeled according to [Eqs 4.1-4.3] below. The constraints for maximum WT and PV capacity for generation are given in [Eqs 4.4-4.5].

$$ld_i^t = \frac{\%ld_i^{w,t}}{100} * \frac{\%ld_i^{d,t}}{100} * ld_{cy,i} \; \forall i \in \{1,N\} \tag{4.1}$$

$$PV_i^t = \frac{\%PV_{al,i}^t}{100} * PV_{cy,i} \; \forall i \in \{1,N\} \tag{4.2}$$

$$W_i^t = \frac{\%W_{al,i}^t}{100} * W_{cy,i} \; \forall i \in \{1,N\} \tag{4.3}$$

$$PV_{min,i} \leq PV_i^t \leq PV_{max,i} \; \forall i \in \{1,N\} \tag{4.4}$$

$$W_{min,i} \leq W_i^t \leq W_{max,i} \; \forall i \in \{1,N\} \tag{4.5}$$

4.1.2.2 Battery Energy Storage System Modeling

The BESS allows the storage of electrical energy for use at a later time. This improves the flexibility and adaptability of the system. The BESS is charged by the MG whenever the RE generation is greater than the load ($PV_i^t + W_i^t > ld_i^t$) and when $BE_i^t < BE_i^{max}$. Similarly, it discharges whenever the RE generation is lesser than the load in an MG ($PV_i^t + W_i^t < ld_i^t$) and when $BE_i^t > BE_i^{min}$. The maximum charging and discharging power constraints for BESS at a particular time are given by [Eqs 4.6-4.7]. The energy capacity of BESS at a specific hour is given by [Eq. 4.8]. The energy stored in the BESS is limited by [Eq 4.9]. The flowchart of BESS scheduling in an MG is given in Fig. 4.2.

$$BP_{i,c}^{min} \leq BP_{i,c}^t \leq BP_{i,c}^{max} \; \forall i \in \{1,N\} \tag{4.6}$$

$$BP_{i,d}^{min} \leq BP_{i,d}^t \leq BP_{i,d}^{max} \; \forall i \in \{1,N\} \tag{4.7}$$

$$BE_i^t = BE_i^{t-1} + \left(BP_{i,c}^t * \eta_c * \Delta(t) - \frac{BP_{i,d}^t}{\eta_d} * \Delta(t) \right) \quad \forall i \in \{1,N\} \tag{4.8}$$

$$BE_i^{min} \leq BE_i^t \leq BE_i^{max} \; \forall i \in \{1,N\} \tag{4.9}$$

Where, η_c and η_d are considered as 0.95 and 0.92 [71]. $\Delta(t)$ is the time period for which the battery is charging or discharging i.e., 1 hour.

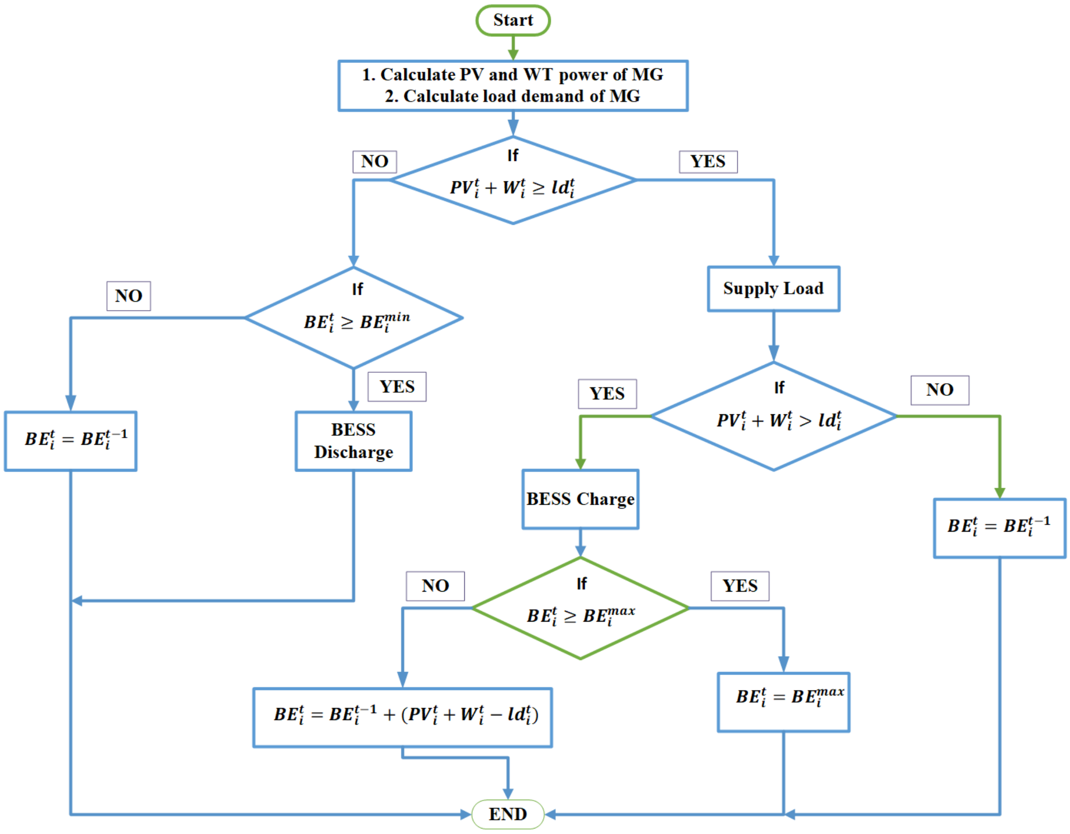


Figure 4.2: BESS Scheduling in MG.

4.1.3 Energy Trading Strategy in NMG

Energy is either excess or deficit in an MG at a given hour 't', depending on the load and generation balance in the corresponding MG. If $PV_i^t + W_i^t > ld_i^t$ where $i \in \{1,N\}$, at a particular hour, then the MG_i, initially stores excess energy in the BESS, as per the strategy. If the MG still has excess energy remaining after charging BESS, then

MG_i acts as a seller in the NMG framework. In a contrary case, where $PV_i^t + W_i^t < ld_i^t$, MG_i will discharge BESS to meet the load demand. If the load is still not satisfied, MG_i is required to buy energy and acts as a buyer. S represents the set of all MGs with excess energy, whereas B is the set of MGs with deficit energy. [Eq 4.10] gives the excess/deficit energy in MG_i at time 't' based on the set it belongs to.

$$MG_{i,sur}^t = \begin{cases} (PV_i^t + W_i^t - (BE_i^{t-1} + \\ BP_{i,c}^t * \eta_c * \Delta(t)) - ld_i^t) \quad \forall i \in S \\ (PV_i^t + W_i^t + \Big(BE_i^{t-1} - \\ \frac{BP_{i,d}^t}{\eta_d} * \Delta(t)\Big) - ld_i^t) \quad \forall i \in B \end{cases} \tag{4.10}$$

The total amount of excess/deficit energy with seller MGs and buyer MGs is given in [Eqs 4.11 and 4.12] respectively.

$$E_{T,ex}^t = \sum_{i=1}^{S} (MG_{i,sur}^t) \; \forall \; S \subset N \tag{4.11}$$

$$E_{T,df}^t = \sum_{i=1}^{B} (MG_{i,sur}^t) \; \forall \; B \subset N \tag{4.12}$$

Excess energy from the seller MG is sold according to the proportional sharing method as given in [Eq 4.13] and the amount of energy received by the buyer MG, is given by [Eq 4.14], for different conditions.

$$PMG_{s,i}^t = \begin{cases} \frac{MG_{i,sur}^t}{E_{T,df}^t * E_{T,ex}^t} & if(E_{T,df}^t + E_{T,ex}^t \geq 0) \\ MG_{i,sur}^t & if(E_{T,df}^t + E_{T,ex}^t < 0) \end{cases} \tag{4.13}$$

$$PMG_{b,i}^t = \begin{cases} MG_{i,sur}^t & if(E_{T,df}^t + E_{T,ex}^t \geq 0) \\ \frac{-MG_{i,sur}^t}{E_{T,df}^t * E_{T,ex}^t} & if(E_{T,df}^t + E_{T,ex}^t < 0) \end{cases} \tag{4.14}$$

The excess energy remaining with seller MGs after trading among the NMGs is sold to the grid, and vice versa for buyer MGs, as given in [Eq 4.15]. The flowchart for energy trading in the NMGs based on proportional sharing is shown in Fig. 4.3. In the NMG framework, the overall energy generation, intra-MG energy trading, and grid-supplied energy must collectively meet the total load, ensuring a comprehensive fulfillment of the energy requirements of MGs. It is assumed the MGs are physically connected near by so the component of active power losses is neglected.

$$PG_{s,b,i}^{t} = \begin{cases} MG_{i,sur}^{t} - PMG_{s,i}^{t} & if(MG_{i,sur}^{t} \geq 0) \\ MG_{i,sur}^{t} - PMG_{b,i}^{t} & if(MG_{i,sur}^{t} < 0) \end{cases} \tag{4.15}$$

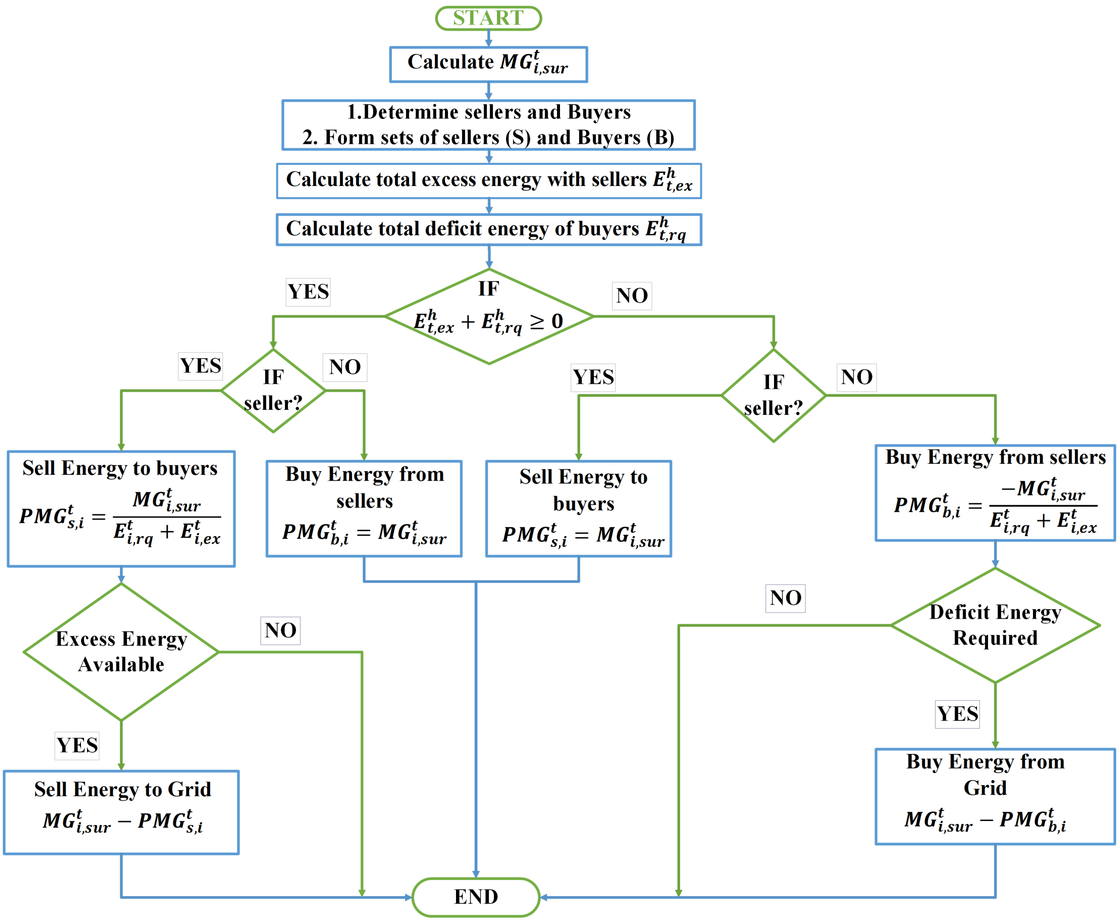


Figure 4.3: Proportional P2P Energy Trading in NMG.

4.2 Problem Formulation

The objective of this part of study is to optimize the capacity of PV-WT-BESS in the NMG system considering P2P energy trading such that minimum AEC is achieved while guaranteeing reliable power. The reliability of power is calculated using the index LPSP.

Annual Energy Cost: AEC depends on several parameters: income from power utilization of RES and BESS, salvage income, investment cost, operation, and maintenance cost, the cost of energy traded with the grid, and NMG framework. The AEC for each MG is given by [Eq 4.16]. The AEC for the total NMG framework is given by [Eq 4.17].

$$AEC_i = C_i^{INV} + C_i^{O\&M} - I_i^{U,RE} - I_i^{U,B} - I_i^{SL} - C_i^{EC} \tag{4.16}$$

$$AEC_{NMG} = \sum_i^N AEC_i \; \forall i \in \{1, N\} \tag{4.17}$$

Investment Cost The amortized cost for installing the RES and BESS is determined using [Eq 4.18].

$$C_i^{INV} = P_i^{G,cy} * E_i^{IC} * \frac{D(1+D)^{L_i}}{((1+D)^{L_i} - 1)} \tag{4.18}$$

Operation & Maintenance Cost (O&M) The O&M cost of RES and BESS is obtained using [Eq 4.19].

$$C_i^{O\&M} = P_i^{G,cy} * E_i^{O\&M} \tag{4.19}$$

Income from Utilization of RE Generation The total RE power generated during 't' is given in [Eq 4.20]. The amount of RE utilized in an MG during each 't' depends on the total RE power generated and load as given by the [Eq 4.21]. The income generated for energy utilized from RES in each MG is given in [Eq 4.22].

$$P_i^{G,RE,t} = PV_i^t + W_i^t \tag{4.20}$$

$$P_i^{U,RE,t} = \begin{cases} PV_i^t + W_i^t & P_i^{G,RE,t} \leq ld_i^t \\ ld_i^t & P_i^{G,RE,t} > ld_i^t \end{cases} \tag{4.21}$$

$$I_i^{U,RE} = \sum_{t=1}^T E_{p,b}^t * P_i^{U,RE,t} \tag{4.22}$$

Income from Utilization of BESS The battery is discharged whenever the load exceeds the total RES power generated and vice versa, based on different constraints. The total power consumed in MG is given in [Eq 4.23]. Annual income generated from the utilization of BESS is given in [Eq 4.24].

$$P_{i,CD}^{t} = ld_i^t + (BE_i^t - BE_i^{t-1}) \tag{4.23}$$

$$I_i^{U,B} = \sum_{t=1}^{T} E_{p,b}^{t} * (BE_i^t - BE_i^{t-1}) \tag{4.24}$$

Salvage Income This is the income generated by selling the RES and BESS equipment at the end of their useful life. The salvage income from BESS is neglected. The salvage income values for RES are calculated and the time period is made as other components using [Eq 4.25].

$$I_i^{SI} = P_i^{G,cy} * E_i^{SI} * \frac{D}{((1+D)^{L_i} - 1)} \tag{4.25}$$

Cost of Energy Traded with Grid and NMG The cost of energy traded with the main grid reflects the financial impact of purchasing or selling energy to meet the MG's requirements or capitalize on excess energy generation as given in [Eq 4.26]. The cost for energy traded within the NMG framework provides insights into the economic considerations of energy exchanges among peer MGs as given using [Eq 4.27]. The total cost of energy traded with grid and within the NMG is given in [Eq 4.28]. The costs would be negative when energy is sold by the MG and vice versa.

$$C_i^{EG,t} = PG_{s,b,i}^{t} * E_{p,s,b}^{t} \tag{4.26}$$

$$C_i^{EMG,t} = PMG_{b,s,i}^{t} * E_{p,MG}^{t} \tag{4.27}$$

$$C_i^{EC} = \sum_{i=1}^{T} (C_i^{EG,t} + C_i^{EMG,t}) \tag{4.28}$$

4.2.1 Loss of Power Supply Probability

The reliability of the NMG is calculated using the index of LPSP. The LPSP is used to measure the probability that optimized PV, WT, and BESS capacity, can satisfy the load demand of the corresponding MG. The LPSP is calculated as the total number of hours the load is not satisfied divided by the total number of hours in the evaluation period. The value of LPSP is in the range [0,1]. If the power generated from the optimized RES and BESS satisfies the demand at each hour, LPSP converges to zero. For a single MG, the LPSP is calculated using [Eq 4.29].

$$LPSP_{MG_i} = \frac{\sum_{t=1}^{T} H_t}{T} \tag{4.29}$$

$$H_t = \begin{cases} 1 & if \left(ld_i^t - PV_i^t - W_i^t + \left(\frac{BE_i^t - BE_i^{t-1}}{\Delta(t)} \right) \right) > 0 \\ 0 & otherwise \end{cases} \tag{4.30}$$

Where H_t returns 1 when the optimized hybrid RESs and battery do not satisfy the load for the t^{th} hour and 0 for all other cases.

For the NMG, LPSP and its calculation considering the P2P energy trading is given in [Eq 4.31]. In the NMG framework, the additional power with the seller MG is sold to the buyer MGs in proportion and the remaining excess/deficit energy after selling/buying is sold/bought from the main grid.

$$LPSP_{NMG} = \left(\frac{\sum_{i=1}^{N} LPSP_{MG_i}}{N} \right) \forall\, i \in 1,2,..,N \tag{4.31}$$

The multiple objectives of the problem under consideration, are to minimize the AEC and simultaneously minimize LPSP as given by [Eq. 4.32].

$$F = min[AEC_{NMG}, LPSP_{NMG}] \tag{4.32}$$

4.3 Multi-Objective Optimization (MOO)

MOO is used for solving problems with multiple objective functions which can be either conflicting or agreeing. The MOO either minimizes or maximizes multiple conflicting objective functions, as described in [Eq 4.33].

$$
\begin{aligned}
Minimize\ F(x) = [f_1(x), f_2(x), ..., f_n(x)] \\
\text{subject to} \\
g_i(x) \leq 0,\ i = 1,2,..,m \\
h_i(x) = 0,\ i = 1,2,..,k
\end{aligned}
\tag{4.33}
$$

Where x is the decision variable vector, $f_i(x)$ $i = 1,...,n$ are the objective functions of x to be minimized or maximized, and $g_i(x)$ and $h_i(x)$ are the constraint functions for the problem. The MOPSO approach is utilized in this part of work to solve the considered multi-objective problem.

4.3.1 MOPSO

In comparison to PSO, in MOPSO, each objective function has its own neighbourhood to update its position [76]. The velocity update of particles for MOPSO is given in [Eq 4.34]. The global best particle for each objective function is stored in the REP. The values stored in the REP are non-dominated results and are used for updating the particles. The mutation operator is applied to increase the diversity of the search in order to obtain the optimal solution [77]. The particles stored in the REP after convergence are considered solutions. The step-by-step procedure for MOPSO is presented in Algorithm 1.

$$
\begin{aligned}
v_i^t = \omega * v_i^{t-1} + c_1 * rand() * (x_{pbest_i} - x_i^t) + \\
c_2 * Rand() * (REP(h) - x_i^t)
\end{aligned}
\tag{4.34}
$$

where $REP(h)$ is a value considered from the repository.

The step-by-step procedure for minimization of AEC and LPSP problem as MOO using MOPSO is shown in the Fig. 4.4.

