J. Electrical Systems 20-11s (2024):1528-1538

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Optimization of Operational Costs in Multi-Microgrid Systems with Renewable Energy and Energy Storage Systems

Abstract: - Microgrids (MGs) play a vital role in the era of deregulated power systems. The number of MGs connected to the power grid increases the complexity of energy management among the main grid and MGs. A multi-microgrid (MMG) system utilizes all available energy sources (renewable and non-renewable) and energy storage systems to manage power exchange efficiently within the MGs and the main grid, enhancing system reliability, stability, and efficiency. With the integration of renewable and non-renewable energy sources, the system can adapt to different energy availability scenarios. This paper presents an optimized energy management scheme for MMG, implemented using multiple integer nonlinear programming in GAMS software. The objective is to minimize the overall operational cost of MMG and reduce emission costs. The dynamic nature of renewable energy sources, the fluctuating demand patterns, and the operational constraints of both the MGs and the main grid. The proposed approach is applied to an MMG system interconnected with the main grid, incorporating both renewable and non-renewable energy sources. The simulation results demonstrate the effectiveness of the presented energy management strategy in lowering system costs for two operating case-I and case-II. The impact of integrating energy storage systems has also been evaluated on the overall cost of the system, revealing their potential to enhance the overall efficiency and cost-effectiveness of the energy management system (EMS). The results show that overall operational cost has been reduced from \$1163 in case-I to \$1096 in case-II and MMG becomes more independent in case-II as power demand from the main grid is reduced from 10259 kW(case-I) to 9171kW (case-II).

Keywords: Multi-microgrid (MMG), Renewable energy sources, microgrid scheduling.

I. INTRODUCTION

Increasing energy demand is certainly a substantial contributor to global warming. Most of the world's energy needs are still generated from fossil fuels like coal, oil, and natural gas, which release carbon dioxide and other greenhouse gases. These gases trap heat in the Earth's atmosphere, which leads to a rise in global temperatures and results in climate change [1], [2]. To mitigate this issue, there is a growing need for a transition to cleaner and more sustainable energy sources such as solar, wind, hydroelectric, and geothermal power, etc. Out of these Photovoltaic systems and wind turbines are very common, available, and economical energy sources [3], [4], [5]. Irrespective of the advantages of using renewable energy sources these are uncertain. With the integration of renewable energy sources, it led the system to more complexity [6]. To overcome the problem of uncertainty several solutions have been introduced in the literature which target to improve energy management and reliability. In [7], an optimally sized pump storage unit is used in a grid-connected mode to analysis the impact of generation from distributed energy sources, enabling reliable bidding in day-ahead electricity markets while reducing operational costs. A two-stage stochastic programming approach for MG energy management, representing that including Demand Response Programs (DRPs) suggestively reduces operational costs of grid-connected and island modes while accounting for uncertainties in price, load, wind speed, and solar radiation[8]. MG is a solution in which decentralized control is used and Energy management within the MGs is the challenge [9].

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To further enhance the MG reliability, stability, and operation cost and to reduce emissions interconnected MG can be implemented. The interconnected MGs in multi-MG systems which provide energy exchange within the MGs lead to a reduction in the operating cost of MGs and the potential to reduce possible load shedding.