4.4 Results and Discussions

The NMG system given in [71] is modified in this paper as shown in Fig. 4.1, for the implementation of the proposed method. The modified system is considered to have interconnected MGs for trading and the conventional generation is neglected from the

Algorithm 1 Algorithm for MOPSO

Require: $c_1, c_2, w, iter_{max}, swarmsize, repositorysize$
Require: $gridsize, mutationrate, InflationRate$
Require: $LeaderSelectionPressure,$
$DeletionSelectionPressure$

```
Initialize Swarm.
Initialize leaders into the repository i.e. external archive.
for i = 1 : iter_max do
    Select Leader
    for i = 1 : swarmsize do
        Update Velocity using Eq. (4.34).
        Update Particle Position using Eq. (3.37).
        Verify if the particles are satisfying constraints.
        Calculate Fitness.
        Apply Mutation.
        Calculate Fitness.
        Check for Dominance.
        Update Personal Best.
    end for
    Update leaders in the repository.
    i=i++
    if i = iter_max then
        Get Results from the external archive.
    end if
end for
```

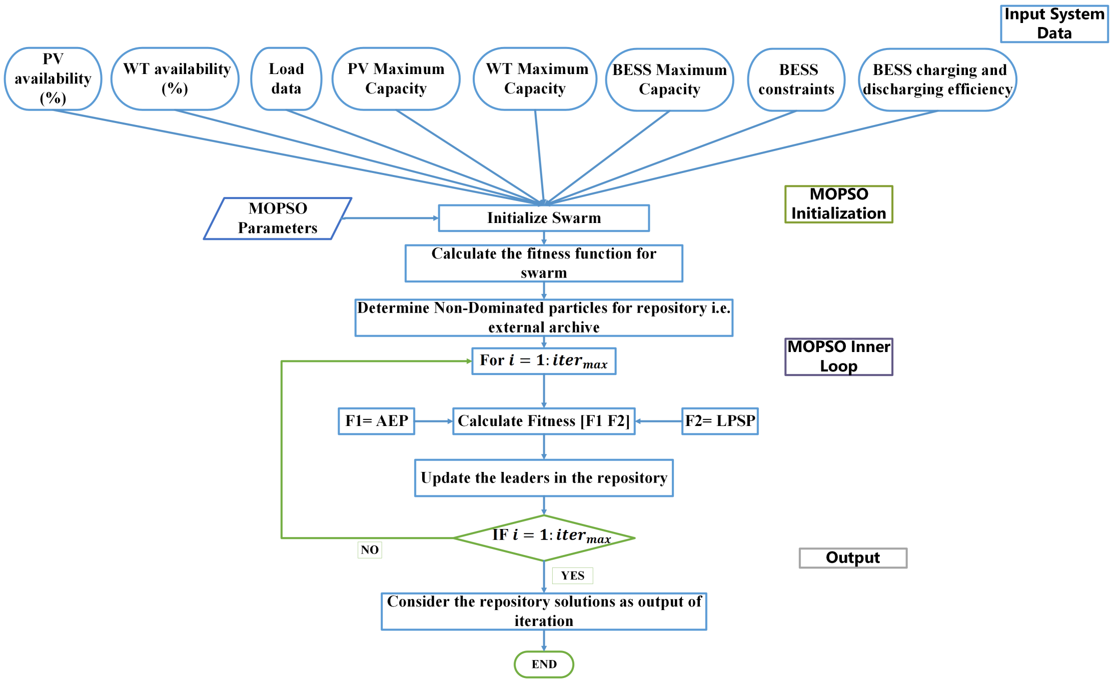


Figure 4.4: Flowchart for the implementation of MOPSO for minimization of AEC and LPSP.

standard benchmark system. The system consists of four distinct MGs, where the first bus of each MG is considered as a slack bus. The maximum capacity of PV, WT, and BESS permitted in each MG and details of NMG are shown in Table 4.1. The input parameters considered for calculations are shown in Table 4.2 [43]. The optimization is applied for annual data but for representation purposes we have shown results for single day. The optimization techniques are implemented in MATLAB software.

The results in this study are presented in a two-fold manner as shown in the Fig. 4.5. First, we analyze the AEC and LPSP individually using PSO for both the P2G trading and P2P trading scheme. Then an analysis for the same NMG framework considering multi-objective optimization using MOPSO for both trading schemes is presented. The prices for trading are assumed to be fixed and given in Table 4.3 [43].

4.4.1 Optimization of Individual Objectives

In this section, the results for the minimization of AEC and LPSP as individual objectives, using PSO are presented. The optimum RES and BESS sizes for each objective are compared in Tables 4.4 and 4.5. The PSO is run for 200 iterations, 100 particles, and the acceleration coefficients c_1 and c_2 are considered to be 2. The ω and ω_{damp} are

Table 4.1: Details of MGs in NMG system

MGs	Buses	Lines	PV Range (kW)		WT Range (kW)		BESS Range			
							Energy (kWh)		Power (kW)	
			Min	Max	Min	Max	Min	Max	Min	Max
MG1	6	11	0	6400	0	0	0	10,000	0	6400
MG2	9	8	0	5600	0	1300	0	12,000	0	5600
MG3	18	17	0	5600	0	1700	0	12,400	0	5600
MG4	7	8	0	5600	0	0	0	12,000	0	5600

Table 4.2: Input Parameters for NMG

Parameters	Value
D	12%
L_{WT}	20 Years
E_{WT}^{IC}	770 $/kW
$E_{WT}^{O\&M}$	20 $/(kW.Year)
E_{PV}^{IC}	1890 $/kW
L_{PV}	20 Years
$E_{PV}^{O\&M}$	20 $/(kW.Year)
L_{BESS}	10 Years
E_{BESS}^{IC}	100 $/kW
$E_{BESS}^{O\&M}$	1 $/(kW.Year)
E_{WT}^{si}	77 $/kW
E_{PV}^{si}	189 $/kW

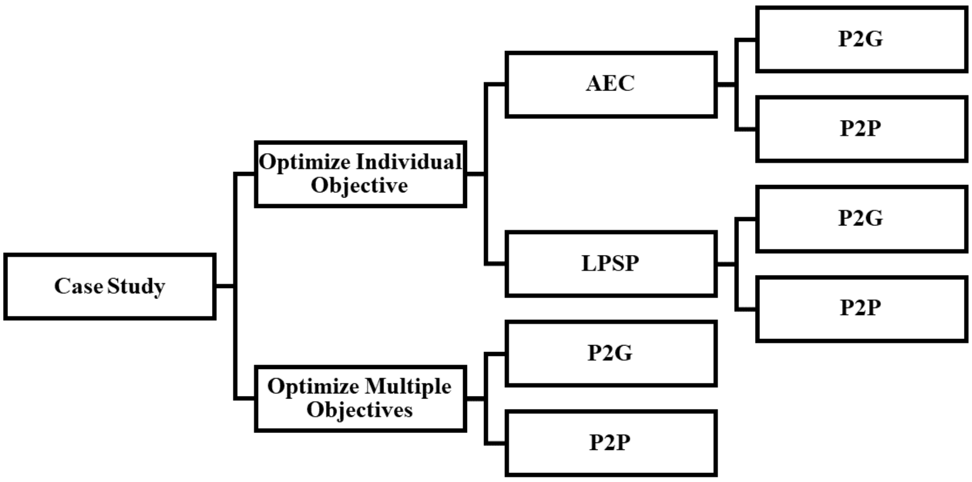


Figure 4.5: Classification of Case Study.

Table 4.3: Energy Trading Prices

Parameters	Value
$(E_{p,MG}^{t})$	0.15 $/kWh
$(E_{p,s}^{t})$	0.10 $/kWh
$(E_{p,b}^{t})$	0.28 $/kWh

considered to be 1 and 0.99, respectively.

Table 4.4: Comparison of P2G and P2P Energy Trading for AEC Minimization

MG	Optimal Size			P2G Energy Trading		P2P Energy Trading	
	PV (kW)	**WT (kW)**	**BESS (kWh)**	**LPSP**	**AEC ($)**	**LPSP**	**AEC ($)**
MG1	6400	0	0	0.95557	37273107.21	0.95278	37252885.65
MG2	5600	1300	0				
MG3	5600	1700	3716.23				
MG4	5600	0	10603.05				

Table 4.5: Comparison of P2G and P2P Energy Trading for LPSP Minimization

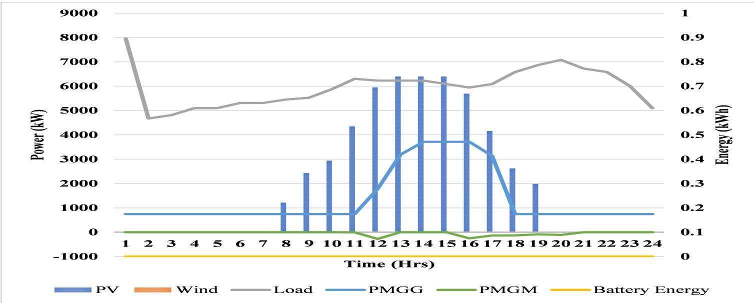
MG	Optimal Size			P2G Energy Trading		P2P Energy Trading	
	PV (kW)	**WT (kW)**	**BESS (kWh)**	**LPSP**	**AEC ($)**	**LPSP**	**AEC($)**
MG1	6400	0	979.913	0.95184	37368050.9	0.95062	37353669.22
MG2	5600	1300	12000				
MG3	5600	1700	9920				
MG4	5600	0	10375.07				

4.4.1.1 AEC Minimization

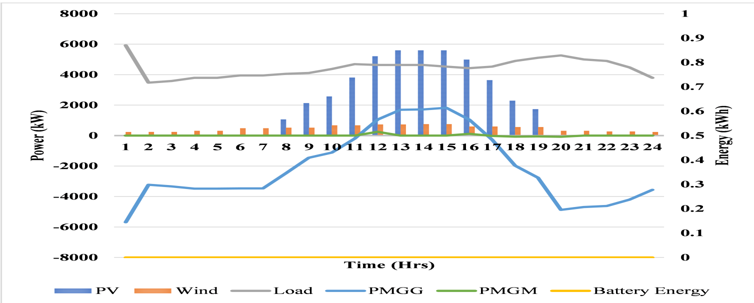
For AEC minimization, the cost is reduced for P2P energy trading compared to P2G energy trading as shown in Table 4.4. The optimal size of BESS for MG_1 and MG_3 obtained is 0 kW. Based on the sizing obtained, the RES generation, the BESS charging and discharging pattern for MGs, the amount of energy traded with the grid (PMGG), and among the MGs for P2P energy trading (PMGM) is shown in Fig. 4.6. Similarly for P2G energy trading results are shown in Fig. 4.7.

4.4.1.2 LPSP Minimization

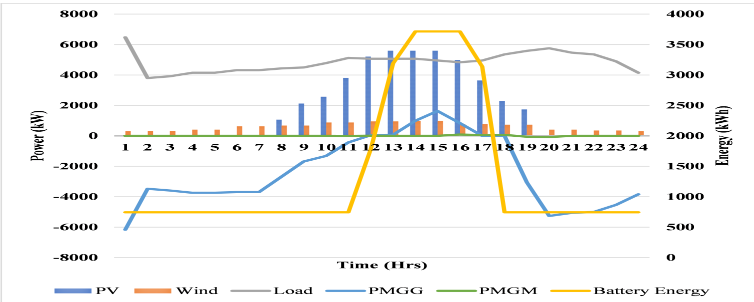
LPSP is minimized for P2P energy trading compared to P2G energy trading as shown in Table 4.5. Considering LPSP, as the objective function, the RES generation, charging and discharging of BESS, energy traded with the grid, and among MGs is shown in Fig. 4.8 for P2P energy trading. Similarly, for P2G energy trading, LPSP is minimized, and the results are shown in Fig. 4.9.



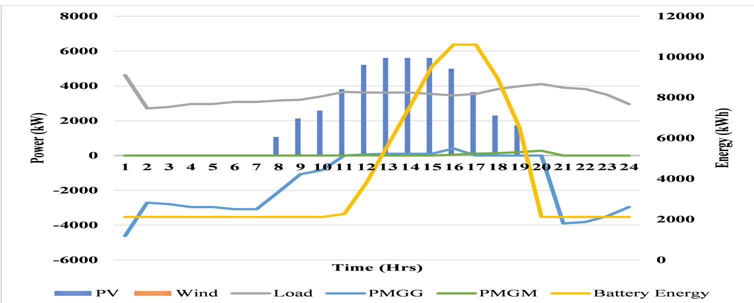
(a) MG1.



(b) MG2.

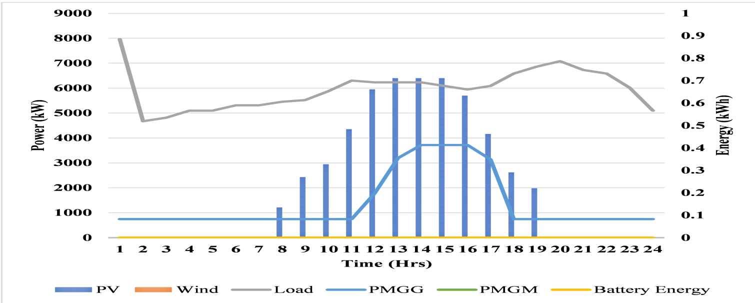


(c) MG3.

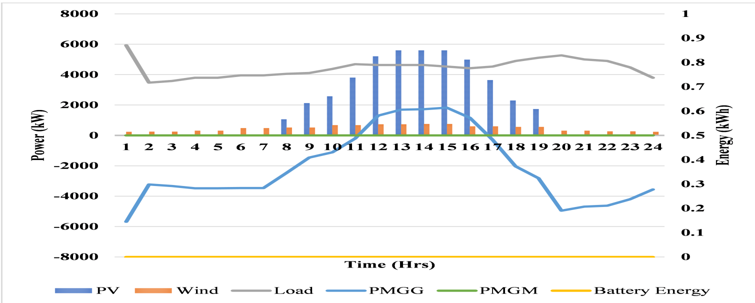


(d) MG4.

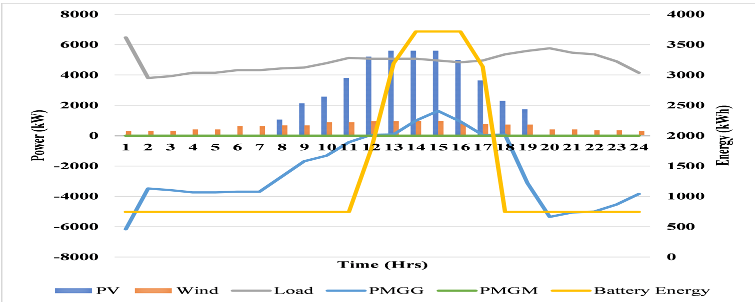
Figure 4.6: P2P energy trading pattern for AEC



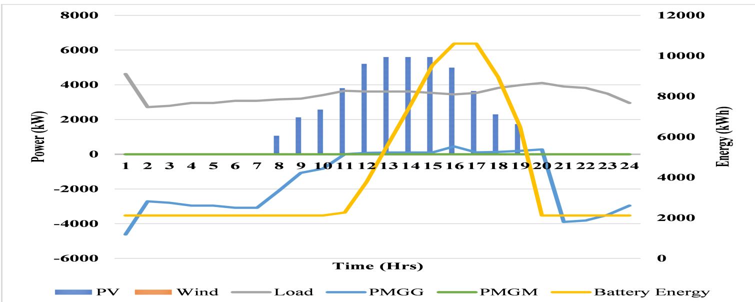
(a) MG1.



(b) MG2.

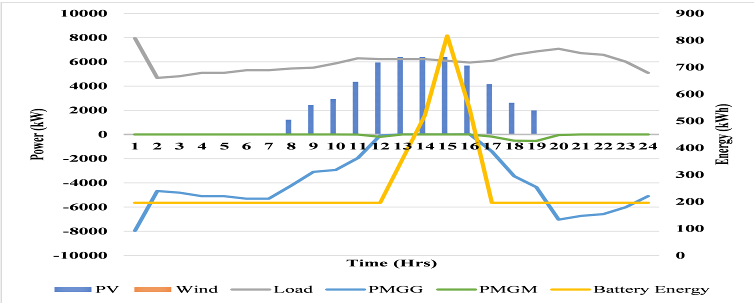


(c) MG3.

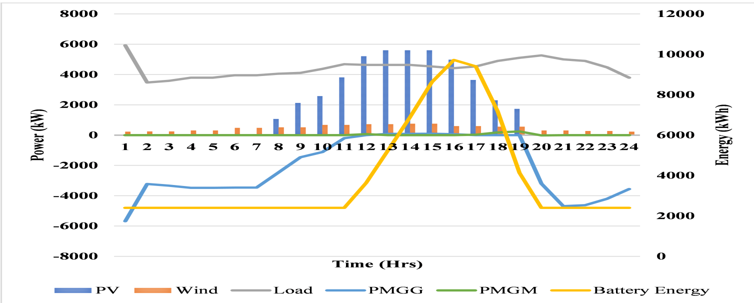


(d) MG4.

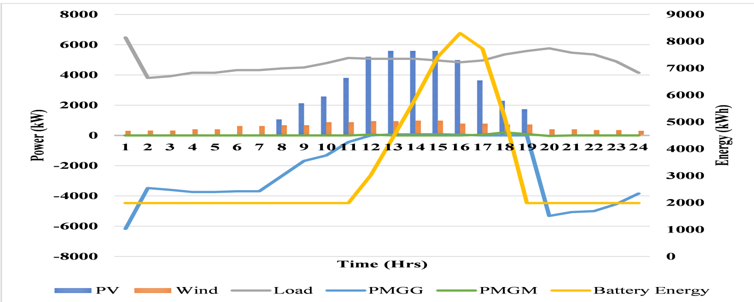
Figure 4.7: P2G energy trading pattern for AEC



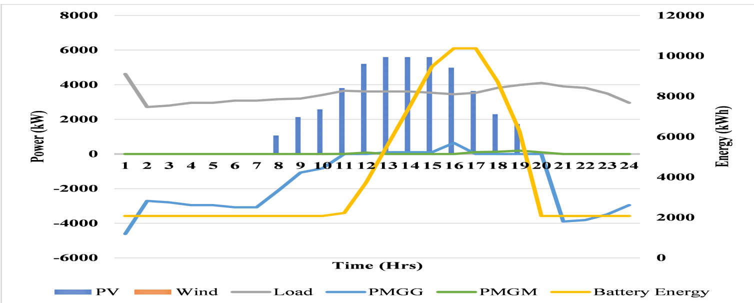
(a) MG1.



(b) MG2.

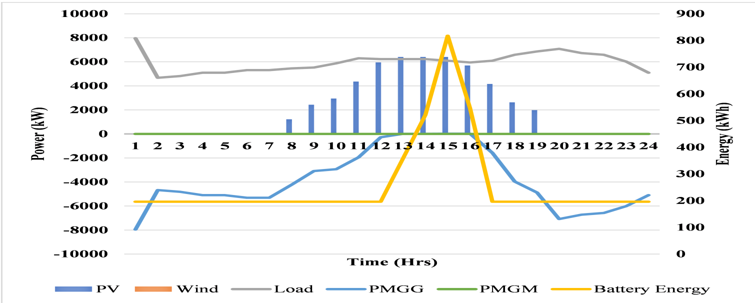


(c) MG3.

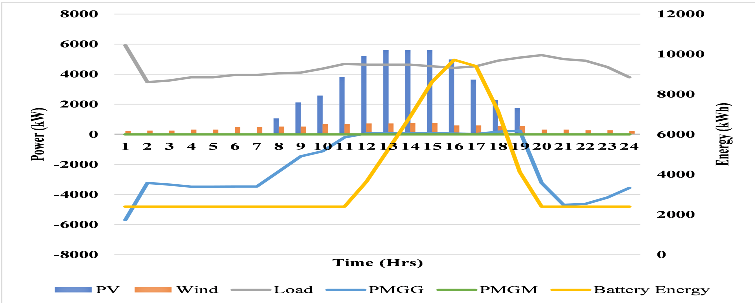


(d) MG4.

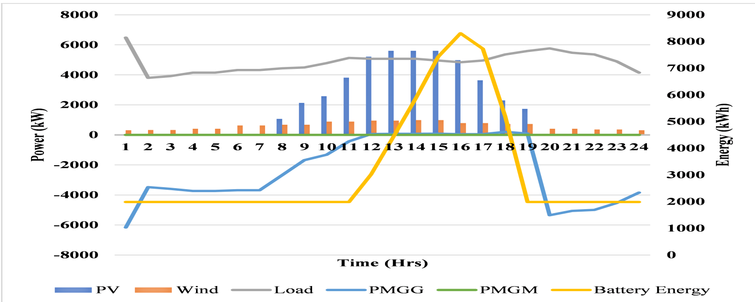
Figure 4.8: P2P energy trading pattern for LPSP



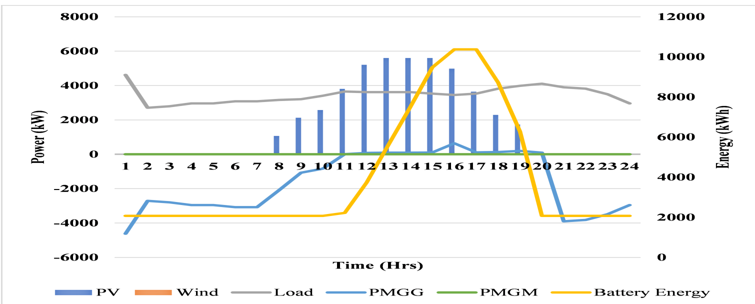
(a) MG1.



(b) MG2.



(c) MG3.



(d) MG4.

Figure 4.9: P2G energy trading pattern for LPSP

The optimal size of RES remains the same when AEC and LPSP are optimized individually. The capacity of BESS is more while optimizing the LPSP than AEC. The cost is lower when considering AEC as an objective compared to LPSP. Similarly, while considering LPSP as an objective, reliability is improved as compared to the objective being AEC. In both objectives, the results are better for P2P energy trading when compared with P2G energy trading.

4.4.2 Multi-Objective Optimization using MOPSO

In this section, the results for MOO using MOPSO are presented. MOPSO is run for 200 iterations and 100 particles. The MOPSO parameters: repository size is considered to be 100, the acceleration coefficients c_1 and c_2 are considered 2, inflation rate (α) is 0.1, leader selection pressure (β) is 2, deletion selection pressure (γ) is 2, mutation rate (μ) is 0.1, ω is 1 and ω_{damp} is 0.99. The optimum RES and BESS sizes obtained for MOPSO are shown in Table 4.6. The results for P2G and P2P energy trading considering MOPSO are shown in Fig. 4.10 and Fig. 4.11.