Nomenclature		$L_{i,t}^{D}$	Load of each MG at t
		C_i^{DG}	Cost of generation by Diesel Generation of i-th MG
Abbreviation		C_i^{MG}	Cost of exchange between MG
ESS	Energy Storage System	C_{emm}^{DGi}	Cost of Emission by each Diesel Generation
MMG	Multi Microgrid	C_i^{Grid}	Cost of grid power purchase by each MG
MG	Mircogrid		
SOC	State of Charge	$P_{DGi,t}$	DG generation power at t of i-th MG
WT	Wind Turbine	$B_{DGi,t}$	On/off state of DG of i-th MG at t
PV	Photovoltaic System	$X_{DGi,t}^{on}$ $/X_{DGi,t}^{off}$	Number of hours for DG remains on/ off
DG	Diesel Generators	$U_{DGi}^{on}/D_{DGi}^{off}$	Minimum on/off time of DG of i-th MG
T	Time	$R_{DGi}^{Up}/R_{DGi}^{Dn}$	Ramp-up/ramp-down limit of DG of i-th MG
Parameter		$U_{ESS,\mathrm{ch,t}}$ $/U_{ESS,\mathrm{dch,t}}$	1 if ESS charging otherwise 0 / 1 if ESS discharging otherwise 0
a_i, b_i, c_i	Coefficients of the power generation cost of the DG	$\mathrm{PB}_{\mathrm{ESS,ch,t}}$	ESS power at t
P_{DGi}^{min} $/P_{DGi}^{max}$	Minimum/maximum Generation of DG of i-th MG	$\eta_{\mathrm{ESS,ch}}$ $/\eta_{\mathrm{ESS,dch}}$	Charging/discharging efficiency of the ESS
∇t	1hour	$\mathrm{P}_{\mathrm{ESS,ch,t}}$ $/\mathrm{P}_{\mathrm{ESS,dch,t}}$	Charged/discharged power of ESS at t
$P_{i,j,t}^{MG}$	Power exchange between MGs at t	ESScap	Capacity of the Energy storage system
$P_{i,t}^{PV}$	Power generation of PV at t	$\mathrm{SOC}_{\mathrm{ESS,i,t}}$	State of charge at t
$P_{i,t}^{WD}$	Power generation of Wind at t	$\mathrm{SOC}_{min,i}$	Minimum state of charge
$P_{i,t}^{Grid}$	Power exchange between MG and grid at t	$\mathrm{SOC}_{max,i}$	Maximum state of charge

An optimal MG sizing, utilizing battery storage units for multi-functionality, minimizing costs, emissions, and power inconsistencies, with uncertainties addressed using Moth-Flame and Hybrid Firefly Particle Swarm Optimization algorithms in MATLAB [10]. A two-stage stochastic decision-making approach is used to optimize the design and operation of MMG systems, balancing cable installation costs and energy dispatch efficiency within the uncertainty of renewable energy generation[11]. MGs exchange power between them and with the utility grid to meet their load demand from renewable energy or low-cost available sources which reduces the power generation from conventional sources [12]. Literature shows the number of advantages of using an MMG against MGs operating separately. In [5], [13], [14], it is shown that each MGs have a different load demand and different load characteristics which provide an optimized reduced operational cost of MMG. MMG are three types radial, daisy-chain, and Meshed topology. The details of each MMG topology are available in [15]. Implementation complexity becomes more challenging and increases cooperation among the MGs from radial to meshed topology. In this paper, meshed topologies are implemented to get results with optimized cost, carbon emission, power exchange between MGs, and power exchange between MGs and Grid. MG's scheduling is affected by local generation, and demand and influenced by other MG's.

In literature four most common models of EMSs are: a) centralized b) decentralized c) hybrid d) nested [16]. In this paper, centralized EMS is used. For optimal operation of MMG uncertainties are considered in renewable energy sources, demand, and price of power exchange. The Monte Carlo simulation method is used to generate the scenario based on past data. The rest of the paper is organized as follows. In Section 2, Problem formulation along with mathematical modelling of MMG components. Section 3 illustrates the simulation results of an MMG operating with and without an Energy storage system. Finally, conclusions derived from this study are detailed in Section 4.

II. PROBLEM FORMULATION

A. Optimization of the operating cost

In this system, the operational cost of each MG is minimized with the price of the grid and the adjoining MGs, also considering the constraint of other units as given in Eqs.(1)-(16) [17]. Considering three MG, each MG has a DG, a wind generator, a Photovoltaic system, an ESS unit, and a local load. A key point is that energy can be exchanged directly between any two of the three connected MGs and between each MG and the grid without needing an intermediary. This means that the three MGs can share energy and interact with the grid more efficiently and seamlessly. To avoid intermediary, it is required to address during operation that MGs might buy or sell their excess or deficient power without engaging in power mediation to make more profit. If this is not controlled, some MGs could benefit at the expense of others, by buying power cheaply and selling it at higher prices to other MGs [18]. To avoid this, it is ensured that no MG in the MMG system buys and sells power simultaneously from/to neighbouring MGs or the grid. To achieve this, each parameter is split into two positive components. By multiplying each component with a binary variable, it can regulate the power exchanges [19].