Table 4.6: Comparison of P2G and P2P Energy Trading

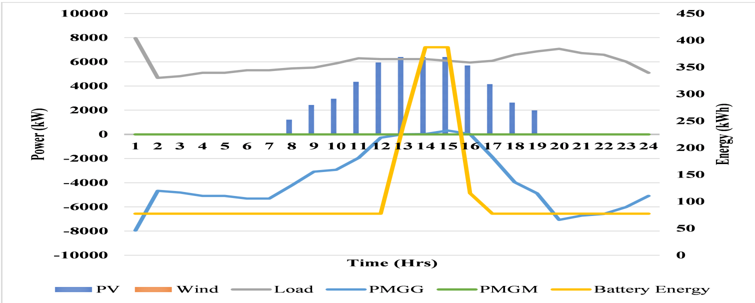
MG	Optimal Size			P2G Energy Trading		P2P Energy Trading	
	PV (kW)	WT (kW)	BESS (kWh)	LPSP	AEC ($)	LPSP	AEC ($)
MG1	6400	0	387.064	0.95278	37262735.86	0.95139	37249249.21
MG2	5600	1300	5613.047				
MG3	5600	1700	6340.179				
MG4	5600	0	9390.615				

From Table 4.6, the AEC achieved is lesser for P2P trading compared to P2G trading. Also, the LPSP is minimized when considering P2P energy trading. A comparison of various costs and income for different MGs considering P2P and P2G energy trading in the NMG framework using MOPSO is shown in Table 4.7.

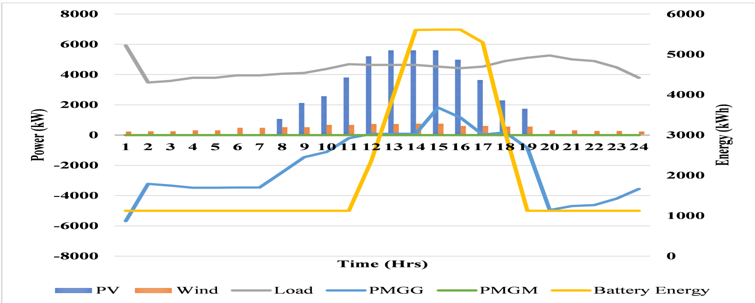
The optimal sizes of RES and BESS in MG_1, MG_2, MG_3, and MG_4 obtained are shown in Fig. 4.12. In Table 4.8, a comparison of the different single-objective results obtained through PSO and the multi-objective result obtained through MOPSO is shown.

4.5 Summary

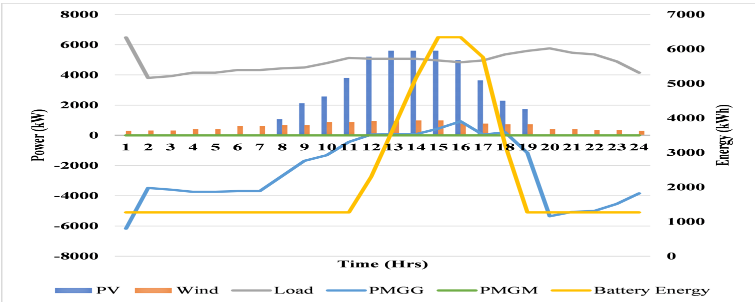
The optimal sizing of RES and BESS for MGs in the NMG framework is presented in this section of research, with cost minimization and reliability enhancement as objec-



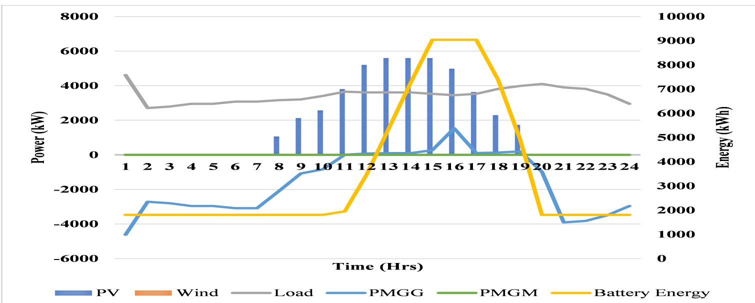
(a) MG1.



(b) MG2.

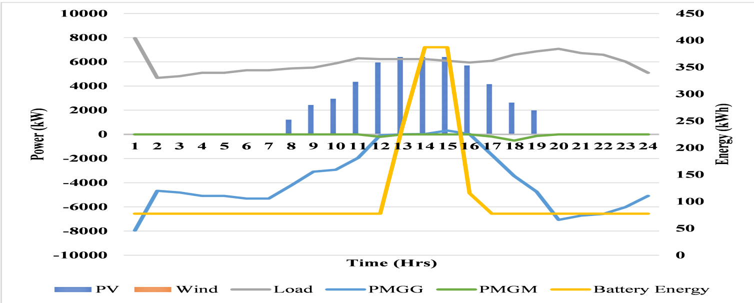


(c) MG3.

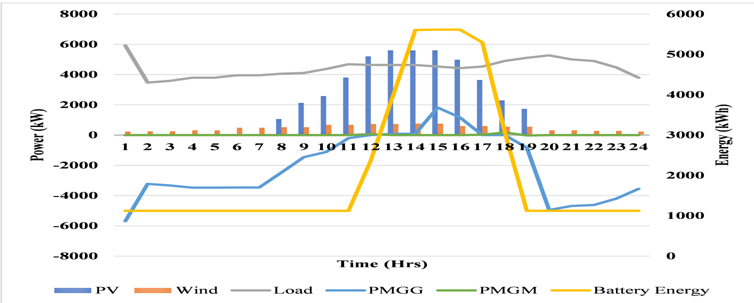


(d) MG4.

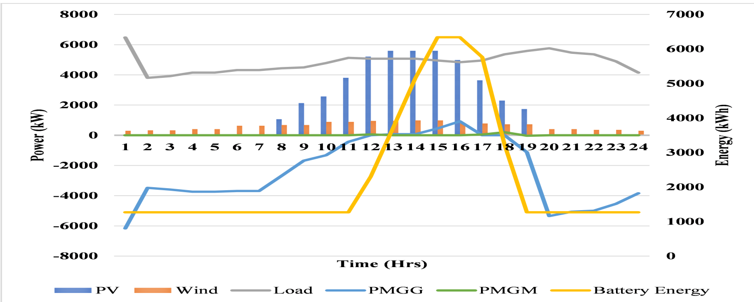
Figure 4.10: P2G energy trading pattern



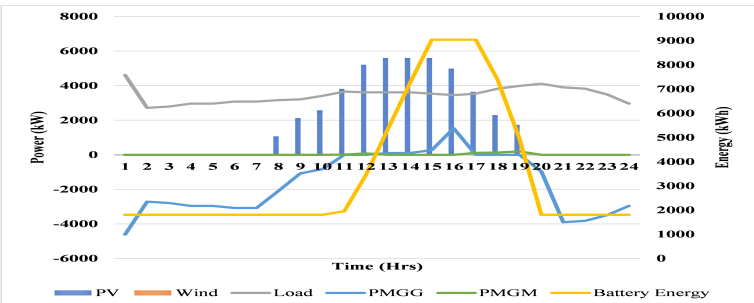
(a) MG1.



(b) MG2.



(c) MG3.

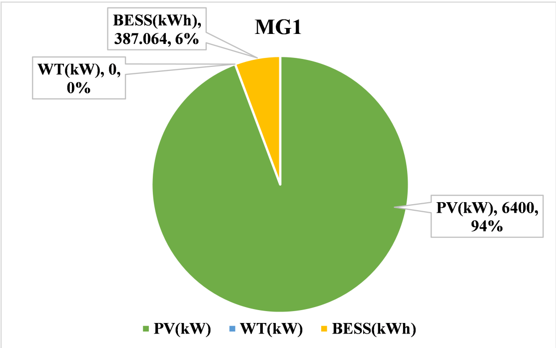


(d) MG4.

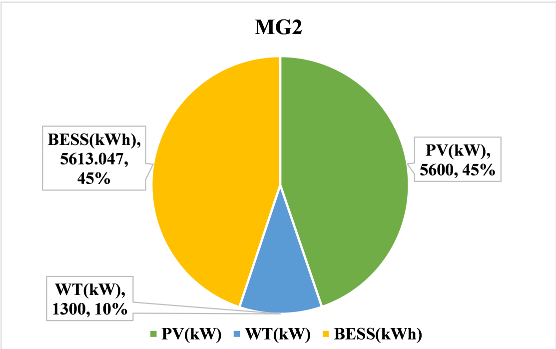
Figure 4.11: P2P energy trading pattern

Table 4.7: Comparison of P2P and P2G Trading

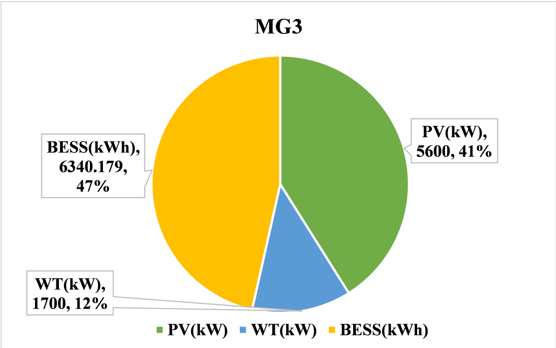
Parameter ($)	Maximum Capacity	P2G Trading	P2P Trading
Investment cost MG1	1753276.50	1624579.69	1624579.69
Investment cost MG2	1711640.20	1626132.45	1626132.45
Investment cost MG3	1758230.02	1677101.87	1677101.87
Investment cost MG4	1577627.54	1537994.27	1537994.27
O&M Cost MG1	138000	128387.06	128387.06
O&M Cost MG2	150000	143613.05	143613.05
O&M Cost MG3	158400	152340.18	152340.18
O&M Cost MG4	124000	121039.61	121039.61
Cost of Trade with Grid MG1	-14369000.00	-14388000.00	-14370000.00
Cost of Trade with Grid MG2	-9678900.00	-9685900.00	-9686500.00
Cost of Trade with Grid MG3	-10681000.00	-10684000.00	-10682000.00
Cost of Trade with Grid MG4	-7517700.00	-7519300.00	-7524000.00
Cost of Trade with NMG MG1	-9418.60	0.00	-9479.40
Cost of Trade with NMG MG2	1822.10	0.00	1988.60
Cost of Trade with NMG MG3	260.20	0.00	492.30
Cost of Trade with NMG MG4	7336.40	0.00	6998.50
Income Utilization of RES MG1	2856800.00	2856300.00	2856300.00
Income Utilization of RES MG2	3126000.00	3118300.00	3118300.00
Income Utilization of RES MG3	3333300.00	3330800.00	3330800.00
Income Utilization of RES MG4	2438600.00	2417600.00	2417600.00
Income Utilization of BESS MG1	4183.40	1718.10	1718.10
Income Utilization of BESS MG2	64353.00	52302.00	52302.00
Income Utilization of BESS MG3	47288.00	44914.00	44914.00
Income Utilization of BESS MG4	150950.00	139040.00	139040.00
Salvage Income MG1	16787.77	16787.77	16787.77
Salvage Income MG2	16078.57	16078.57	16078.57
Salvage Income MG3	16506.03	16506.03	16506.03
Salvage Income MG4	14689.30	14689.30	14689.30
Annual Cost MG1	13391675.37	13266037.59	13257822.07
Annual Cost MG2	8332292.53	8268950.37	8267572.08
Annual Cost MG3	9199735.76	9120756.24	9119196.24
Annual Cost MG4	6607773.509	6606991.661	6604658.82
AEC	37531477.18	37262735.86	37249249.21



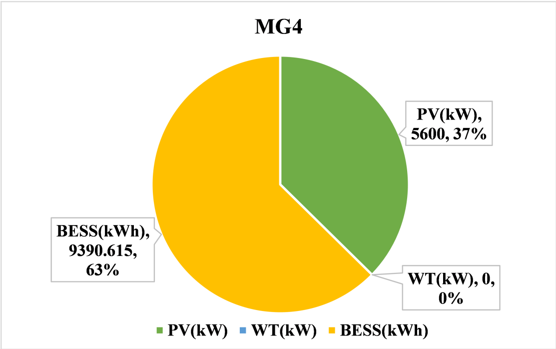
(a) Optimal Capacity of MG_1.



(b) Optimal Capacity of MG_2.



(c) Optimal Capacity of MG_3.



(d) Optimal Capacity of MG_4.

Figure 4.12: Optimal Capacity of MGs in NMG.

Table 4.8: Output for Single and Multi-Objective Optimization

Method	AEC ($)	LPSP
PSO - AEC	37252885.65	0.95278
PSO - LPSP	37353669.22	0.95062
MOPSO	37249249.21	0.95139

tives. While determining the ideal sizes of RES and BESS for MGs, two energy trading schemes, P2G and P2P, based on a proportional sharing approach, are employed. A MOO problem is modeled and implemented using MOPSO. P2P energy trading among MGs reduces cost and increases reliability when compared to P2G energy trading. The difference in cost between maximum capacity and optimal capacity obtained through P2P energy trading using proportional sharing for each MG is: MG_1- 133853.30 ($), MG_2- 64720.45 ($), MG_3- 80539.52 ($), MG_4- 3114.69 ($). As a result, RES utilization is maximized, the interaction with the grid is decreased, and the BESS capacity required is lowered through P2P energy trading using a proportional sharing approach.

4.6 Limitations and Applicability in Real World Power System

The study on MG optimization and energy trading strategies, while insightful, has inherent limitations. These include simplified assumptions, fixed energy prices, and a lack of in-depth analysis on market dynamics and regulatory considerations. The model's complexity and scalability to larger systems also pose challenges, and real-world validation is absent. Despite these limitations, the findings offer valuable insights for adapting the proposed strategies to real-world power systems. However, successful implementation requires careful consideration of local context, dynamic power system nature, regulatory compliance, stakeholder engagement, economic viability, technological advances, and environmental considerations. Continuous monitoring and collaboration are crucial for the sustainable integration of MG solutions into existing power infrastructures.

Chapter 5

Economic Analysis of Energy Scheduling and Trading in Multiple-Microgrids Environment

5.1 Introduction

In the pursuit of enhancing the economic viability and operational efficiency of NMG systems, optimal energy scheduling and strategic energy trading has emerged as a focal point of research. This part of the thesis delves into an exploration of diverse strategies for combined energy scheduling and energy trade of interconnected MGs. The fundamental premise revolves around the MG's capacity to not only cater to its local energy demand but also to judiciously manage excess energy through various avenues, including storage in ESS, supplying to the grid, or engaging in proportional energy exchanges with other MGs. The operational flexibility of MGs in managing surplus energy introduces a multitude of scenarios, each presenting unique opportunities for economic optimization. This part of work seeks to systematically compare and analyze these scenarios, unraveling the intricate dynamics of energy scheduling and trade within MGs. The overarching objective is to evolve strategies that not only bolster the economic resilience of individual MGs but also contribute to the overall improvement of revenue generation of MGs. The central theme of this study lies in addressing the post-local load supply phase, where MGs are presented with choices on how to manage their surplus energy. This crucial decision-making juncture involves considerations such as storing excess energy in ESS for future use, selling it to the central power grid, or engaging in collaborative energy trading with other autonomous MGs. The work navigates through these scenarios, shedding light on the implications of each choice and the strategic evolution required for effective energy management. By comparing and contrasting different operational paradigms, the study aims to provide valuable insights into the nuanced decision-making processes that can optimize revenue streams for MGs.

5.2 System Architecture

The MMG system considered in this part of the thesis consists of three interconnected MGs linked to one another and the grid. The MMG system used for analysis is shown in Fig 5.1. Within each MG, there is a combination of PV systems, ESS, and loads, all managed by a local EMS [54]. The power flow and energy trading amongst the MGs and with the grid are controlled through the EMO. The system considered is an MMG operating in grid-connected mode, such that each MG can sell or buy power from the grid or other MGs, through EMO. The government grants subsidy (θ) to each MG with PV systems in proportion to the amount of energy generated for clean power generation. The MG prefers to meet its own load demands through RES and charges the ESS with excess generation. If the generation of PV is insufficient, the MG will buy power from the other MG or grid. EMO decides the price of selling and buying of energy between MGs such that the MMG system is economically benefited from internal trading. The relation between internal buying price (P^b_{mg}) and selling price (P^s_{mg}) of the MGs as compared to the price of selling (P^s_g) or buying power (P^b_g) from the grid is given in [Eq 5.1] . This condition encourages more trading among MGs and helps the MG to gain more profits from energy trading with other MGs compared to trading with the power grid.

$$(P^b_g) \leq (P^b_{mg}) \leq (P^s_{mg}) \leq (P^s_g) \tag{5.1}$$

Each MG is assumed to be equipped with PV such that it generates energy (PV^t_{geni}) during a certain hour 't' of the day. Each MG is initially required to fulfill its load demand (L^t_i). In case, if the $PV^t_{geni} > L^t_i$ then the MG_i, where $i \in N$, acts as a seller or stores excess energy, as per the strategy. For an opposite condition, where $PV^t_{geni} < L^t_i$, MG_i is required to buy energy or discharge ESS to meet the load demand. The set of all MGs which have excess energy will be represented by S. After serving its own load at hour 't', the seller MG will have excess energy given by [Eq 5.2].

$$E^t_{i,ex} = (PV^t_{geni} - L^t_i) \geq 0 \; \forall \; i \in S \tag{5.2}$$

The amount of energy required for a buyer MG is given in [Eq 5.3] where B represents all buyer MGs.

$$E^t_{i,req} = (L^t_i - PV^t_{geni}) \forall i \in B. \tag{5.3}$$

The MMG's total excess energy and deficit energy are expressed by [Eqs 5.4 and 5.5], respectively.

$$E^t_{t,ex} = \sum_{i=1}^{n} (PV^t_{geni} - L^t_i) \; where \; \forall \; i \in S \tag{5.4}$$

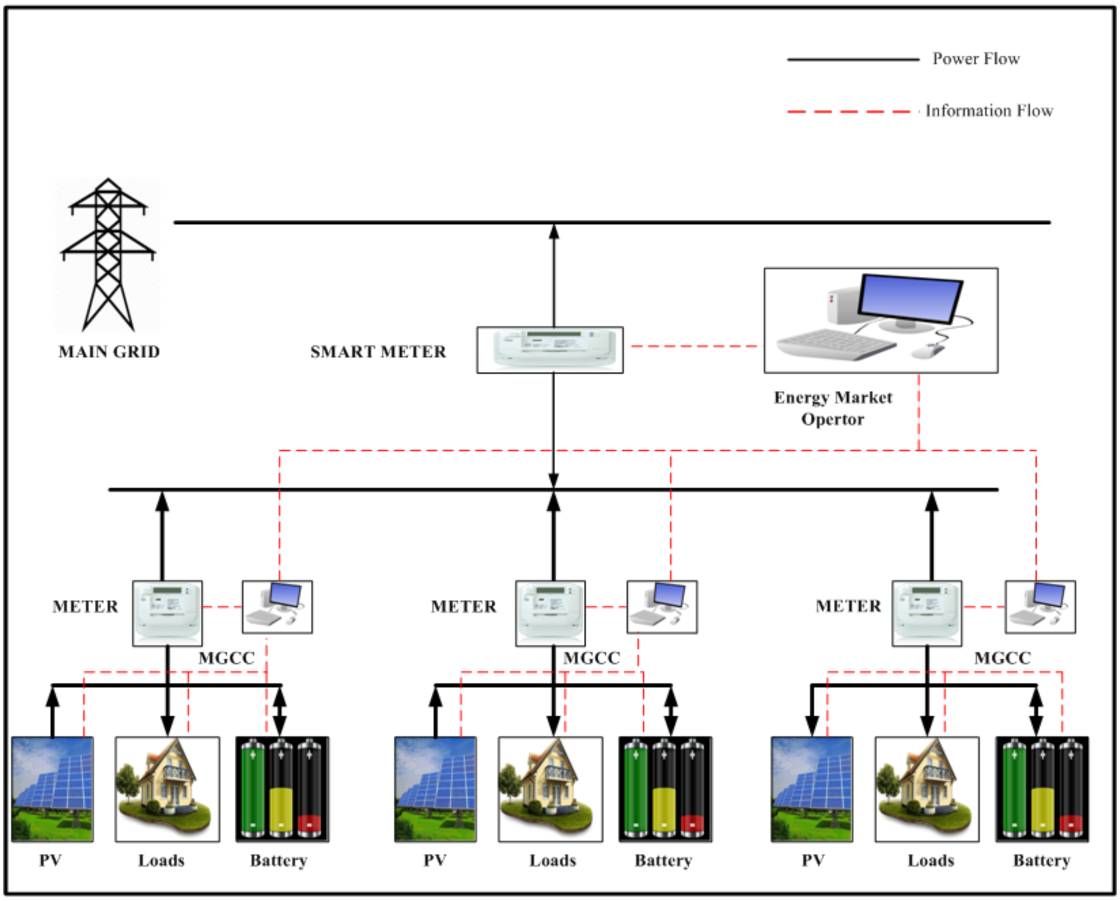


Figure 5.1: Structure of MMG system.

$$E_{t,rq}^{t} = \sum_{i=1}^{n} (L_i^t - PV_{geni}^t) \ where \ \forall \ i \in B \tag{5.5}$$

This information on excess and deficit energy in NMGs is provided to the EMO. The EMO then fixes the selling and buying prices for every hour according to [Eq 5.1].