B. Diesel generator and its constraints

To operate a diesel generator in MMG limitations associated with it must be considered which are as follows:

$$P_{DGi}^{min}B_{DGi,t} \leq P_{DGi,t} \leq P_{DGi}^{Max}B_{DGi,t} \tag{1}$$

$$\left(X_{DGi,t-1}^{on} - U_{DGi}^{on}\right)\left(B_{DGi,t-1} - B_{DGi,t}\right) \geq 0 \tag{2}$$

$$X_{DGi,t}^{on} = \left(1 - B_{DGi,t-1}\right)B_{DGi,t} + B_{DGi,t}B_{DGi,t-1}\left(1 + X_{DGi,t-1}^{on}\right) \tag{3}$$

$$\left(X_{DGi,t-1}^{off} - D_{DGi}^{off}\right)\left(B_{DGi,t} - B_{DGi,t-1}\right) \geq 0 \tag{4}$$

$$X_{DGi,t}^{off} = \left(1 - B_{DGi,t}\right)B_{DGi,t-1} + \left(1 - B_{DGi,t}\right)\left(1 - B_{DGi,t-1}\right)\left(1 + X_{DGi,t-1}^{on}\right) \tag{5}$$

$$P_{DGi,t} - P_{DGi,t-1} \leq \left(1 - B_{DGi,t}\left(1 - B_{DGi,t-1}\right)\right) * R_{DGi}^{Up} + B_{DGi,t}\left(1 - B_{DGi,t-1}\right)P_{DGi}^{min} \tag{6}$$

$$P_{DGi,t-1} - P_{DGi,t} \leq \left(1 - B_{DGi,t-1}\left(1 - B_{DGi,t}\right)\right) * R_{DGi}^{Dn} + B_{DGi,t-1}\left(1 - B_{DGi,t}\right)P_{DGi}^{min} \tag{7}$$

$$C_{EMM}^{DGi} = EMM_{Cost\ Gas} * EMM_{value\ Gas} * P_{DGi,t} * B_{DGi,t} \tag{8}$$

$$C_i^{DG} = a_i + b_iP_{DGi,t} + c_i\left(P_{DGi,t}\right)^2 \tag{9}$$

Eq. (1) represents the minimum and maximum power generation of the diesel generator in each MG [7]. DG minimum time for which it will remain off/on is represented in Eq.(2) and Eq. (4). Eq. (3) and Eq. (4) shows the time for which DG remains on/off. Ramp-up and ramp-down limitations for DG are shown in Eq. (6) and Eq. (7) respectively [20]. Emission cost is modelled in Eq. (8) to reduce the emission of these gases [7]. The equation used various parameters, as shown in table 1.

Table.1

Gas	$EMM_{Cost\ Gas}$[\$/kg]	$EMM_{value\ Gas}$[kg/kWh]
NO_X	9.324	0.000198
SO_X	2.1978	0.0000036
CO_2	0.03108	0.0007182

C. Power exchange

Constraints with the Energy storage system are considered as follows

$$\mathrm{SOC_{ESS,i,t}} = \mathrm{SOC_{ESS,i,t-1}} + \left(\left(\eta_{\mathrm{ESS,ch}}\mathrm{P_{ESS,ch,t}} - \frac{\mathrm{P_{ESS,dch,t}}}{\eta_{\mathrm{ESS,ch}}}\right)\nabla \mathrm{t}\right)\mathrm{ESScap} \tag{10}$$

$$\mathrm{SOC}_{min,i} \leq \mathrm{SOC_{ESS,i,t}} \leq \mathrm{SOC_{max,i}} \tag{11}$$

$$0 \leq \mathrm{P_{ESS,ch,t}} \leq \mathrm{P_{ESS,ch,t}^{\mathit{max}}}U_{ESS,\mathrm{ch,t}} \tag{12}$$

$$0 \leq \mathrm{P_{ESS,dch,t}} \leq \mathrm{P_{ESS,ch,t}^{\mathit{max}}}U_{ESS,\mathrm{dch,t}} \tag{13}$$

$$U_{ESS,\mathrm{ch,t}} + U_{ESS,\mathrm{dch,t}} \leq 1 \tag{14}$$

$$\mathrm{PB_{ESS,ch,t}} = \mathrm{P_{ESS,ch,t}} - \mathrm{P_{ESS,dch,t}} \tag{15}$$

Eq. (10) represents the State of charge of MG's ESS and Eq. (11) shows the maximum and minimum State of charge of each ESS [21]. ESS power charging and discharging are specified in Eq. (12)-(13) respectively [12]. The fundamental role of MGs is the economic equilibrium between supply and demand through the regulation of supplied power and management of the demand side [22]. This equilibrium is represented by the Load and Generation Equivalence equation, as depicted in Eq. (16) [23]. Typically, a positive sign within the equation signifies the buying of power, while a negative sign denotes the provision of selling power to the grid.

$$P_{DGi,t} + P_{i,j,t}^{MG} + P_{i,t}^{PV} + P_{i,t}^{WD} + P_{i,t}^{Grid} + \mathrm{P_{ESS,dch,t}} = \mathrm{P_{ESS,ch,t}} + L_{i,t}^{D} \tag{16}$$

D. Objective function

The objective function is used to reduce the overall cost of each MG and the total cost of MMG. To obtain this formula is provided in Eq. (17) [18], [21].

$$C_T = Min(\textstyle\sum_{t=1}^{T} Cost) = Min(C_i^{DG} + C_i^{MG} + C_{EMM}^{DGi} + C_i^{Grid}) \tag{17}$$

III. SIMULATION RESULT

This part consists of the proposed model of MMG that has been implemented with the MMG system is grid-connected and it has three MGs each consisting of wind generation, solar generation, diesel generation, and local load. Specifications of DG are shown in Table 2. Wind turbines rating and working constraints are given in Table 3 and wind generation for each MG at every hour are shown in Fig. 1. For this work, the modelling of the photovoltaic module is used to generate a maximum of power 100kW, 250kW, and 450kW at 1000W/m² (100%) solar irradiation at 20°C for MG1, MG2, and MG3 respectively and solar generation of each MG can be seen in Fig.2.

Table 2

Rating and working constraints of Diesel Generators

DG	Ai	bi	ci	Pmax	Pmin	IS (hr)	Mint(hr)	SUP ($)	SDP ($)
MG1	0.0019	0.0047	0.000024	500	50	0	4	15	5
MG2	0.0024	0.0005	0.000025	700	90	2	2	45	10
MG3	0.002	0.00049	0.000026	900	65	0	4	45	10

Table 3

Wind generator rating and constraints

WT	Rating (kW)	Rated speed(m/s)	Cut in (m/s)	Cut off
MG1	700	12	3	24
MG2	700	12	3	24
MG3	1500	12	3	24