The primary objective of local EMS i.e. MGCC in each MG is to fulfill the local demand. The secondary objective of MGCC is to schedule the load and ESS, for gaining optimal benefits from trading within MMG based on internal prices set by EMO. To increase the profits of the MMG and the EMO there are a number of constraints to be considered. The energy balance constraint of MG_i is represented in [Eq 5.6].

$$P_{b,i}^t - P_{s,i}^t = l_i^t + E_{ch,i}^t - PV_{geni}^t \tag{5.6}$$

In [Eq 5.6], $P_{b,i}^t$ is the amount of energy bought and $P_{s,i}^t$ is the amount of energy sold by MG_i in time slot 'h', l_i^t is the internal load supplied in MG_i, $E_{ch,i}^t$ is the amount of energy for charging ESS.

Eq [5.7] represents the constraint on maximum power flow allowed between an MG and power grid.

$$0 \leq P_{b,i}^t, P_{s,i}^t \leq P_{f,i}^{\max} \tag{5.7}$$

In addition to the above constraints of power flow, the constraints with respect to ESS are given in [Eqs 5.8 - 5.11].

$$E_i^t = E_{ch,i}^t - E_{dis,i}^t \tag{5.8}$$

$$0 \leq E_{ch,i}^t \leq E_{ch,i}^{max} \tag{5.9}$$

$$0 \leq E_{dis,i}^t \leq E_{dis,i}^{max} \tag{5.10}$$

$$SOC_i^{min} \leq SOC_i^t \leq SOC_i^{max} \tag{5.11}$$

In [Eqs 5.8 - 5.11], $E^t_{ch,i}$ $E^t_{dis,i}$ are the charging and discharging energy of ESS in MG_i, $E^{max}_{ch,i}$, $E^{max}_{dis,i}$ are the maximum amount of charge and discharge allowed in ESS and SOC^{min}_i, SOC^{max}_i are the limits for state of charge of ESS.

In this study, it is considered that forecasted data on PV generation, load, grid power selling and buying prices, and internal MMG prices are already known. The forecasted data of PV and load is obtained based on a prediction algorithm, the internal prices are obtained using Stackelberg game theory [54].

5.3 Evolution of Strategies

The objective is to establish an efficient EMS in MMGs to maximize profitability of individual MGs and the EMO, by analysing different scheduling strategies. The profitability depends on various factors such as time of power generation by RES, charging and discharging of ESS, amount of power deficit in MG, excess energy available with other MGs, etc. The objective function for this is defined as in [Eq 5.12].

$$max f(x) = \sum_{t=1}^{24} [\theta * PV^t_{geni} - P^{sh}_g * P^t_{bt} + P^{bsh}_{mg} * P^t_{ld} + P^{bh}_g * P^t_{ex}] \tag{5.12}$$

Where θ is the subsidy, P^{sh}_g and P^{bh}_g is the selling and buying price of energy from grid to concerned MG, respectively. P^{bsh}_{mg} is the internal buying or selling price of energy within the MMG. P^{bsh}_{mg} will be positive when the MG sells energy and vice versa. The amount of energy traded within NMGs is P^t_{ld} and P^t_{ex} is the energy sold to the grid. The objective function will be evaluated for each hour 't'.

The strategies are evolved from 1 to 4 and finally resulting in the 5^{th} strategy with an objective of maximizing profits of individual MGs. The different EMS used in this analysis are shown through flowchart in Figs 5.2 and 5.3. Fig 5.2 shows the flowcharts for the first 4 proposed strategies and Fig 5.3 gives the last strategy. The main sources of RES is a PV unit in all strategies and we schedule the ESS to satisfy the loads. All proposed strategies are described in the following subsections.

Strategy 1:

In this case, the PV power generated ($PV^t_{gen,i}$) in each MG_i is self-consumed i.e., supplied to the load l^t_i and remaining energy after supplying to load i.e., excess energy

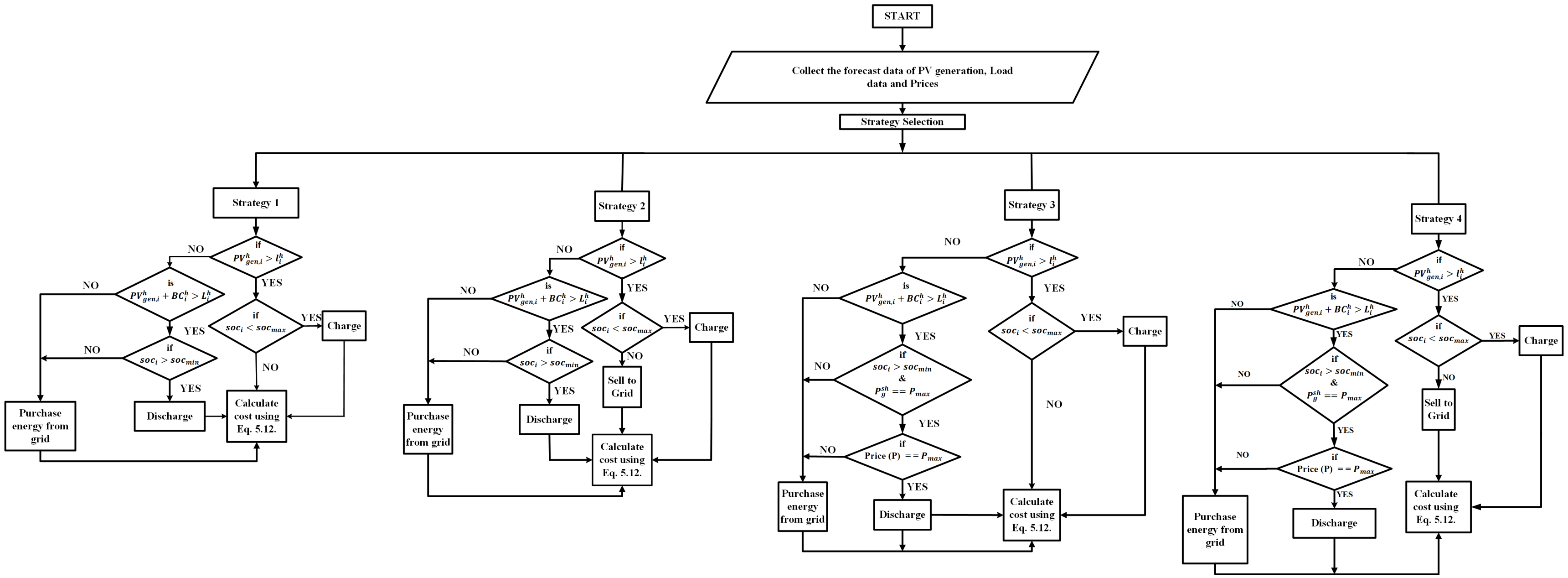


Figure 5.2: Flowchart for strategies 1-4

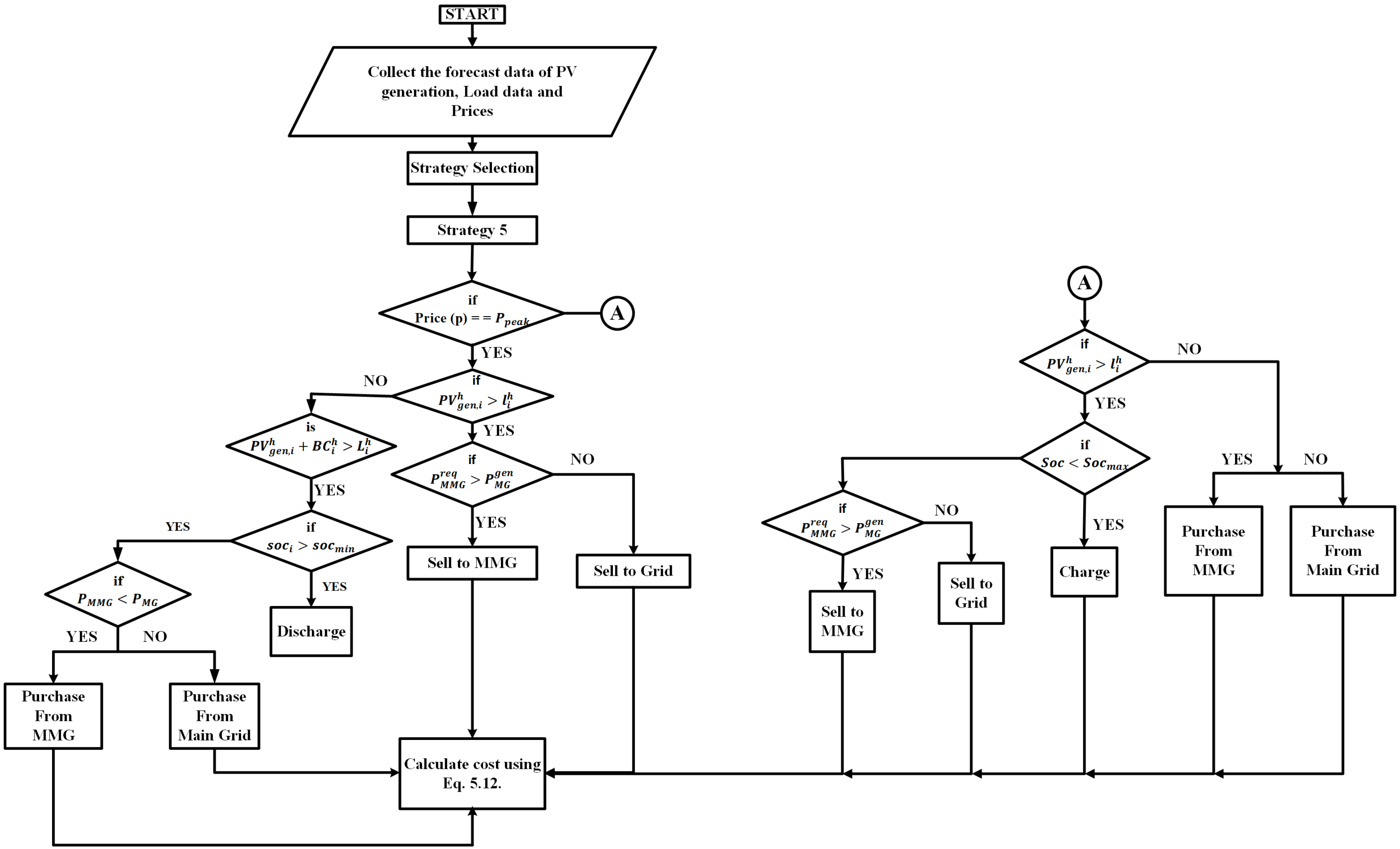


Figure 5.3: Flowchart for strategy 5

$E^t_{i,ex} = (PV^t_{geni} - L^t_i)$ is stored in the ESS as shown in [Eq 5.13] by satisfying the constraints of [Eqs 5.8-5.11 and 5.14]. The excess energy is not supplied to other MG or to the grid i.e., the concept of energy trading is not implemented. In case, PV power generation and battery capacity are inadequate to supply the load, the energy is purchased from the grid to meet local load demand only as shown in [Eq 5.15] by complying with the constraints in [Eqs 5.6-5.7]. The ESS is not scheduled and discharges irrespective of peak period to the local load obeying [Eq 5.14]. The cost incurred is determined using [Eq 5.12]. The operation of PV generation, consumption, and role of ESS is shown as flowchart in Fig 5.2.

$$BC^t_i = BC^{t-1}_i + (PV^t_{gen,i} - l^t_i) \tag{5.13}$$

$$BC^{min}_i \leq BC^h_i \leq BC^{max}_i \tag{5.14}$$

$$P^t_{b,i} = l^t_i - (PV^t_{gen,i} + (BC^t_i - BC^{t-1}_i)) \tag{5.15}$$

Strategy 2:

In an enhancement to the previous strategy, in this case. the ESS charging and discharging pattern is similar to strategy 1, but the excess energy generated by PV ($PV^t_{gen,i}$) is utilized for trading. Here the generated PV power ($PV^t_{gen,i}$) in each MG_i is supplied to the local load l^t_i and the remaining energy after supplying to the local load is supplied to the ESS. However, after supplying local load and ESS, the excess energy generated by the PV ($PV^t_{gen,i}$) is traded with the grid as shown in Fig 5.2. The excess energy supplied to the grid is given by [Eq 5.16] and the amount of energy purchased from the grid is shown in [Eq 5.15].

$$P^t_{s,i} = PV^t_{gen,i} - (l^t_i + (BC^t_i - BC^{t-1}_i)) \tag{5.16}$$

Strategy 3:

In strategy 3, the ESS charging pattern is kept similar to the strategies 1 and 2, but the excess PV generated is not coordinated as in strategy 1. This strategy improves the profit by discharging the ESS only during peak periods to supply the local load of the MG as shown in Fig 5.2. The battery charges and discharges based on the constraints followed in the above two strategies. The energy deficit is purchased from grid as indicated in [Eq 5.15].

Strategy 4:

This case is a combination of strategy 2 where the excess energy produced by PV is supplied to the grid and strategy 3 where the ESS discharges during peak period only as shown in Fig 5.2. The excess energy produced by the PV is supplied to the grid according to [Eq 5.16]. This strategy is evolved from and is a combination of earlier strategies.

Strategy 5:

Strategy 5 leads us to the threshold of evolution, as we move from strategies 1 to 4. In strategies (1-4), trading within the MGs in MMG is not considered. Also in strategies (1-4), the ESS is charged after the load demand is met. Strategy 5 is developed with a sole purpose of optimizing the profits of an MG and not satisfying the loads of the MG, as the primary objective. The ESS, similar to strategies 3 and 4, discharges during peak time only. The excess energy generated by the PV unit is either sold to the grid or MG during peak period. The energy stored in the ESS may also be discharged during peak periods to realize an increase in profits. In case, the total energy required $E^t_{t,rq}$ by other MG's in MMG is zero, the total excess energy $E^t_{t,ex}$ is sold to the grid.

5.4 Results

To analyze the performance of the proposed EM schemes, an MMG system consisting of 3 interconnected MGs as shown in Fig 5.1 is used. Each MG consists of a PV, ESS, and EMS for controlling the power flow. The strategies (1-4), as discussed, deal with EM in an MMG with load satisfaction as its main objective, and excess energy is traded with grid in strategies 2 and 4. In strategy 5, trading amongst MMG is considered with profit making as the primary objective. Table 5.1 lists the various parameters used for case study. A typical day is divided into 24 segments, for each hour. It is assumed that the generation and load are constant during an hour. The typical PV generation, load demand, and TOU tariff of MGs in a day are considered from [54]. The grid selling and buying price and the internal prices in each MG and trading with other MGs are shown in Fig 5.4. The relation between the selling and purchase prices is as shown in [Eq 5.1].

Table 5.1: System Data for Case Study

Parameter	Value
Battery capacity (BC)	100kW
Charging Rate/Discharge Rate	0.5
SOC_i^{min}	0.2
SOC_i^{max}	1
Subsidy (θ)	4.46 INR/kWh

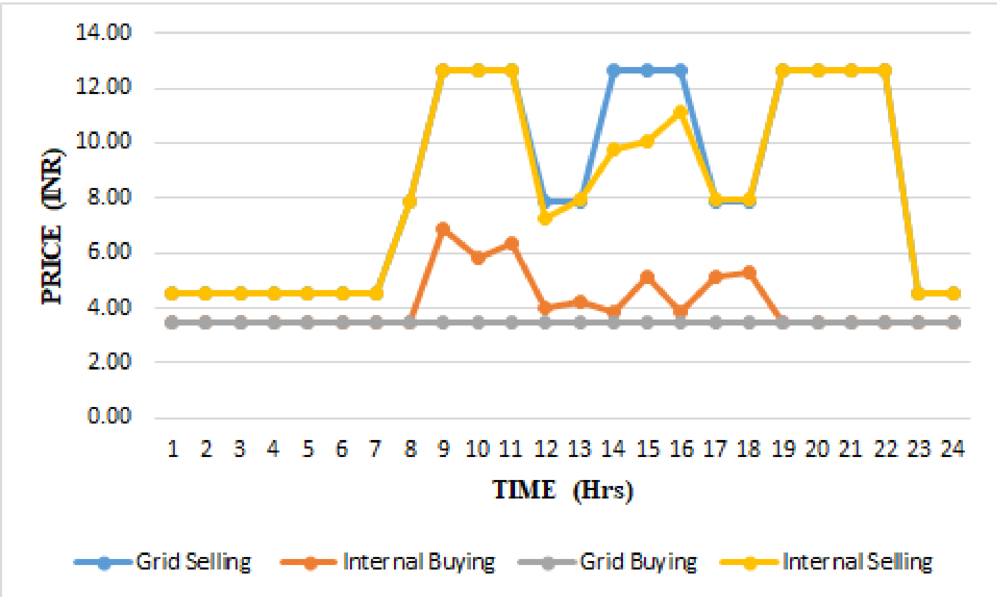


Figure 5.4: Time Of Use Prices

PV generation is present during daytime, which encourages more energy trading in MMG or with the grid during this time. Visual Basic for Applications (VBA) programming is employed to implement and analyze the proposed strategies.

Strategy 1:

The ESS schedule details for strategy 1 are outlined in Fig. 5.5a. In this strategy, the ESS charging pattern is shown as follows: in MG_1, charging continues until the 17^{th} hour, in MG_2 until the 15^{th} hour, and in MG_3 until the 11^{th} hour, reaching full capacity. Following the charging phase, the ESS discharges strategically to support the load demand. The revenue generated by strategy 1 is presented in Fig 5.6a. The price includes both negative and positive values. Negative values signify instances where the combined energy generated from PV and energy stored in the ESS is insufficient to meet the load demand, occurring notably during the 1-8 hours and 18-24 hours periods. The cost variations across the three MGs (MG_1, MG_2, and MG_3) are comprehensively depicted in Fig 5.6a. The total revenue generated by individual MGs is - MG_1 - 4197.60 INR, MG_2 - 7916.66 INR, MG_3 - 5763.76 INR.

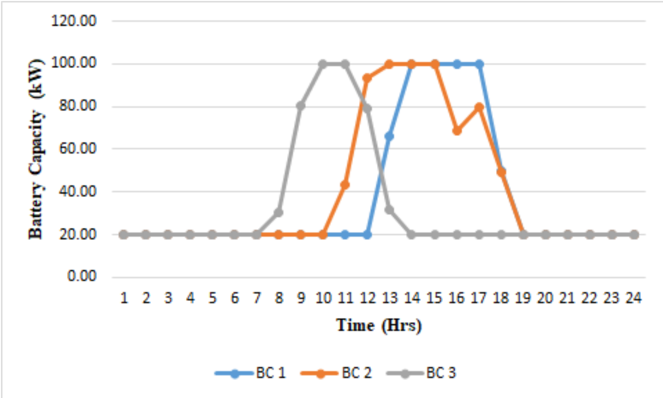
Strategy 2:

This strategy is identical to strategy 1, but in this strategy, the excess energy generated during 9-17 hours as shown in Fig 5.7 by the PV system is sold to the grid. The charging and discharging pattern of ESS is observed to be similar as strategy 1, as shown in Fig 5.5a. Fig 5.6b, provides the revenue generated by each MG and the total combined revenue of all MGs for each hour. The selling of excess energy generated at various hours by the PV unit to the grid, improves the revenue of each MG. The total revenue generated by each MG is- MG_1 - 5606.89 INR, MG_2 - 8407.17 INR, and MG_3 - 5993.05 INR in comparison to strategy 1.

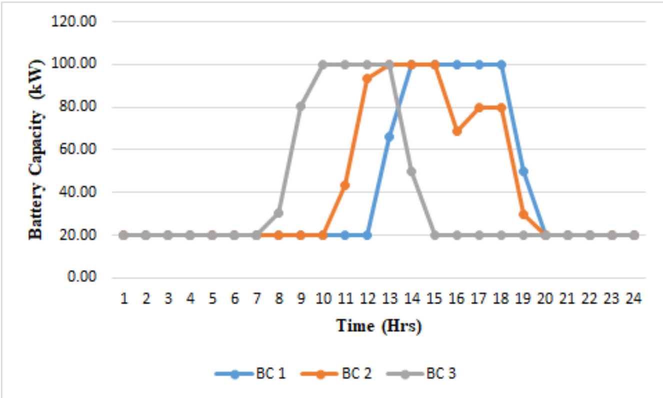
Strategy 3:

In this strategy, each MG profits by discharging ESS only during the peak demand hours i.e 9-11, 14-16, and 19-22 hours as shown in Fig 5.4. The battery charging and discharging patterns are shown in Fig 5.5b. Under this strategy, the excess energy is not utilized as in strategy 1. The results of revenue generated by each MG and the combined revenue of all MGs are shown in Fig 5.6c. The total revenue of MGs in this strategy are MG_1 - 5459.49 INR, MG_2 - 8133.65 INR, and MG_3 - 6390.10 INR.

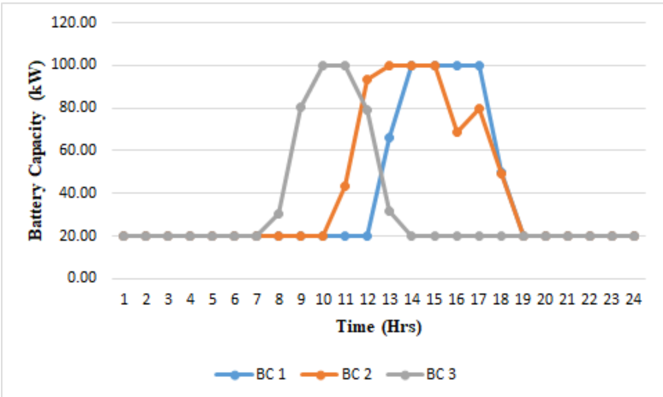
Strategy 4:



(a) Strategy 1 and 2.