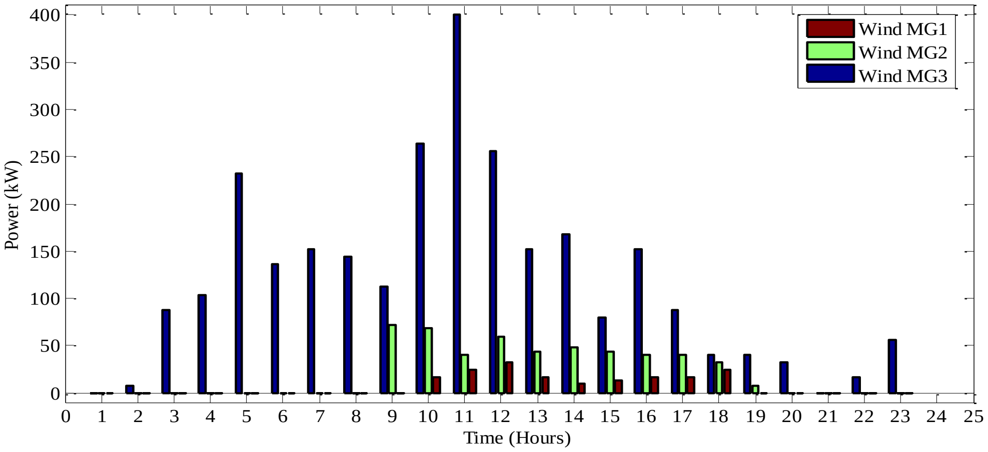

Fig.1 Wind power generation of MG1, MG2 and MG3

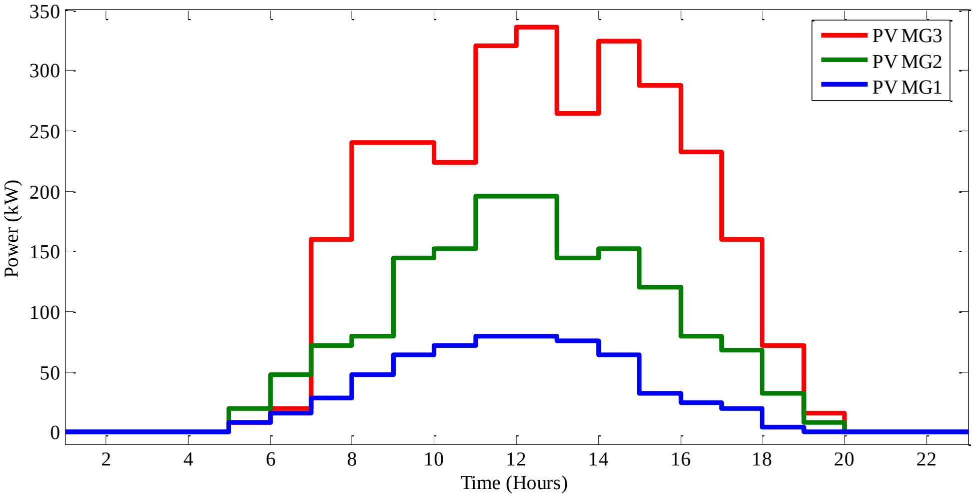

Fig.2 Solar power generation of MG1, MG2 and MG3

To analyze three MGs with different load profiles as shown in Fig 3 are considered. In MG1 peak load demand can be seen from 18.00 to 20:00, MG2 from 06:00 to 08:00, 20:00 to 22:00, and MG3 from 10:00 to 12:00. Another point needs to be addressed that the generation capacity of MG1 is less than its load demand. On another hand, MG2 has surplus power with a lower cost of generation than grid cost. the system has been investigated under two different cases (Case I & Case II).

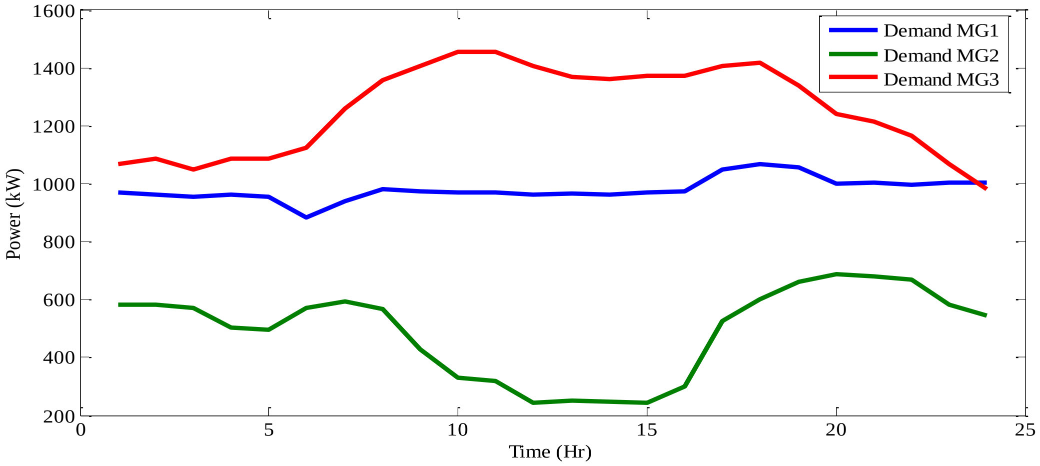

Fig.3 Load profile of each MG

A. *Case-I Grid Connected MMG with RES*

In this case study, all the MGs are connected in a mesh configuration with each other, each MG consists of a wind generator, PV modules, load, and diesel generator. The load profile of each MG is different from the other as shown in Fig. 3. MG1 has peak load demand in mid of the day, where MG2 is during early and late hours, and MG3 is during the middle of the day. The load profile also shows that MG1 has deficit power whereas MG2 has surplus power in most of the hours. As MG1 has deficit power therefore diesel generator running at full load from 3:00 h to 5:00 h and 7:00 h to 24:00 h to meet load demand and to reduce cost as grid price during this time is high. In fig.4. showing diesel generation of all the MGs and during the 1:00 h, 2:00 h, and 5:00 to 6:00 h generation is low compared to time 3:00 h to 4:00 h and after 7:00 h because when grid cost is high then DG operates to its full capacity and rest of time with limitation constraint. MGs buy power from the grid with tie line limitation and when the cost of the grid is lower than the cost of DG and adjoining MGs. As MG1 has deficit power therefore it buys power from MG2 and the grid. Fig.6. showing power purchase by MG1 from the grid with time of purchase and amount of power. During initial hours up to 8:00 h, 11:00 h to 14:00 h, and 17:00 h to 24:00 h it purchases power from the grid to minimize its cost. MG1 also purchases power from MG2 when the price of MG2 is less than the grid price and when the MG2 has surplus power as shown in Fig. 5. MG1 purchases power from MG2 at 4:00 h, 7:00 h to 19:00 h, 21:00 h, and 23:00 h to 24:00 h as during these hours MG2 has surplus power and price is less as compare to grid price.

MG2 purchases power from the grid only at 1:00 h to 2:00 h and 6:00 h because at this time price of grid power is least and DG of MG2 has reduced its generation at the same time. When the grid price is high MG2 sells its power to the grid during the 10:00 h to 16:00 h and 18:00 h to reduce its net cost.

MG3 has the highest renewable generation as compared to MG1 and MG2 therefore MG3's DG operates at its full capacity only at times when the grid price is at its peak. In the early hours of the day, when renewable energy is not available MG3 draws power from the grid to the maximum tie line limit and rest from DG. After 2:00, renewable energy increases, power exchange from MG2, and power generation with DG from 3:00 to 4:00 as grid prices are high which leads to a decrease in power purchase from the grid. With further increases in renewable energy from wind and solar and a decrease in grid price power generation of DG drop significantly. In Fig. 6. power purchase from the grid to MG3 reduces to zero at 10:00 and 13:00, it supplies power to the grid at 11:00, 12:00, 14:00, and 16:00 as the grid price further increases. When the renewable generation reduces and load demand is high it forces MG3 to buy power at 17:00 and 18:00 at a higher price. In late hours MG3 balances its load demand and generation from DG, wind generation, and gird.

The optimized cost of all the MGs in case-I is shown in Table 6. MG2 cost is negligible as compared to MG1 and MG3 because it has surplus power most of the time, which sells this power grid and adjoining MGs, therefore it reduces its cost.