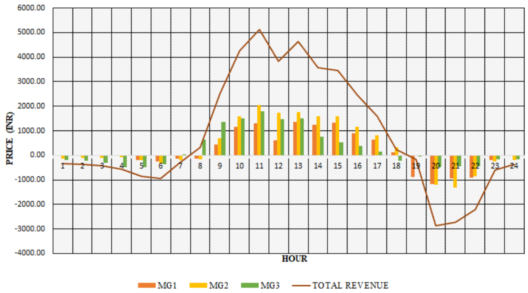


(b) Strategy 3 and 4.

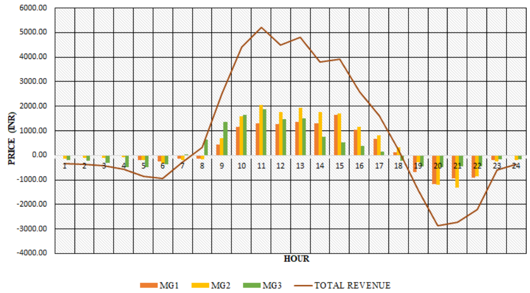


(c) Strategy 5.

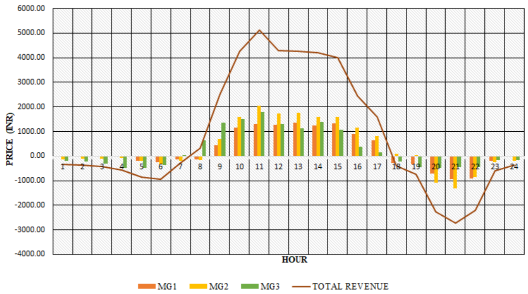
Figure 5.5: ESS charging and discharging for Strategies 1-5.



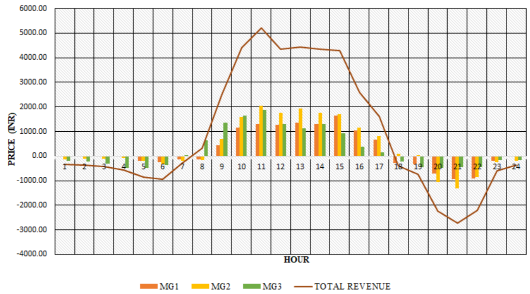
(a) Strategy-1.



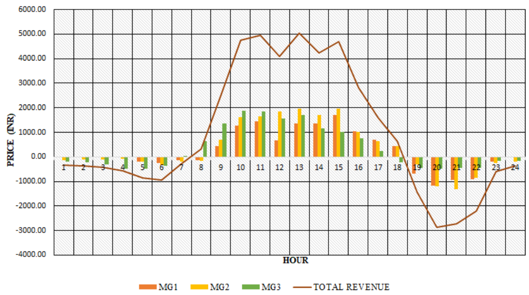
(b) Strategy-2.



(c) Strategy-3.



(d) Strategy-4



(e) Strategy-5

Figure 5.6: Revenue of different strategies.

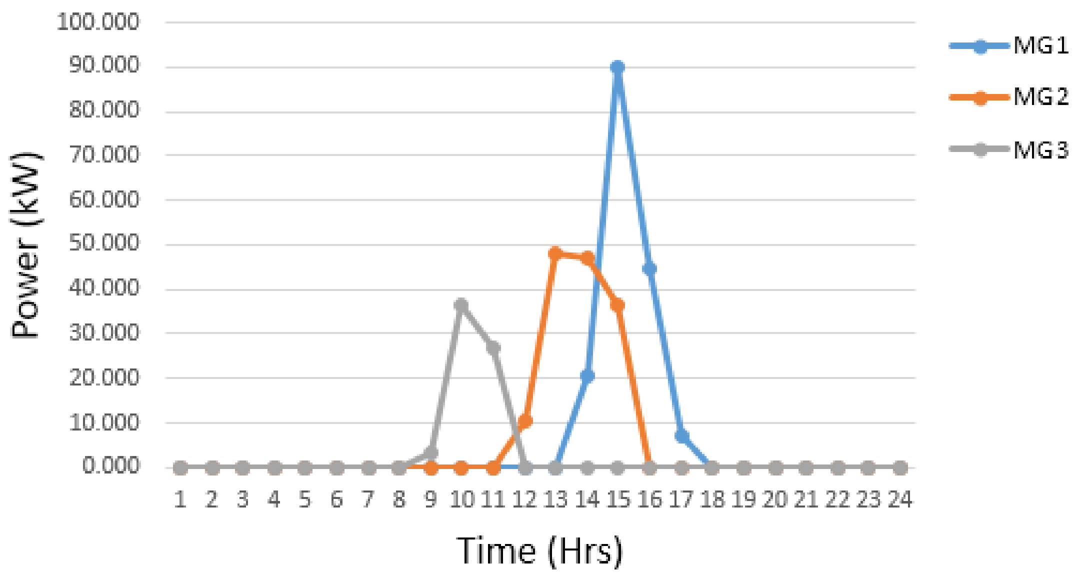


Figure 5.7: Excess energy sold in Strategy 2 and Strategy 4

It is identical to strategy 3, but trades excess energy generated by PV similar to strategy 2 as shown in Fig 5.7. The charging and discharging of ESS is shown in Fig 5.5b, while the revenue obtained by each MG and total revenue of all MGs is shown in Fig 5.6d. The total revenue of MGs in this strategy are MG_1 - 6019.14 INR, MG_2 - 8657.97 INR and MG_3 - 6389.90 INR.

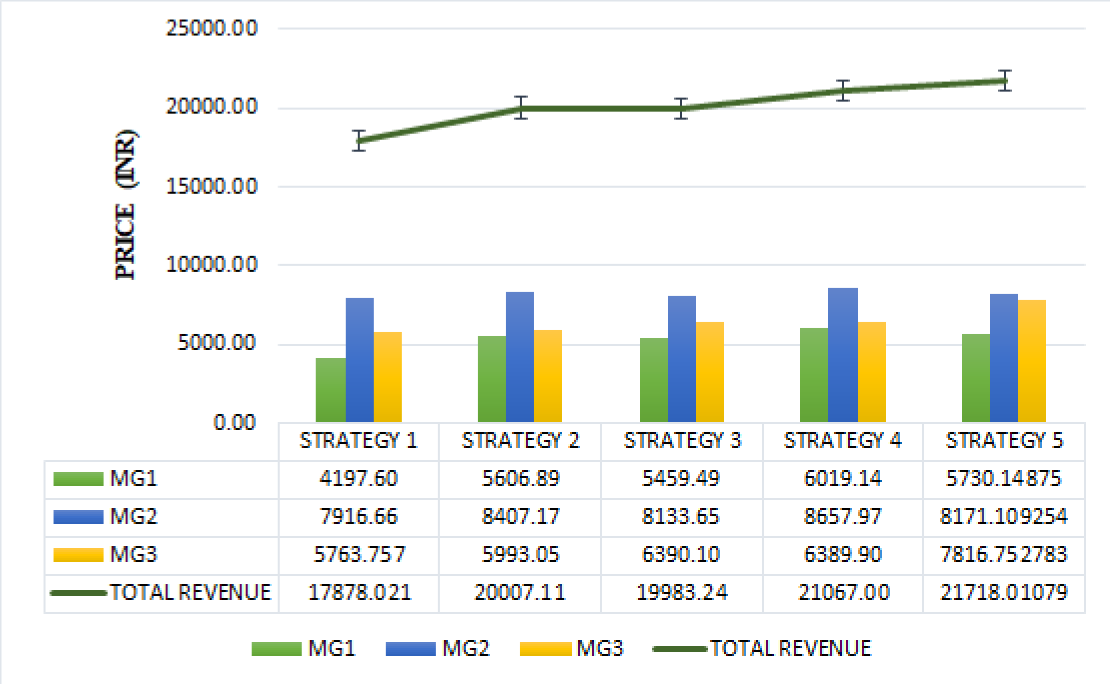
Strategy 5:

In this strategy, the excess generated energy is traded amongst the MGs or with the grid. The role of each MG during each hour is given in Table 5.2. The energy trading between MGs is done between the 9^{th} and 17^{th} hour. The ESS charging and discharging pattern is shown in Fig 5.5c and revenue generated is shown in Fig 5.6e.

Table 5.2: Roles of MG in Energy Trading

Hour	MG1	MG2	MG3
1-8	Buyer	Buyer	Buyer
9-10	Buyer	Buyer	Seller
11	Buyer	Seller	Seller
12	Buyer	Seller	Buyer
13-15	Seller	Seller	Buyer
16	Seller	Buyer	Buyer
17	Seller	Seller	Buyer
18-24	Buyer	Buyer	Buyer

MMG trading improves the combined revenue of all MGs as compared to individual MG operation as shown in Fig 5.8.



	STRATEGY 1	STRATEGY 2	STRATEGY 3	STRATEGY 4	STRATEGY 5
MG1	4197.60	5606.89	5459.49	6019.14	5730.14875
MG2	7916.66	8407.17	8133.65	8657.97	8171.109254
MG3	5763.757	5993.05	6390.10	6389.90	7816.752783
TOTAL REVENUE	17878.021	20007.11	19983.24	21067.00	21718.01079

Figure 5.8: Total Revenue of each MG

5.5 Summary

Various strategies are formulated based on optimum utilisation of DER in an MMG environment, in order to maximize individual MG revenues. These strategies are developed on the basis of i) energy available at ESS and ii) TOU rates. Compared to individual MG operation, the revenue of MGs increased by 11.90%, 11.77%, 17.84%, and 21.57% for respective MMG trading strategies. The proposed energy trading strategy 5, generates more revenues in comparison to other strategies.

5.6 Limitations and Applicability in Real World Power System

The study on optimal energy scheduling and strategic energy trading within interconnected MGs presents insightful strategies aimed at enhancing economic viability and operational efficiency. However, certain limitations must be acknowledged. The simplifications in modeling, reliance on accurate forecasting, and static TOU tariff assumptions may not fully capture the dynamic and uncertain nature of real-world MG operations. The strategies proposed, while comprehensive, may not encompass all emerging scenarios in the rapidly evolving energy landscape. Grid connectivity assumptions and a focus primarily on economic optimization might limit the direct applicability of findings to off-grid or islanded microgrid scenarios and may not address broader social and environmental considerations. Furthermore, the lack of real-world validation and exploration of practical implementation challenges suggests a cautious interpretation of the study's outcomes. While the study provides valuable insights, its findings should be considered within the broader context of societal, environmental, and regulatory dynamics that influence the complexities of real-world power systems.

Chapter 6

Development and Analysis of Scheduling Strategies for Utilizing Shared Energy Storage System in Networked Microgrids

6.1 Introduction

This chapter of the thesis delves into the comprehensive exploration of scheduling and trading strategies within NMGs, addressing critical aspects such as load imbalance, TOU pricing, and the incorporation of IESS and SESS. The objective of this part of research is to minimize the overall operating cost of NMGs, thereby paving the way for sustainable and economically efficient energy management. The chapter focuses on two pivotal aspects: DA optimal scheduling of IESS and SESS in NMGs, and the intricate dynamics of energy trading within the NMG framework. By optimizing the scheduling of ESS based on RES power output, load demand, and TOU pricing, the study seeks to achieve cost minimization while ensuring the reliability of the NMG. The energy trading mechanisms explored in this research revolve around the proportional trading of energy among MGs within the NMG framework. This involves facilitating P2P energy trading between buyers and sellers, offering a nuanced approach to balance demand and supply, optimize resource utilization, and minimize overall costs. The proposed proportional energy trading approach introduces a novel perspective on achieving efficient and economically viable energy exchange within NMG systems.

6.2 Problem Formulation

The main objective of this part of the research, is to minimize the overall operating cost of NMG. To achieve this goal, the study focuses on two key aspects: DA optimal scheduling of IESS and SESS in NMGs, as well as energy trading within the NMG. The scheduling aspect involves considering various factors such as RES power output and load demand within NMG, and TOU pricing from the external grid. By optimizing the scheduling of IESS and SESS based on these factors, cost minimization is achieved. The energy trading within NMG depends on excess and deficit energy at a particular hour for each MG. This means that if a particular MG has an excess of energy beyond its load requirements during a certain hour, it can trade that surplus energy with other MGs that may be facing a deficit or higher demand. The energy trading mechanism enables NMGs to balance demand and supply, optimize resource utilization, and leads to cost minimization. The formulation of energy trading prices is based on several factors, including FIT, and TOU pricing from the grid, as well as load and generation within the NMG system. By considering these variables and formulating appropriate energy trading prices, the research aims to facilitate efficient and economically viable energy exchange for the NMG. The NMG framework, incorporating both IESS and SESS, is illustrated in Fig. 6.1. Each MG within the NMG consists of various components, including loads, RES such as solar PV, wind turbines, and ESS. The MGCC of each MG communicates information about excess and deficit energy to the NMG manager/aggregator. The NMG manager/aggregator decides the amount of energy to be traded among the MGs. The MGs can share energy among themselves using dedicated power lines. In both the cases, the MGs have the option to trade energy with the grid, and the ESS can also engage in energy trading with the grid.

For the NMG framework with IESS, as shown in Fig. 6.1a, each MG is equipped with its own individual ESS. The NMG framework with SESS is depicted in Fig. 6.1b, where the ESS is shared among the MGs. In this framework, MGs trade energy with the SESS through dedicated lines. The SESS acts as an individual player and has an independent decision-making system.

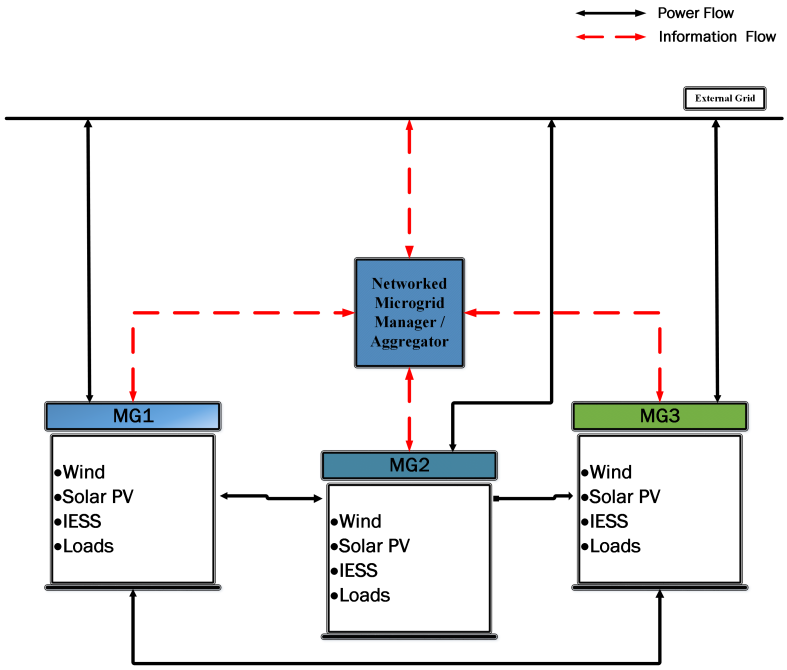
6.2.1 Objective Function

The objective is to minimize the total operating cost of the NMG system. The operating costs include:

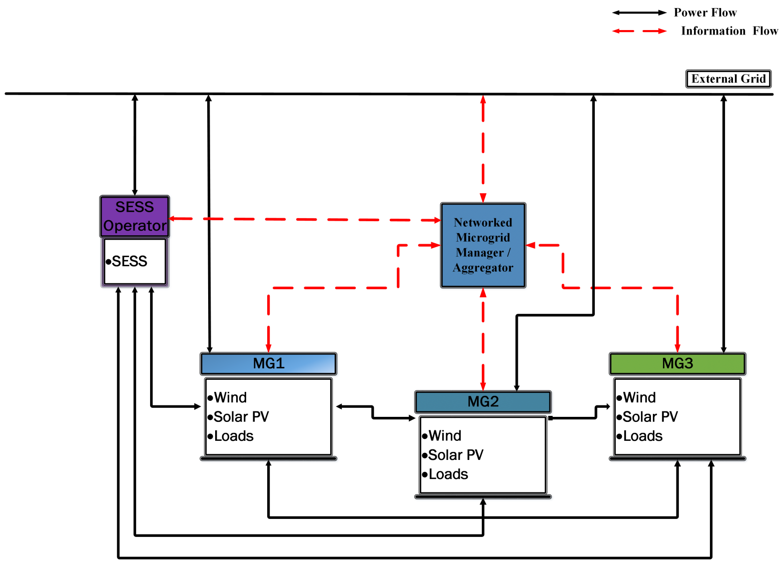
- the operation and maintenance cost of RES in each MG.
- the cost of energy traded with the grid.
- the cost of energy traded within NMG.
- the cost of energy traded with ESS.

The objective function is given below in [Eq 6.1].

$$Min\ C = \sum_{i=1}^{MG} C_{OM}^{i} + C_{G,TD}^{i} + C_{N,TD}^{i} + C_{ESS}^{i} \tag{6.1}$$



(a) NMG Framework with IESS



(b) NMG Framework with SESS

Figure 6.1: NMG Framework with IESS and SESS

6.2.1.1 Operation and Maintenance (O&M) Cost

The O&M is the cost associated with operating and maintaining the RES. The O&M cost of the RES in each MG_i is given in [Eq 6.2].

$$C_{OM}^{i} = \sum_{t=1}^{T} \rho_{PV}^{i,t}.P_{PV}^{i,t} + \rho_{WT}^{i,t}.P_{WT}^{i,t} \tag{6.2}$$

6.2.1.2 Cost of Energy Traded with Grid

In instances when the load exceeds the generation, the MG_i purchases power from the grid because IESS/SESS or NMG trading cannot supply the deficit energy. When generation exceeds load, the MG_i sells the extra energy to the grid after charging IESS/SESS and/or NMG trading. The cost for energy traded by each MG_i with the grid is given in [Eq 6.3].

$$C_{G,TD}^{i} = \sum_{t=1}^{T} \rho_{b,G}^{i,t}.P_{b,G}^{i,t} - \rho_{s,G}^{i,t}.P_{s,G}^{i,t} \tag{6.3}$$

6.2.1.3 Cost of Energy Traded within NMG

The MGs with excess/deficit energy trade energy within the NMG to satisfy the load and minimize the cost. The cost for energy traded by each MG_i within the NMG is given in [Eq 6.4].

$$C_{N,TD}^{i} = \sum_{t=1}^{T} \rho_{b,N}^{i,t}.P_{b,N}^{i,t} - \rho_{s,N}^{i,t}.P_{s,N}^{i,t} \tag{6.4}$$

6.2.1.4 Cost of Energy Traded with ESS

In the NMG framework with SESS, the SESS operates as an individual entity and sells/buys the energy to/from NMG or the grid based on the proposed strategy. The cost for energy exchanged by each MG_i with ESS is given in [Eq 6.5].

$$C_{ESS}^{i} = \sum_{t=1}^{T} \rho_{b,ESS}^{i,t}.P_{b,ESS}^{i,t} - \rho_{s,ESS}^{i,t}.P_{s,ESS}^{i,t} \tag{6.5}$$

6.2.2 Constraints

The objective considered in this work should satisfy the power balance in each MG and ESS charging/discharging constraints.

6.2.2.1 Power Balance

At any time 't', the sum of power generated in MG_i must balance the power consumption as shown in [Eq 6.6]. The power generation in the MG_i consists of power generated by RES within MG_i, power bought from the grid or NMG, and discharging of IESS/power bought from the SESS. The power consumption in MG_i consists of the load in MG_i, power sold to the grid or NMG, and charging of IESS/power sold to the SESS.

$$\begin{aligned} P_{PV}^{i,t} + P_{WT}^{i,t} + P_{b,G}^{i,t} + P_{b,N}^{i,t} + P_{b,ESS}^{i,t} = \\ P_{L}^{i,t} + P_{s,G}^{i,t} + P_{s,N}^{i,t} + P_{s,ESS}^{i,t} \end{aligned} \tag{6.6}$$

6.2.2.2 Energy Storage System (ESS)

The energy capacity of ESS at a particular hour depends on discharged/charged power given by [Eq 6.7]. The energy in the ESS is limited by Eq. 6.8. The charging and discharging power constraints for the ESS at a particular time are given by [Eqs 6.9-6.10].

$$ESE_i^t = ESE_i^{t-1} + \left(P_{s,ESS}^{i,t} * \eta_c * \Delta(t) - \frac{P_{b,ESS}^{i,t}}{\eta_d} * \Delta(t) \right) \tag{6.7}$$

$$ESE_i^{min} \leq ESE_i^t \leq ESE_i^{max} \tag{6.8}$$

$$P_{s,ESS}^{min} \leq P_{s,ESS}^{i,t} \leq P_{s,ESS}^{max} \tag{6.9}$$

$$P_{b,ESS}^{min} \leq P_{b,ESS}^{i,t} \leq P_{b,ESS}^{max} \tag{6.10}$$

6.2.3 Energy Trading Formulation

The energy trading formulation in this part of the work is built upon our previous work presented in chapter 4. According to chapter 4, based on the load and generation conditions within the MG, the load imbalance is calculated at a given hour 't'. In the NMG framework with the IESS, after calculating the load imbalance, the IESS is scheduled. After satisfying the load and scheduling IESS, the MGs with excess energy act as sellers. The excess energy with seller MGs is shown in [Eq 6.11]. On the contrary, those with a deficit in energy act as buyers. The deficit energy with buyer MGs is given in [Eq 6.12]. The calculation of load imbalance, scheduling of IESS in MG, and calculation of excess/deficit energy in MG are performed by corresponding MGCC. All the MGs acting as sellers are represented in set S. Whereas all the MGs acting as buyers are represented by set B.

$$\begin{aligned} MG_{i,sur}^{t} = (P_{PV}^{i,t} + P_{WT}^{i,t} - (ESE_{i}^{t-1} + P_{s,ESS}^{i,t} * \eta_c * \Delta(t)) \\ -P_{L}^{i,t}) \geq 0 \,\forall\, i \in S \end{aligned} \tag{6.11}$$

$$\begin{aligned} MG_{i,sur}^{t} = (P_{PV}^{i,t} + P_{WT}^{i,t} + \left(ESE_{i}^{t-1} - \frac{P_{b,ESS}^{i,t}}{\eta_d} * \Delta(t)\right) \\ -P_{L}^{i,t}) < 0 \,\forall\, i \in B. \end{aligned} \tag{6.12}$$

In the NMG framework with the SESS, the MGCC decides the excess and deficit energy in the corresponding MG after calculating the load imbalance within the MG. The excess energy with seller MGs in set S is given in [Eq 6.13]. Similarly, the amount of deficit energy with buyer MGs in set B is given in [Eq 6.14]. After calculating the excess and deficit energy, MGs participate in energy trading within NMG along with SESS.

$$MG_{i,sur}^{t} = (P_{PV}^{i,t} + P_{WT}^{i,t} - P_{L}^{i,t}) \geq 0 \ \forall \ i \in S \tag{6.13}$$

$$MG_{i,sur}^{t} = (P_{PV}^{i,t} + P_{WT}^{i,t} - P_{L}^{i,t}) < 0 \ \forall \ i \in B. \tag{6.14}$$

The total amount of excess/deficit energy with seller MGs and buyer MGs is given in [Eqs 6.15-6.16], respectively.

$$E_{T,ex}^{t} = \sum_{i=1}^{S} (MG_{i,sur}^{t}) \tag{6.15}$$

$$E_{T,rq}^{t} = \sum_{i=1}^{B} (MG_{i,sur}^{t}) \tag{6.16}$$

Based on the proportional approach, the amount of excess energy supplied by seller MG is given in [Eq 6.17], whereas the amount of energy received by the buyer MG is given by [Eq 6.18]. The trading within NMG between sellers and buyers as per the proportional approach is depicted in flowchart as shown in Fig. 6.2.

$$P_{s,N}^{i,t} = \begin{cases} \left(\frac{-MG_{i,sur}^{t}}{E_{T,ex}^{t}}\right) * E_{T,rq}^{t} & if(E_{T,rq}^{t} + E_{T,ex}^{t} \geq 0) \\ MG_{i,sur}^{t} & if(E_{T,rq}^{t} + E_{T,ex}^{t} < 0) \end{cases} \tag{6.17}$$

$$P_{b,N}^{i,t} = \begin{cases} MG_{i,sur}^{t} & if(E_{T,rq}^{t} + E_{T,ex}^{t} \geq 0) \\ \left(\frac{-MG_{i,sur}^{t}}{E_{T,rq}^{t}}\right) * E_{T,ex}^{t} & if(E_{T,rq}^{t} + E_{T,ex}^{t} < 0) \end{cases} \tag{6.18}$$

In the NMG framework with IESS, the excess energy with seller MGs, after trading among the MGs, is sold to the grid, as given in [Eq 6.19]. On the other hand, in case there is demand for power after the settlement of trade in the NMG then the amount of deficit energy required by the buyer MGs is bought from the grid as given in [Eq 6.20].

$$P_{s,G}^{i,t} = MG_{i,sur}^{t} - P_{s,N}^{i,t} \tag{6.19}$$

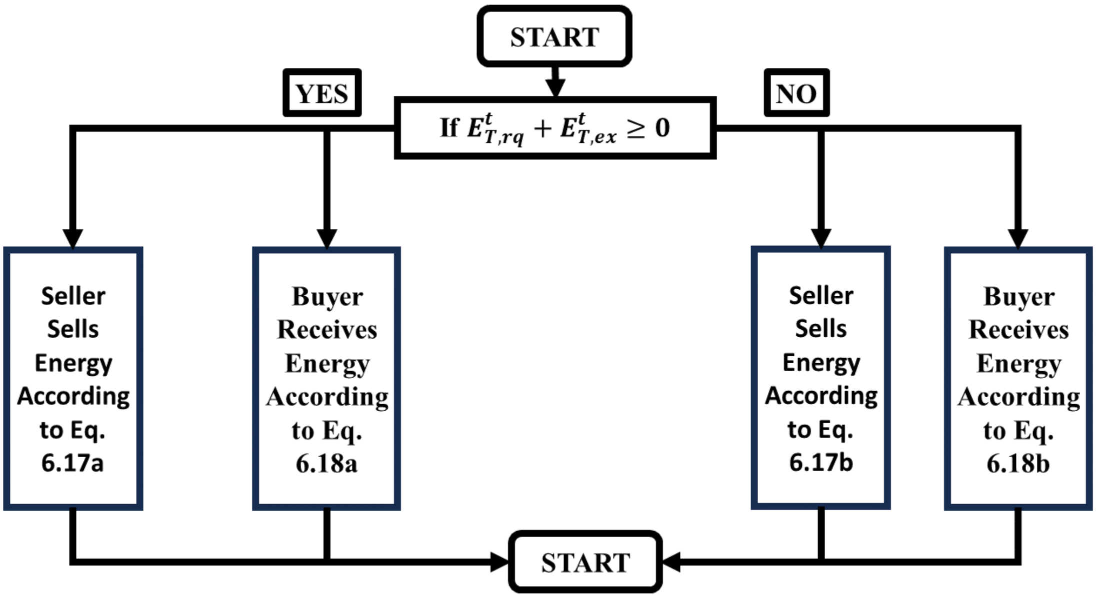


Figure 6.2: Flowchart for Energy Trading among MGs

$$P^{i,t}_{b,G} = MG^t_{i,sur} - P^{i,t}_{b,N} \tag{6.20}$$

In the NMG framework with the SESS, excess/deficit energy of the MGs is exchanged with SESS. The deficit energy with buyer MGs is traded with SESS following energy trading among MGs and vice-versa, according to [Eqs 6.17-6.18]. When trading energy with NMGs, the SESS must adhere to the constraints given in [Eqs 6.8-6.10]. The amount of energy sold to the grid after energy trading among MGs and exchange of energy with SESS is given by [Eq 6.21]. Similarly, the amount of energy bought from the grid after energy trading among MGs and exchange of energy with SESS is given by [Eq 6.22].

$$P^{i,t}_{s,G} = MG^t_{i,sur} - P^{i,t}_{s,N} - P^{i,t}_{s,ESS} \tag{6.21}$$

$$P^{i,t}_{b,G} = MG^t_{i,sur} - P^{i,t}_{b,N} - P^{i,t}_{b,ESS} \tag{6.22}$$

6.2.4 Energy Trading Price Formulation

According to [66,78], the motivation for the prosumers/MGs to participate in the energy trading among them is to minimize the electricity bills and maximize the profits of individuals. For this, energy trading prices among MGs should follow the relation in [Eq 6.23].

$$FIT \leq \rho_{b,N}^{i,t}, \rho_{s,N}^{i,t} \leq TOU^t \tag{6.23}$$

In [78], surplus vs demand-based pricing is used and an aggregated supply-to-demand ratio is considered and in [66], the load to renewable energy generation ratio in an MG, and the FIT are considered as factors for determining the prices of energy trading in an NMG. In this context, the ratio is incorporated into the FIT. However, there are instances where this value exceeds the market price, which is not feasible or accurate. In this part of research, we consider all these factors collectively to determine the electricity price for trading. The electricity price for trading is proposed to be based on the total generation and load in an NMG, FIT, and TOU price as in [Eq 6.24].

$$\rho_{b,N}^{i,t}, \rho_{s,N}^{i,t} = FIT + \left((TOU^t - FIT) * \left(\frac{P_L^{N,t}}{P_L^{N,t} + P_G^{N,t}} \right) \right) \tag{6.24}$$

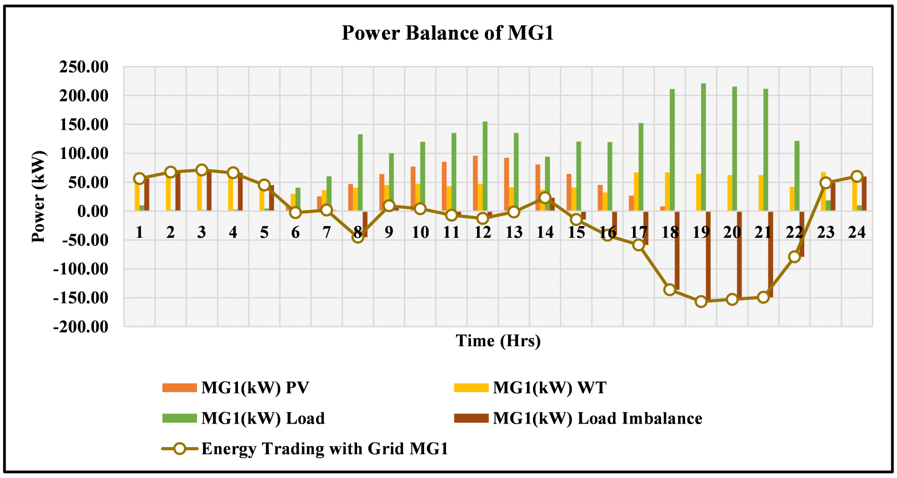
6.3 System Data and Results

This work investigates a series of case studies aimed at maximizing the economic operation of NMG. The case studies involve different strategies based on supply-demand imbalances, TOU prices, forecasted generation, and loads. The developed strategies are investigated in two distinct NMG frameworks: the NMG framework with IESS topology and the NMG framework with SESS topology. MATLAB is employed to evaluate all these cases. The NMG framework studied in this research comprises three MGs, interconnected with each other as depicted in Fig. 6.1. Each MG includes PV and WT generation as well as loads in addition to IESS or SESS. Fig. 6.3 displays the TOU price, representing the selling price of electricity by the grid to the MGs, and the FIT data, which indicates the price at which the grid purchases energy from the MGs. As can be observed from Fig. 6.3, the TOU price is classified into three periods: off-peak, intermediate, and peak periods. The operational parameters of the NMG framework are detailed in Table 6.1.

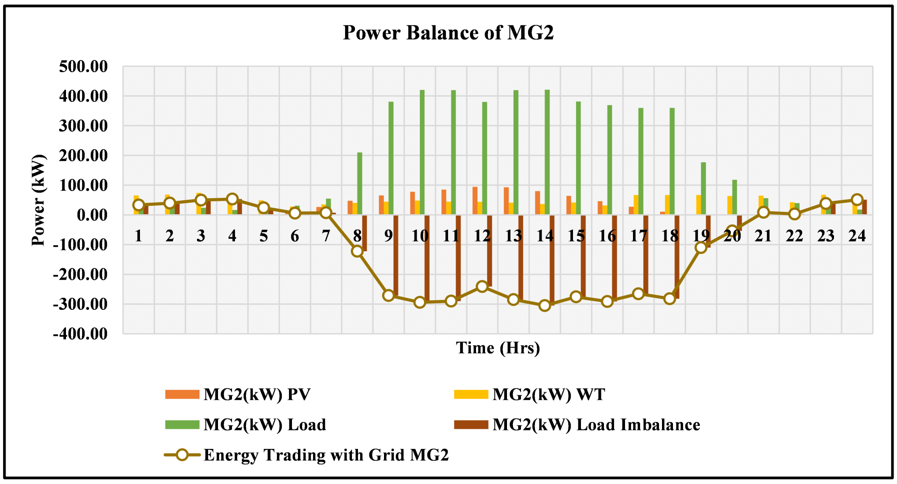
Figure 6.3: TOU and FIT prices.

6.3.1 Case 1: ESS and Energy Trading both Excluded

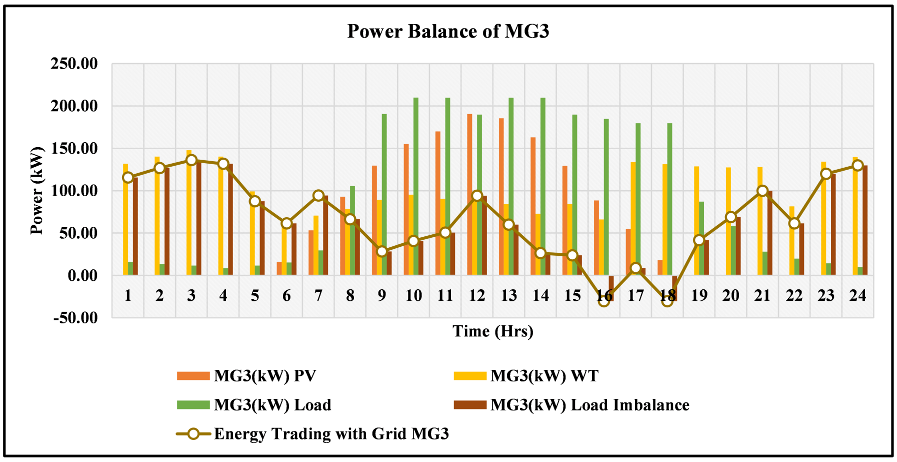
In this case, the IESS/SESS is excluded, and energy trading among MGs is not considered. However, MGs can trade energy with the grid. As there is no IESS/SESS, the excess or deficit energy in the individual MG is directly traded with the grid. The MGs can sell any surplus energy they generate to the grid and purchase energy from the grid to meet their deficits. The power balance of individual MGs within NMG is depicted in Fig. 6.4. In this case, MG_1 generates excess energy during 00:00-04:00, 07:00, 09:00-10:00, 14:00, and 22:00-23:00 hours, while experiencing a deficit energy during the remaining hours. Similarly, MG_2 generates excess energy during 00:00-06:00 and 20:00-23:00 hours and encounters a deficit of energy during other hours. MG_3 generates excess energy during 00:00-14:00, 16:00, and 18:00-23:00 hours, while facing deficit energy during the remaining hours. The total amount of energy traded in NMG for all cases is given in Table. 6.2. The operating cost of each MG, SESS, and total NMG for all proposed strategies is demonstrated in Fig. 6.5.



(a) Power Balance in MG_1 for Case 1

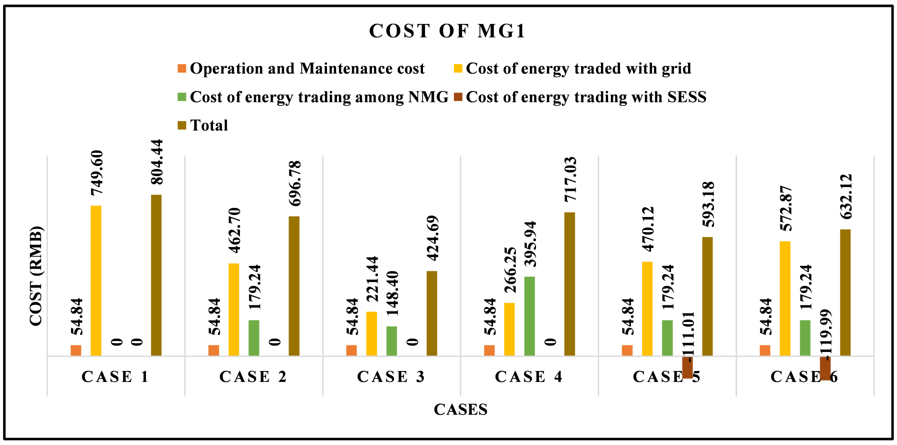


(b) Power Balance in MG_2 for Case 1

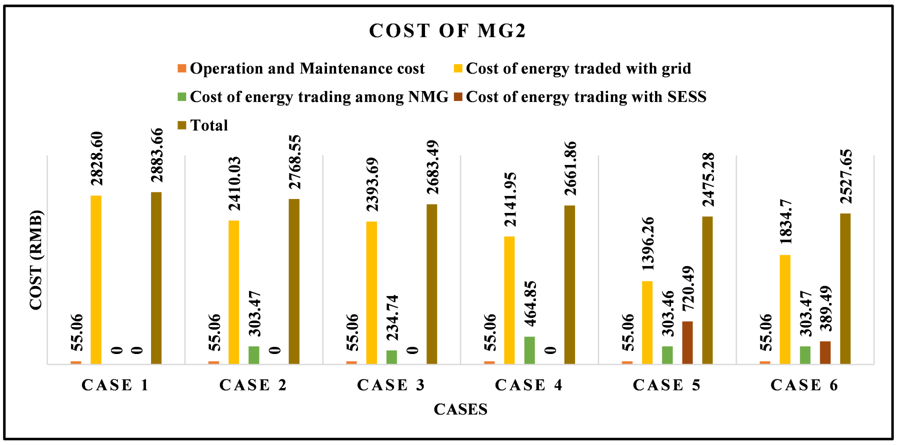


(c) Power Balance in MG_3 for Case 1

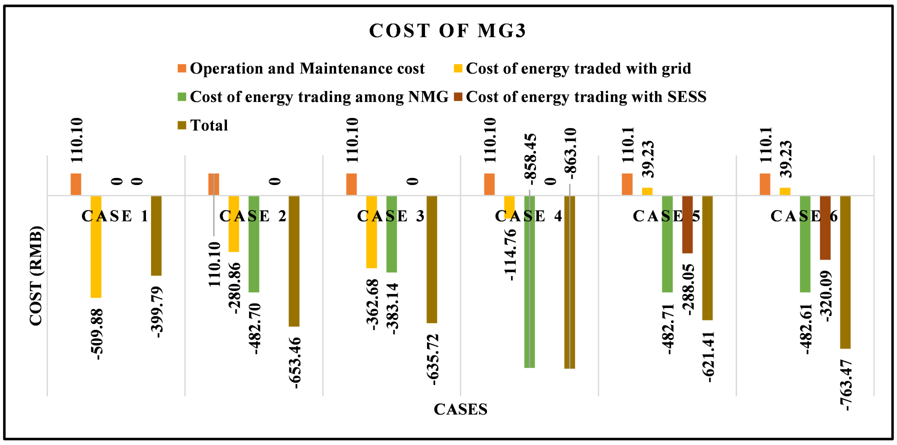
Figure 6.4: Power Balance in NMG for Case 1



(a) Operation Cost of MG_1



(b) Operation Cost of MG_2



(c) Operation Cost of MG_2

Figure 6.5: Total Operating cost of Individual MGs

Table 6.1: NMG Framework Parameters

Parameters	Value
T	24h
Δ	1h
$\rho_{PV}^{i,t}$	0.025 RMB/(kWh)
$\rho_{WT}^{i,t}$	0.029 RMB/(kWh)
η_c	0.98
η_d	0.98
ESE_i^{min}	$0.02.Cap_{ESS}$
ESE_i^{max}	Cap_{ESS}
$P_{s,ESS}^{min}$, $P_{b,ESS}^{min}$	$0.02.Cap_{ESS}$
$P_{s,ESS}^{max}$, $P_{b,ESS}^{max}$	$0.25.Cap_{ESS}$

6.3.2 Case 2: ESS Excluded but Energy Trading Included

The IESS/SESS is not considered while energy trading among MGs is allowed. In case 2, considering energy trading among MGs allows the balancing of excess or deficit energy within MGs in NMG. This is achieved by following the energy trading formulation described in [Eqs 6.17 and 6.18]. The energy trading mechanism enables the seller MGs to trade surplus energy with the buyer MGs or the main grid. Similarly, buyer MGs can satisfy their deficit energy from trading energy among MGs in NMG. The energy trading strategy among MGs and with the grid is depicted as a flowchart in Fig. 6.6. The individual MGs will have excess and deficit energy during the same hours as in case 1. As ESS is excluded charging and discharging hours are mentioned as not available in Table 6.3. In this case, the MGs participate in energy trading within NMG during the hours as provided in Table 6.4. The individual MGs trade with the grid during the following hours: MG_1: 00:00 - 04:00, 06:00 - 07:00, 10:00 - 12:00, 14:00 - 23:00, MG_2: 00:00 - 19:00, 22:00 - 23:00, MG_3: 00:00 - 06:00, 15:00, 17:00, 22:00 - 23:00.