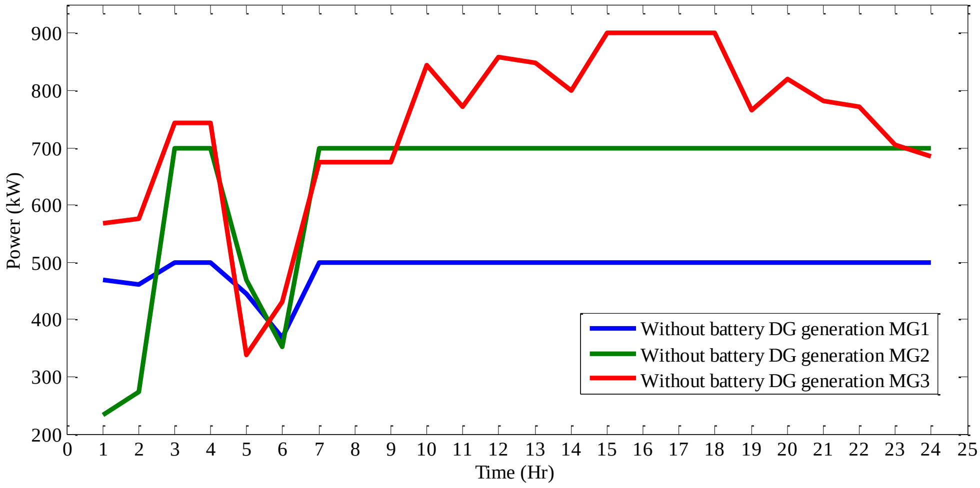

Fig.4 DG Generation of Each MG without ESS

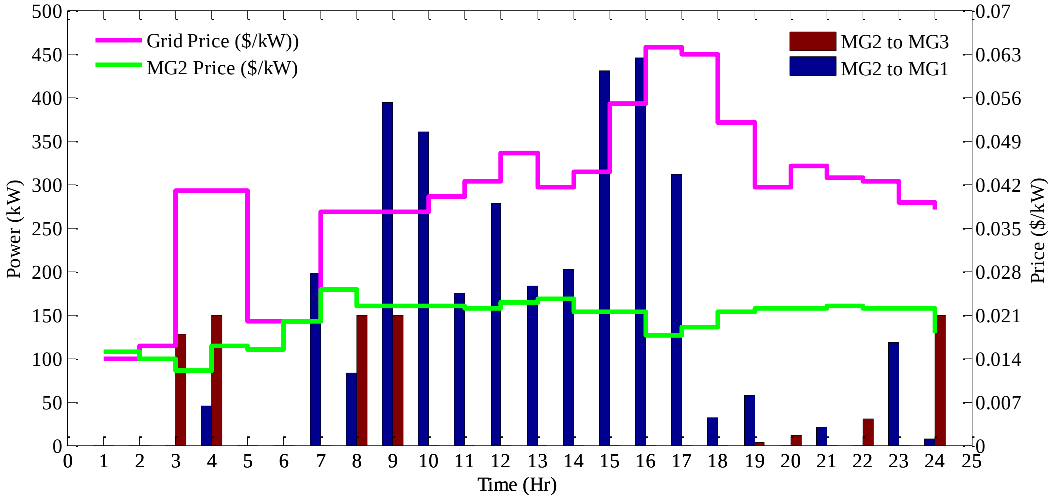

Fig.5 Power exchange between MEGs without ESS and Price of Grid and MG2

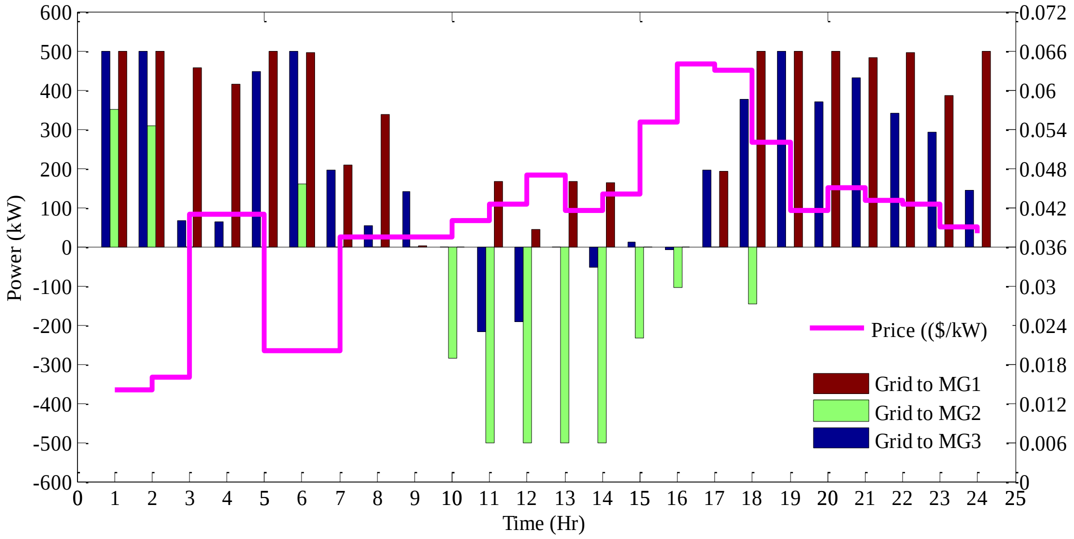

Fig.6 Power exchange between grid and MGs without ESS and price of grid

B. Case-II Grid Connected MMG with RES and Energy storage system

In this case, each MG is provided with an ESS (battery) of different ratings with different charging and discharging rates. MMG operated to obtain the optimized cost of all the MGs. The total cost of all MGs has decreased with the integration of ESS, but MG1's cost has increased due to its power shortage, which requires purchasing electricity from neighboring MGs and the grid. The DG generation with ESS has increased as compared to the previous case with a small amount and therefore carbon emission cost from DG increased by 0.5$. In Fig. 7 DG generation is nearly like case-I. MG2 has doubled the amount of electricity it supplies to the grid, while MG1 and MG3's net power purchases from the grid have increased. MG2 has reduced the amount of electricity it supplies to MG1 and MG3 in Fig. 8. In Fig. 9 MG2 feeds the grid with the power it generates between 3:00 and 4:00 and between 7:00 and 18:00 hours. With the help of ESS, MGs can store energy during times of low grid prices and supply it to the grid during times of high prices. ESS charging and discharging time can be seen in Fig. 10. The Initial state of ESS is fully charged to 90% of its rating therefore ESS of MG1 and MG2 discharge at 1:00 h and then charge at 2:00 h. As prices at 3:00, and 4:00 are high then all ESS of MGs start discharging during this period. This charging and discharging are done in a manner that the system can optimize its cost. When the grid price is its peak at 14:00 to 18:00 h then MG1 and MG2's ESS discharge continuously whereas MG1's ESS discharge at 15:00 to 17:00 h. After 20:00 all MG's ESS charged continuously until reaches 90% of its rating in Fig. 11.