6.3.3 Case 3: Integration of Load Imbalance-based IESS Scheduling and Energy Trading

In this case, each MG is equipped with IESS, and energy trading among the MGs is considered. The IESS is charged when an MG generates excess energy and discharges the energy when there is a deficit i.e. based on load imbalance, as shown in Fig. 6.7. The capacity of the IESS is divided according to the maximum load of each respective MG, with a total capacity of 4000 kWh. The IESS capacity in the respective MGs is 1000 kWh, 2000 kWh, and 1000 kWh. After scheduling the IESS, the excess and deficit

Table 6.2: Energy Trading in NMG

Cases	MGs	NMG (kW)		Grid (kW)		SESS (kW)	
		Sold	**Bought**	**Sold**	**Bought**	**Sold**	**Bought**
Case 1	MG1	NA	NA	453.2	858.09	NA	NA
	MG2			314.09	3087.22		
	MG3			1665.1	60.49		
Case 2	MG1	36.32	277.85	416.9	580.24	NA	NA
	MG2	11.69	443.75	302.4	2643.47		
	MG3	673.6	0	1000.43	60.49		
Case 3	MG1	13.15	219.05	1.7	209.44	NA	NA
	MG2	11.69	351.4	148.23	584.74		
	MG3	545.6	0	1066.7	0		
Case 4	MG1	13.6	599.35	767.31	997.99	NA	NA
	MG2	11.7	779.24	849.22	3833.76		
	MG3	1350.64	0	1126.17	338.38		
Case 5	MG1	36.32	361.78	0	453.99	415.2	42.31
	MG2	11.69	443.75	5.79	1503.14	289.59	1140.32
	MG3	673.59	0	58.97	60.49	847.06	0
Case 6	MG1	36.32	361.78	0	550.88	416.02	29.36
	MG2	11.69	443.75	5.79	2007.1	296.6	636.38
	MG3	673.59	0	58.97	60.49	941.45	0

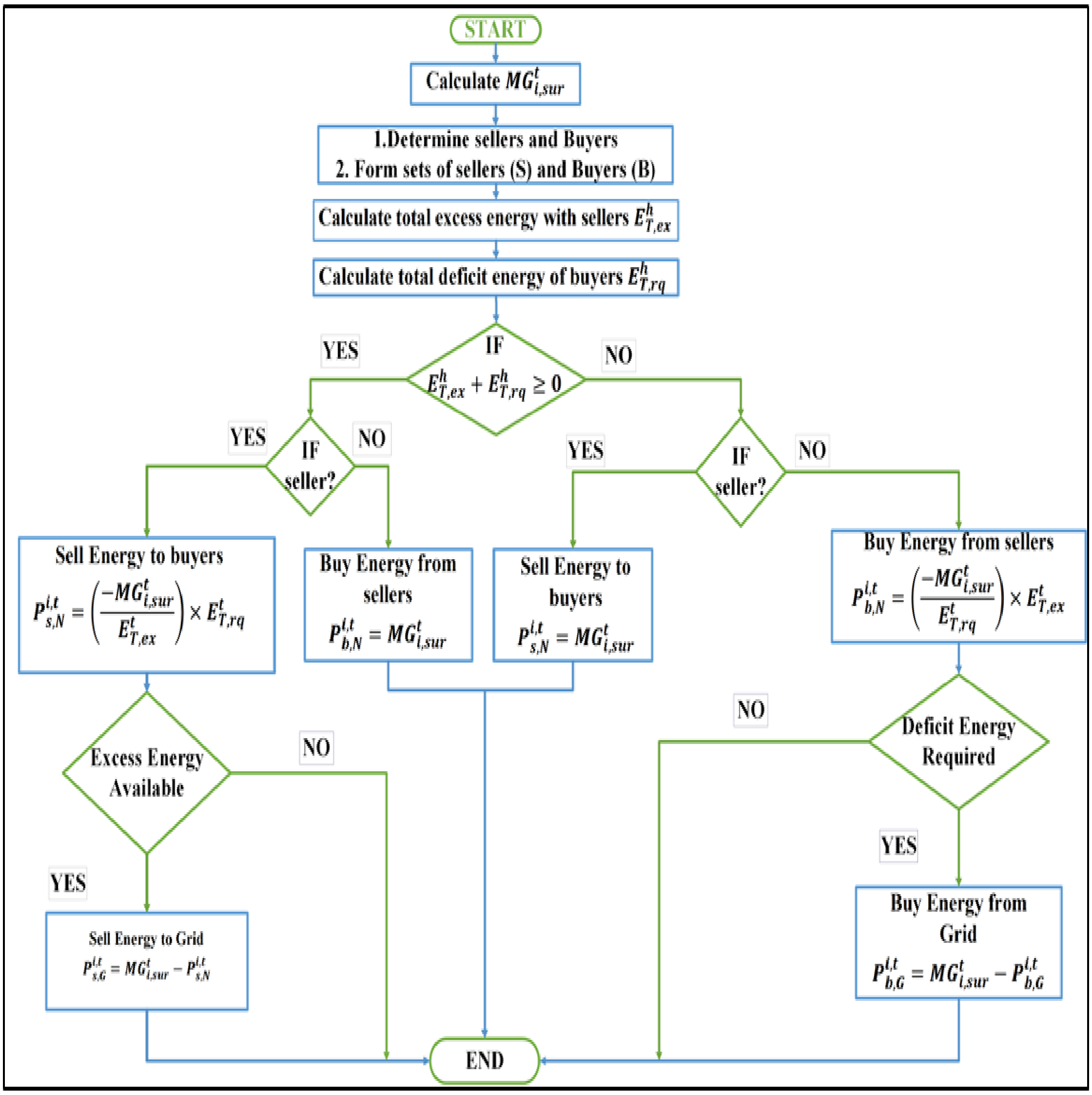


Figure 6.6: Flowchart for Energy Trading in NMGs.

energy in MGs is traded within NMG and with the grid as shown in Fig. 6.6. The IESS in the corresponding MGs i.e. MG_1, MG_2, and MG_3 charges and discharges during the following hours as mentioned in Table 6.3. The MGs participate in energy trading within NMG during the following hours as mentioned in Table 6.4.

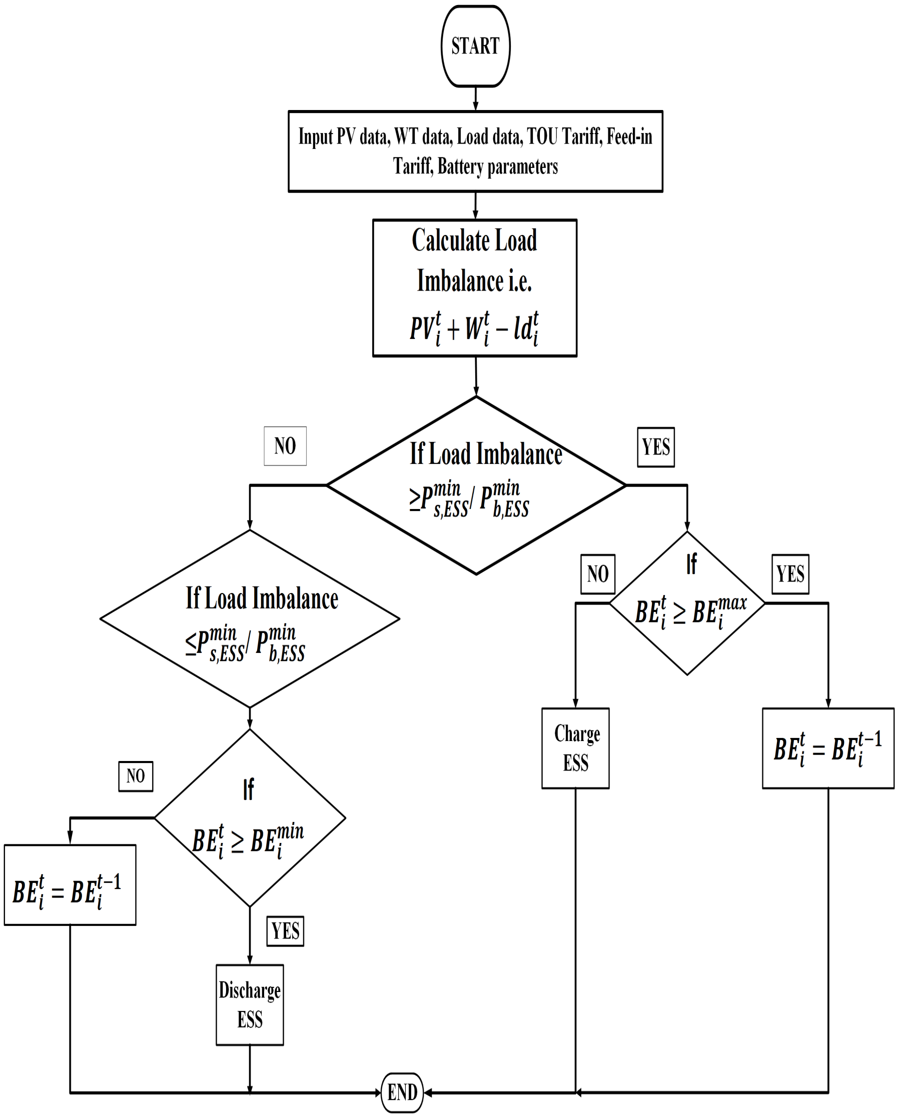


Figure 6.7: Flowchart for Scheduling of IESS based on Load Imbalance.

6.3.4 Case 4: Integration of Load Imbalance and TOU-based IESS Scheduling and Energy Trading

In this case, IESS in each MG is scheduled based on both TOU prices and load imbalance. During the off-peak period, the IESS is charged from both the MG and the grid, while it discharges during the peak period to both the MG and the grid. In the intermedi-

Table 6.3: Charging and Discharging Schedule of IESS and SESS for proposed cases.

Cases	Charging			Discharging			Idle		
	MG1	MG2	MG3	MG1	MG2	MG3	MG1	MG2	MG3
Case 1	NA	NA	NA	NA	NA	NA	NA	NA	NA
Case 2	NA	NA	NA	NA	NA	NA	NA	NA	NA
Case 3	00:00 - 04:00, 13:00, 22:00 - 23:00	02:00 - 03:00, 23:00	18:00 - 19:00	07:00, 15:00 - 18:00	07:00 - 08:00	15:00, 17:00	05:00 - 06:00, 08:00 - 12:00, 14:00, 19:00 - 21:00	00:00 - 01:00, 04:00 - 06:00, 09:00 - 22:00	00:00 - 14:00, 16:00, 20:00 - 23:00
Case 4	00:00 - 03:00, 13:00, 22:00 - 23:00	00:00 - 03:00, 22:00 - 23:00	10:00 - 14:00, 22:00 - 23:00	07:00 - 09:00, 15:00 - 17:00	07:00 - 11:00.	07:00 - 09:00, 15:00, 17:00 - 18:00.	04:00 - 06:00, 10:00 - 12:00, 14:00, 18:00 - 21:00	04:00 - 06:00, 12:00 - 21:00	00:00 - 06:00, 16:00, 19:00 - 21:00
Case 5	00:00 - 04:00, 06:00, 22:00 - 23:00			07:00 - 12:00			05:00, 13:00 - 21:00		
Case 6	00:00 - 04:00, 06:00, 22:00 - 23:00			07:00 - 10:00.			05:00, 10:00 - 21:00		

Table 6.4: Energy Trading Schedule among MGs in NMG

Cases	Hours
Case 1	NA
Case 2	5:00, 07:00-14:00, 16:00, and 18:00-21:00
Case 3	05:00, 08:00-14:00, 16:00 - 17:00, and 19:00-21:00.
Case 4	00:00 - 03:00, 05:00, and 16:00 - 21:00
Case 5, Case 6	05:00, 07:00 - 14:00, 16:00, and 18:00 - 21:00

ate period, the charging/discharging of IESS is determined based on the load imbalance specific to each MG. The strategy of IESS scheduling is depicted in Fig. 6.8. The IESS adheres to the constraints outlined in [Eqs 6.8-6.10] during charging and discharging. Additionally, energy trading among MGs is considered after the IESS scheduling. The IESS charging and discharging schedule in the corresponding MGs is mentioned in Table 6.3. The MGs participate in energy trading within NMG during the following hours as mentioned in Table 6.4.

6.3.5 Case 5: Integration of Load Imbalance and TOU-based SESS Scheduling and Energy Trading

In this case, the ESS is scheduled based on the TOU pricing and the load imbalance similar to case 3. SESS is introduced in NMG and IESS is removed from individual MGs. The SESS competes as an individual player along with other MGs in the energy market. Firstly, in this case, we calculate the excess energy and deficit energy based on load imbalance for each MG in the NMG. After calculating the excess and deficit energy, the energy is traded among the NMGs. Subsequently, the remaining excess/deficit energy with NMG is traded with SESS. The capacity of SESS is considered as 4000 kWh. The scheduling of SESS i.e. charging, discharging, and idle period is shown in Table 6.3. The MGs participate in energy trading within NMG during the following hours as mentioned in Table 6.4.

6.3.6 Case 6: SESS Scheduling Incorporating Forecasted Generation, Load, TOU Prices, and Energy Trading

In this case, a two-level strategy is developed, taking into account various factors such as forecasted generation and load, TOU price, and load imbalance. The SESS is considered an individual player in the energy market and can trade with NMG and the grid. It is assumed that the forecasted generation and load are accurate. The two-level strategy

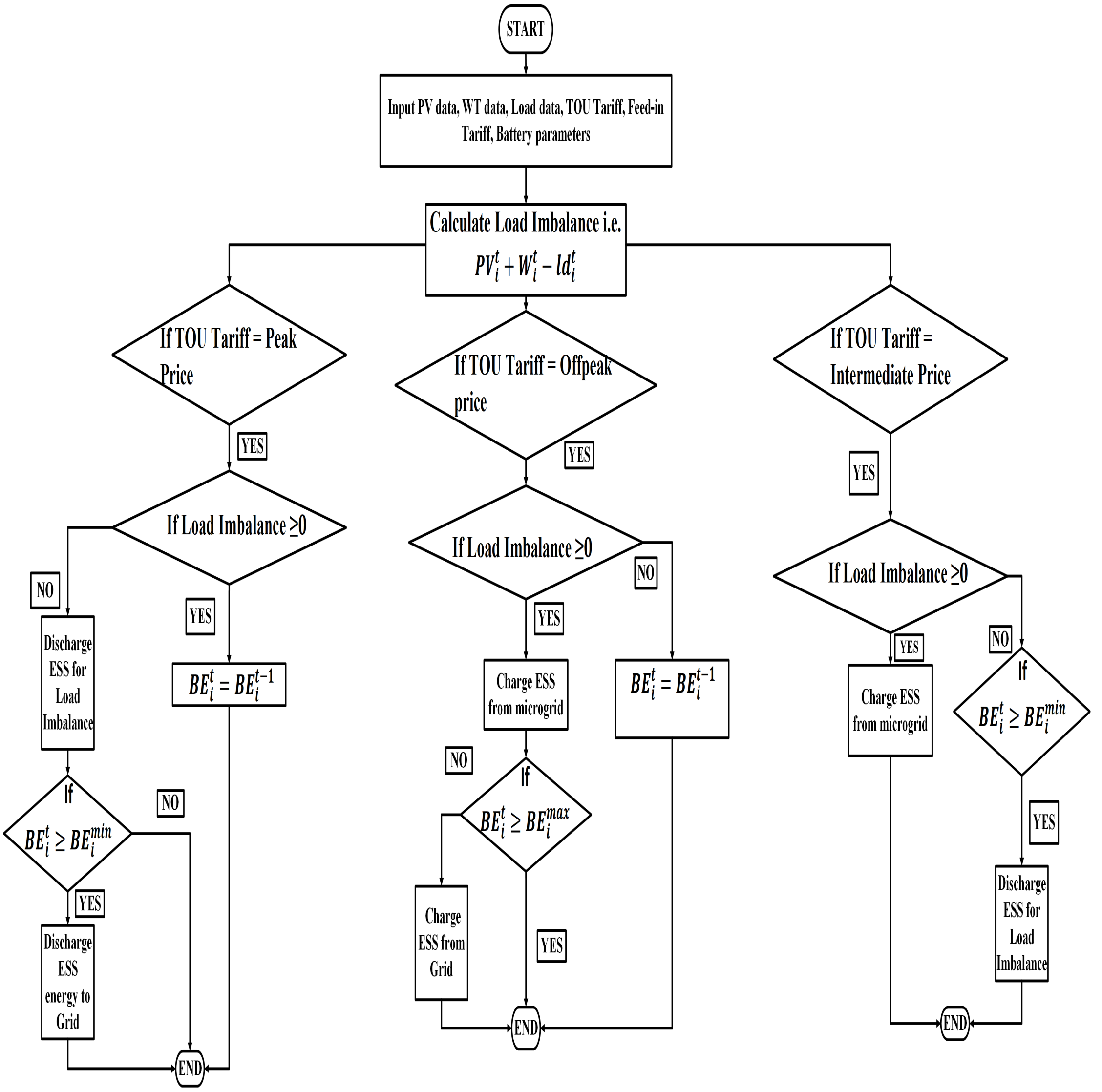


Figure 6.8: Flowchart for Scheduling of IESS based on Load Imbalance and TOU.

operates as follows: In the first stage, the power imbalance for each MG is calculated. Based on this calculation, the excess and deficit energy are determined for the seller and buyer MGs, respectively. Energy trading is then carried out within the NMG. Additionally, depending on the TOU price and the excess/deficit energy within the NMG, the SESS is either charged or discharged, as depicted in the flowchart shown in Fig 6.9. In the second stage, the forecasted generation and load, for each level of TOU (peak, intermediate, and off-peak periods) are evaluated using [Eqs 6.25-6.30]. In this stage, the proposed strategy intelligently determines whether it is more advantageous to charge the SESS using the grid's power or to utilize the energy stored in the SESS to meet the load demand during specific time periods. For this, we determine the forecasted generation and load in different TOU periods i.e. Off peak, Intermediate, and Peak periods. This is achieved by summing up the generation and load for the remaining hours within each respective period. The step-by-step process of this stage is depicted as a flowchart in the Fig. 6.10.

$$FOOP_{G,N}^{h} = \sum_{t=h}^{T} P_{PV}^{i,t} + P_{WT}^{i,t} \; if \; (TOU = off-peak) \tag{6.25}$$

$$FOOL_{L,N}^{h} = \sum_{t=h}^{T} P_{L}^{i,t} \; if \; (TOU = off-peak) \tag{6.26}$$

$$FOI_{G,N}^{h} = \sum_{t=h}^{T} P_{PV}^{i,t} + P_{WT}^{i,t} \; if \; (TOU = Intermediate) \tag{6.27}$$

$$FOI_{L,N}^{h} = \sum_{t=h}^{T} P_{L}^{i,t} \; if \; (TOU = Intermediate) \tag{6.28}$$

$$FOP_{G,N}^{h} = \sum_{t=h}^{T} P_{PV}^{i,t} + P_{WT}^{i,t} \; if \; (TOU = Peak) \tag{6.29}$$

$$FOP_{L,N}^{h} = \sum_{t=h}^{T} P_{L}^{i,t} \; if \; (TOU = Peak) \tag{6.30}$$

Where, $FOOP_{G,N}^{h}$ & $FOOL_{L,N}^{h}$ are the forecasted off-peak generation and load for the corresponding hour h in NMG, $FOI_{G,N}^{h}$ & $FOI_{L,N}^{h}$ are the forecasted intermediate gen-

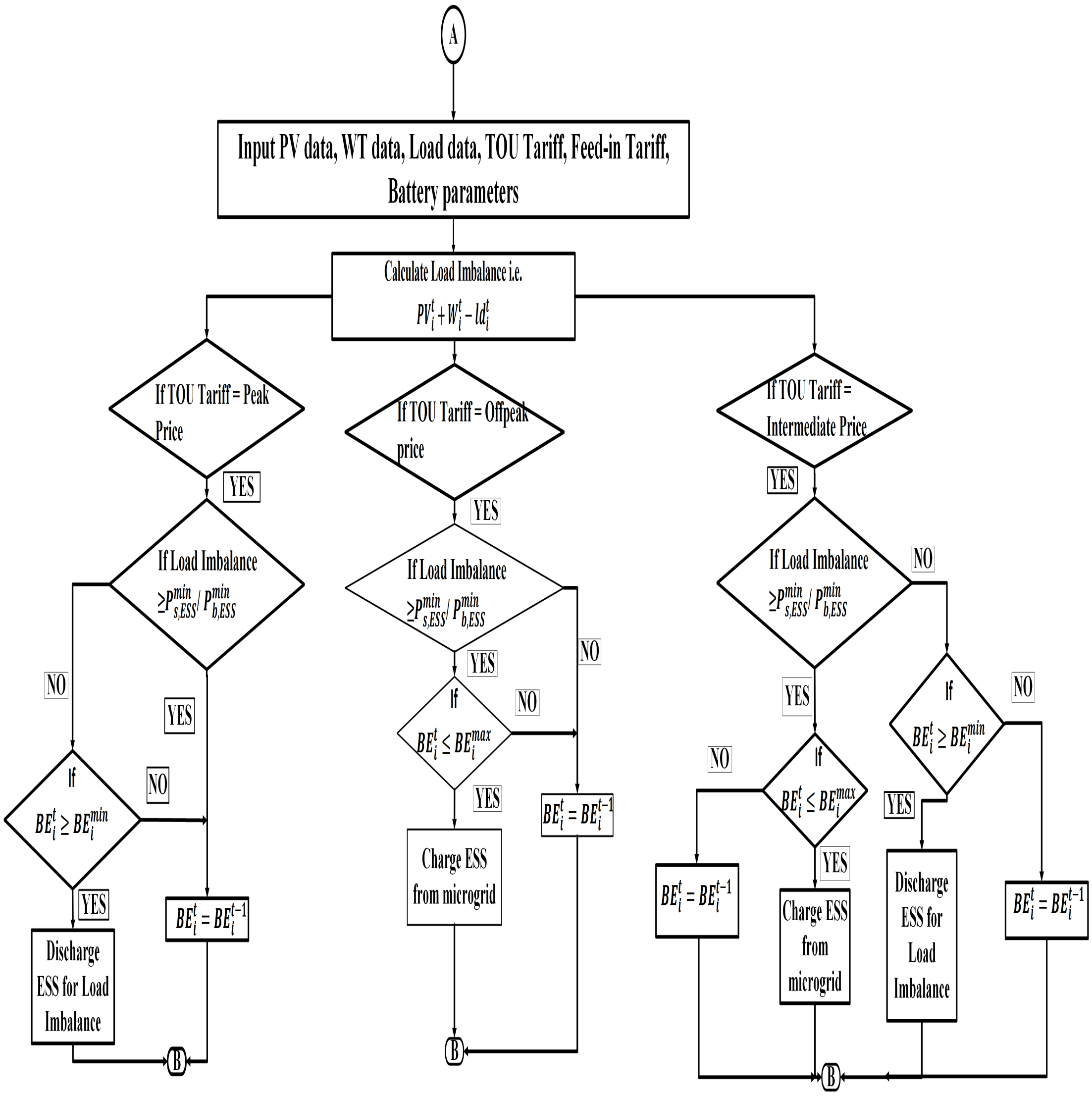


Figure 6.9: Flowchart for Scheduling of SESS based on Proposed Strategy (Level-1).

eration and load for the corresponding hour h in NMG, $FOP^{h}_{G,N}$ & $FOP^{h}_{L,N}$ are the forecasted peak generation and load for the corresponding hour h in NMG.

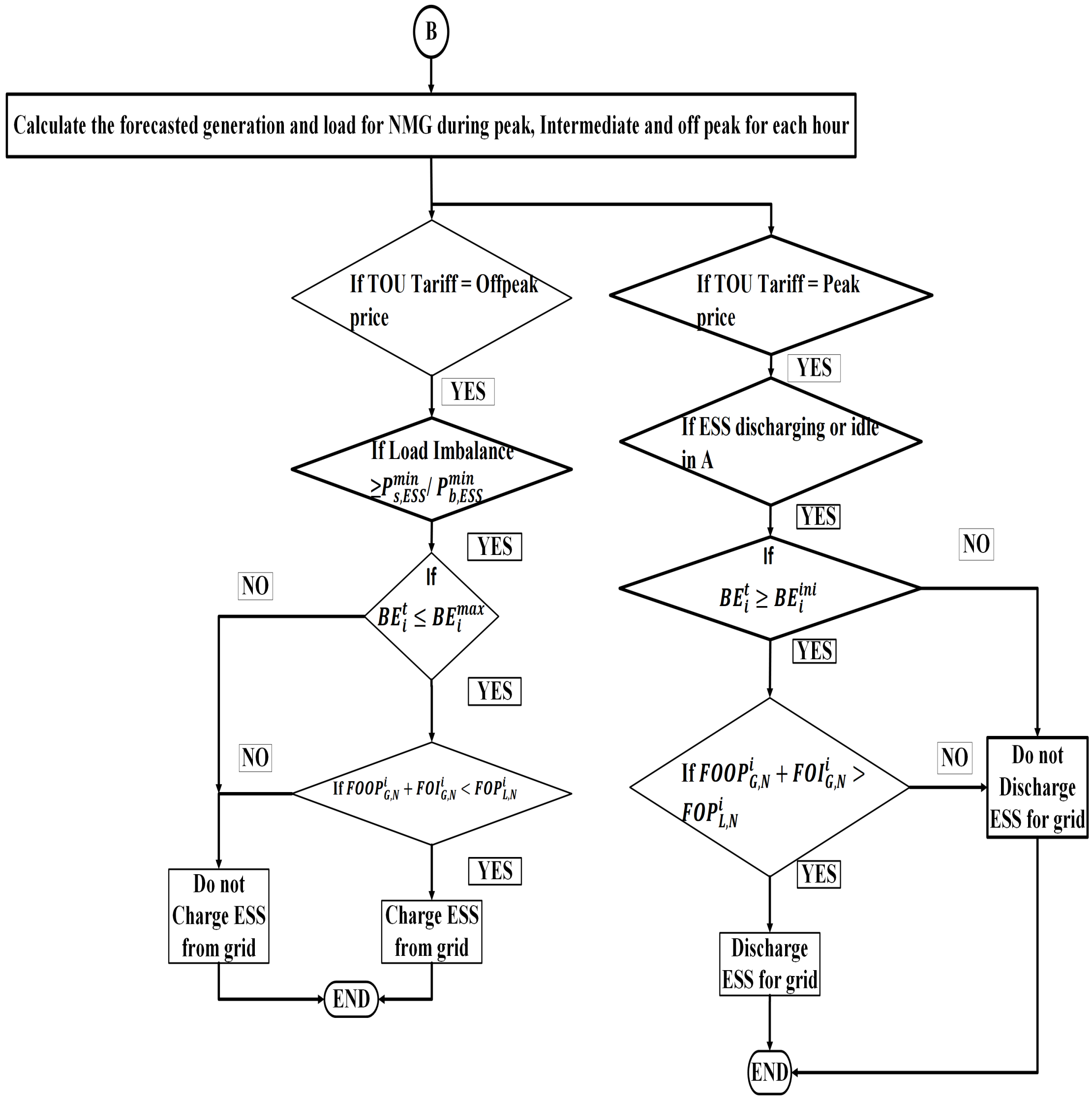


Figure 6.10: Scheduling of SESS based on Proposed Strategy (Level-2).

The power balance of MGs within NMG for case 6 is shown in Fig. 6.11. The scheduling of SESS i.e. charging, discharging, and idle period is shown in Table 6.3. The total profit for SESS after trading with MGs in NMG and the grid is 358.96 (RMB). Table 6.5 shows the profit generated by SESS in case 5 and case 6. The profit earned by SESS from MGs is nullified while calculating the total cost of NMG, whereas the profit generated by trading with the grid results in the reduction of the overall cost. The operating cost of each MG, SESS, and total NMG is demonstrated in Fig. 6.5 and Fig. 6.12.

Table 6.5: Profit of SESS in Case 5 and Case 6

Case	MG_1 **(RMB)**	MG_2 **(RMB)**	MG_3 **(RMB)**	**Grid (RMB)**	**Total (RMB)**
Case 5	-111.01	303.46	-288.05	NA	-95.60
Case 6	-119.99	389.49	-320.09	358.96	308.37

6.3.7 Discussion

In the above cases, different strategies and scenarios are examined to evaluate the operating costs of NMG. A comparison table for the operation costs of all the strategies is presented in Table. 6.6 and Fig. 6.12. In cases involving IESS/SESS (Cases 3, 4, 5, and 6), the operating costs of individual MGs are typically lower, indicating potential revenue generation. From Table 6.6, introducing IESS/SESS and incorporating energy trading within MGs typically results in cost savings for individual MGs and the whole NMG. Strategies that consider TOU pricing and load imbalances, in addition to IESS/SESS and energy trading, tend to optimize the operating costs of NMG more effectively. The two-level strategy with SESS (Case 6) demonstrates the potential of a holistic approach by considering multiple factors, including forecasted generation and load, TOU prices, and load imbalance, resulting in cost-effective energy management.

Table 6.6: Operation Costs of each MG and NMG in Proposed Cases

Case	MG_1 **(RMB)**	MG_2 **(RMB)**	MG_3 **(RMB)**	**NMG (RMB)**
Case 1	804.44	2883.65	-399.78	3288.32
Case 2	696.78	2768.55	-653.46	2811.87
Case 3	424.69	2683.49	-635.72	2472.46
Case 4	717.03	2661.86	-863.10	2515.79
Case 5	593.18	2475.28	-621.41	2447.05
Case 6	632.12	2527.65	-763.47	2206.75

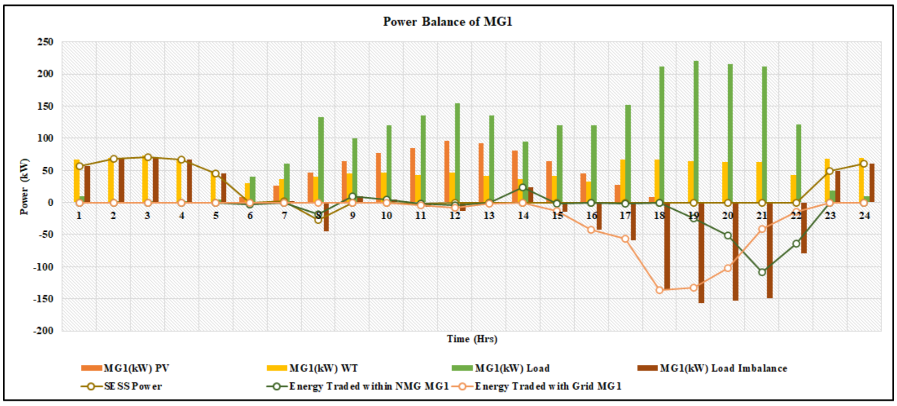
6.4 Summary

In this work, a comparative analysis of scheduling strategies for the utilization of IESS / SESS in NMGs is studied. The scheduling strategies considered a number of factors, including load imbalances, TOU pricing, forecasted generation and load, and energy trading. The application of these strategies for the assessment of the operational costs of NMGs provides valuable insights into the efficacy of proposed strategies. Integration of IESS/SESS played a vital role in reducing load imbalances and optimizing energy consumption, resulting in cost savings. Energy trading mechanism enabled MGs to share excess energy and jointly address energy deficits, thereby enhancing operating cost reduction. In a case-by-case comparison, we observed that excluding energy storage and energy trading (case 1) often leads to higher costs for both individual MGs and the NMG as a whole. Introducing energy trading among MGs (case 2) provided cost savings by 14.48%, but more significant improvements were seen when combining energy storage with trading. The incorporation of intelligent scheduling strategies that consider load imbalance and TOU prices in IESS (cases 3 and 4) reduces the operating cost of NMGs by 24.81% and 23.49% respectively in comparison to case 1. The implementation of SESS considering load imbalance and TOU pricing (case 5) reduces the operating cost of NMGs by 25.58%. The proposed two-level strategy (case 6) considers forecasted generation, load, TOU pricing, and energy trading, leading to a significant reduction in the operating cost by 32.89%.

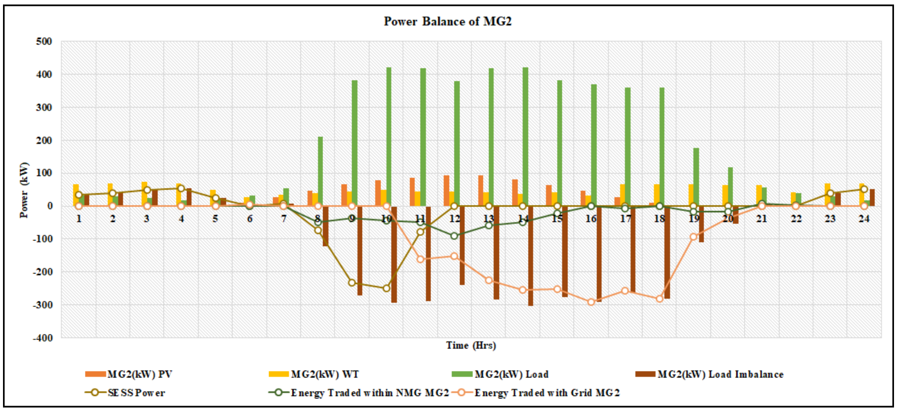
6.5 Limitations and Applicability in Real World Power System

The study presents scheduling and trading strategies for NMGs aiming to minimize operating costs, considering factors such as load imbalance, TOU pricing, and integration of IESS and SESS. While offering valuable insights, the models have limitations such as simplified assumptions, fixed FIT and TOU prices, and a single NMG configuration. Future research should explore more complex models, dynamic pricing, diverse NMG configurations, variable energy storage capacities, and real-world validation. Additionally, incorporating cybersecurity considerations, market dynamics, and regulatory implications would enhance the practical applicability of the proposed strategies.

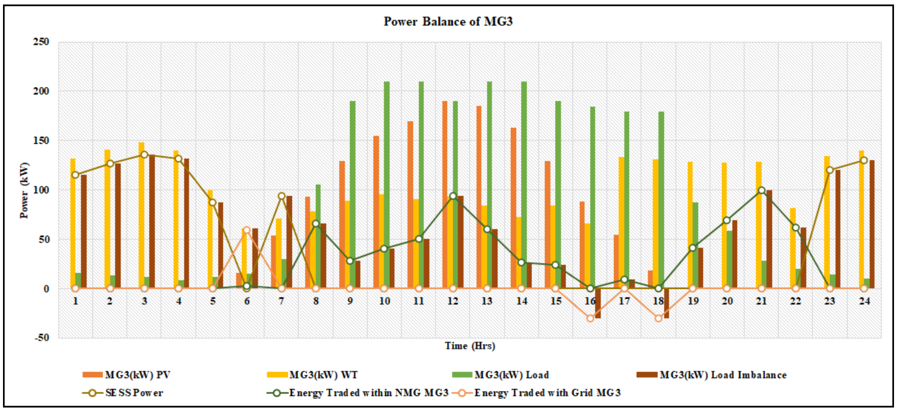
The study's assumptions, such as accurate forecasting, ideal renewable energy performance, and fixed FIT and TOU prices, may deviate from the dynamic and uncertain nature of actual power systems. Implementing the proposed scheduling and trading strategies may face challenges related to regulatory frameworks, market dynamics, and cybersecurity considerations in a real-world context. Furthermore, the study focuses on a specific NMG configuration, and the effectiveness of the strategies may vary across diverse and larger-scale power systems. Validation through real-world pilot projects and simulations with authentic data is essential to assess the practical viability of the proposed strategies.



(a) Power Balance in MG_1 for Case 6



(b) Power Balance in MG_2 for Case 6



(c) Power Balance in MG_3 for Case 6

Figure 6.11: Power Balance in NMG for Case 6

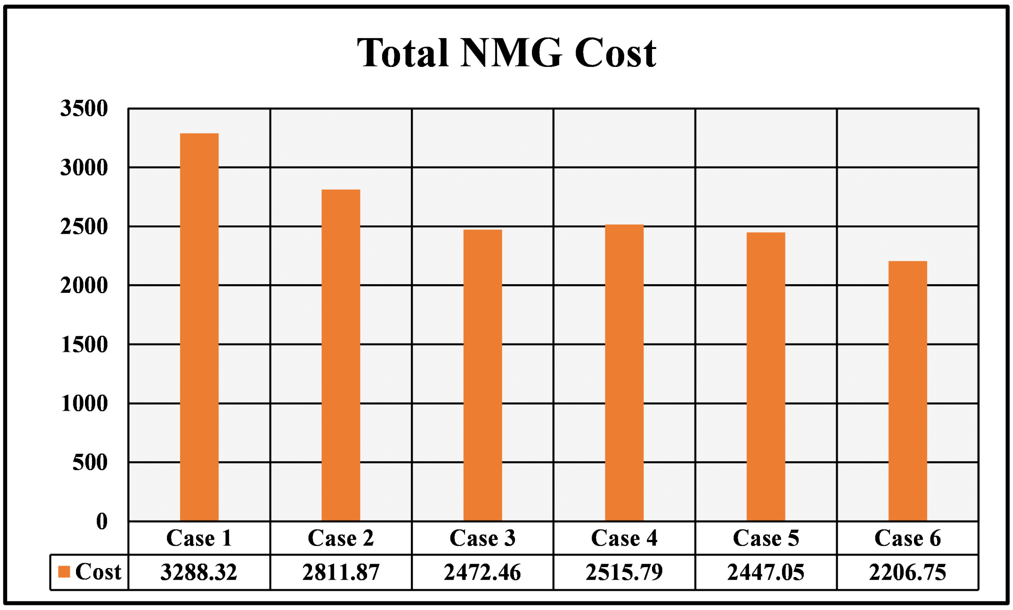


Figure 6.12: Comparison of Total Operation Cost of NMG

Chapter 7
Conclusion

7.1 Summary and Important Finding

MGs are emerging as a promising alternative to centralized power generation. They provide numerous benefits, including reliability, resilience, energy efficiency, flexibility, cost savings, reduced dependence on the grid, grid support, increased RES integration, and increased control over energy supply compared to centralized power generation. However, MGs do suffer from various disadvantages, such as high initial costs, dependence on the main grid during grid-connected mode, limited control, dependence solely on local resources, limited energy supply, and limited scalability. To fully realize the potential of MGs, an NMG framework is required to connect and coordinate multiple MGs. The establishment of an NMG framework offers various advantages, such as enhanced reliability, increased resilience, improved energy efficiency, cost savings, better integration of RES, flexibility, ancillary services, improved demand response, and increased scalability. However, it also brings several challenges, including technical, economic, regulatory, interoperability, cybersecurity, and socio-technical challenges.

There are diverse structural frameworks that facilitate the coordination and interaction of multiple MGs within an NMG setup. These architectures are designed to optimize the integration and functioning of MGs while considering their connections with the main power grid and the management of control mechanisms. Considering all the advantages of NMGs and the comprehensive analysis of various structural frameworks, multiple strategies are being studied to enhance the profitability of individual MGs as well as the overall NMG. These strategies encompass a wide range of approaches aimed at optimizing operational efficiency, enhancing cost-effectiveness, and streamlining energy management processes within the NMG, thereby ensuring a more robust and lucrative energy distribution system. The thesis's objectives are (i) implementing hour block-based demand response program in NMGs, optimize load profiles, reduce operational costs, and reduce the complexity of the DR problem (ii) optimal sizing of RES and BESS in NMGs to reduce annual energy cost and enhancing reliability while introducing proportional P2P energy trading method (iii) economic analysis of energy scheduling and trading in MMGs environment to develop innovative energy management and scheduling strategies within MMGs to maximize individual MG profits and benefit the entire

MMG (iv) development and analysis of scheduling strategies for utilizing shared energy storage systems in networked microgrids to minimize overall operating cost.

In Chapter 3, a novel hour block-based DR approach is proposed to reduce the complexity of DR programs. The method focuses on cost reduction for individual MGs and the overall NMG framework through hour-block based energy trading. The results indicate a notable reduction in operating costs for individual MGs and the NMG framework, with exceptions for MG_4. The use of PSO contributes to obtaining optimal solutions.

Chapter 4 delves into the optimal sizing of RES and BESS for MGs in the NMG framework. Employing P2P energy trading schemes based on proportional sharing, the research aims at cost minimization and reliability enhancement. The results demonstrate that P2P energy trading significantly maximizes RES utilization, decreases grid interaction, and lowers the required BESS capacity, thus achieving the set objectives.

In Chapter 5, various strategies are formulated for the optimum utilization of DER in an MMG environment to maximize individual MG revenues. These strategies, based on energy availability and TOU rates, result in increased combined revenues for MGs, with the committed energy trading strategy proving to be the most lucrative.

Chapter 6 focuses on a comparative analysis of scheduling strategies for the utilization of IESS and SESS in NMGs. The integration of IESS/SESS plays a crucial role in reducing load imbalances and optimizing energy consumption, leading to cost savings. Energy trading among MGs further enhances operating cost reduction, with intelligent scheduling strategies contributing significantly. The proposed two-level strategy, considering various factors such as load imbalance, TOU prices, forecasted generation, and energy trading, proves to be highly effective, achieving a substantial reduction in the operating cost of NMGs.

Overall, these chapters collectively contribute to advancing the understanding and application of efficient strategies for enhancing the performance, reliability, and cost-effectiveness of MGs within a networked framework.

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Author’s Publications

International Journals (Published)

1. **Lokesh Vankudoth** and A. Q. Badar. "Comparison of hour-to-hour and hour-block energy trading for networked microgrids to optimize profits."Distributed Generation & Alternative Energy Journal pp. 1215–1238, 2022. **(River Publishers) (Scopus)**. https://doi.org/10.13052/dgaej2156-3306.37413

2. **Lokesh Vankudoth** and A. Q. Badar, “Hour block based demand response for optimal energy trading profits in networked microgrids,” Distributed Generation & Alternative Energy Journal, pp. 1549–1576, 2022. **(River Publishers) (Scopus)**. https://doi.org/10.13052/dgaej2156-3306.37511

3. **V. Lokesh** and A. Q. Badar, “Optimal sizing of res and bess in networked microgrids based on proportional peer-to-peer and peer-to-grid energy trading,” Energy Storage, p. e464, 2023. **(John Wiley) (ESCI)**. https://doi.org/10.1002/est2.464

International Conferences (Published)

4. **Lokesh Vankudoth**, A. Q. Badar, R. K. Chauhan, and M. Hossain, “Economic analysis of energy scheduling and trading in multiple-microgrids environment,” in 2021 XVIII International Scientific Technical Conference Alternating Current Electric Drives (ACED). IEEE, 2021, pp. 1–6. Ekaterinburg, Russia, 24 - 27 May 2021.

International Journals (Under Review)

5. **Vankudoth Lokesh**, and Altaf Q. H. Badar “Development and analysis of scheduling strategies for utilizing shared energy storage system in networked microgrids” , *submitted to Journal of Energy Storage*, 2023. [Major Revision Submitted]

Book Chapter (Accepted)

6. **Lokesh Vankudoth** and A. Q. Badar, “Networked Microgrids Framework ” in *Handbook on Microgrid: Planning to Practices, CRC Press, USA*, 2023.