Table 4
Net power in (kW) for DG generation, Grid to MGs, and MG to MG is given for the whole day

	MG1 DG (kW)	MG2 DG (kW)	MG3 DG (kW)	Grid to MG1 (kW)	Grid to MG2 (kW)	Grid to MG3 (kW)	MG2 to MG1 (kW)	MG3 to MG1 (kW)	MG2 to MG3 (kW)
MMG with RES	11743.53	15328.31	17674.68	7499.43	-1905.06	4665.98	3339.37	0	772.07
MMG with RES & ESS	11883.69	15510.63	17593.45	8019.5	-3862.08	5014.36	2374.38	112.56	382.46

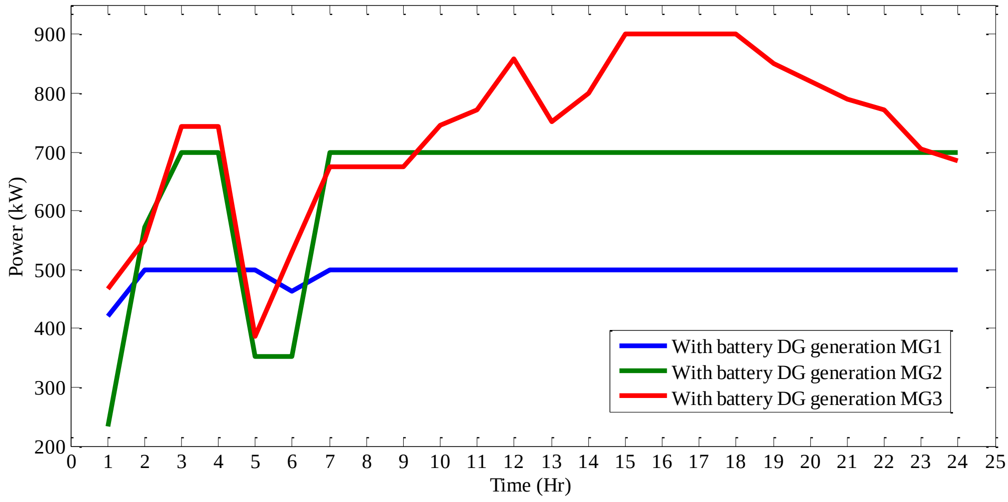

Fig.7 DG Generation of Each MG with ESS

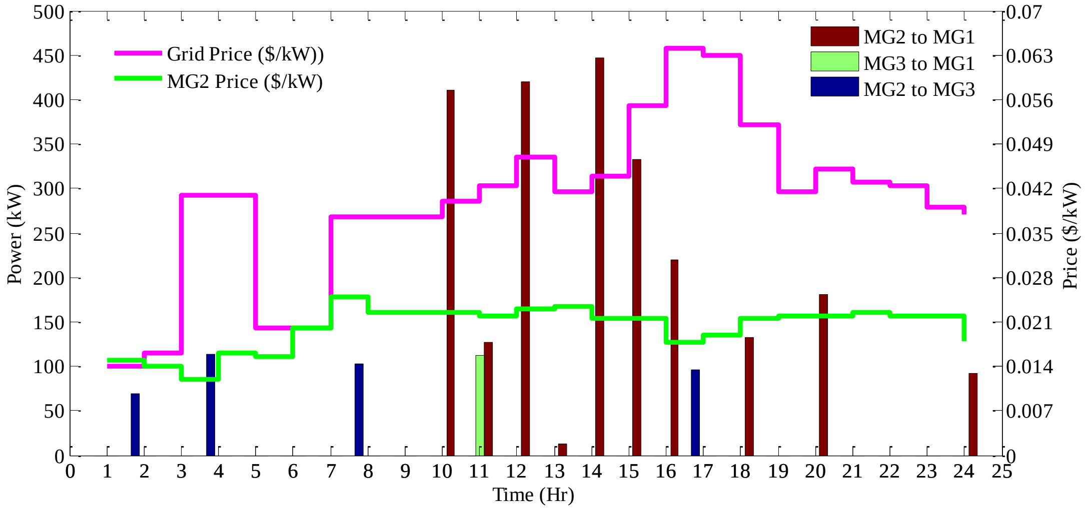

Fig.8 Power exchange between MGs with ESS and price of grid and MG2

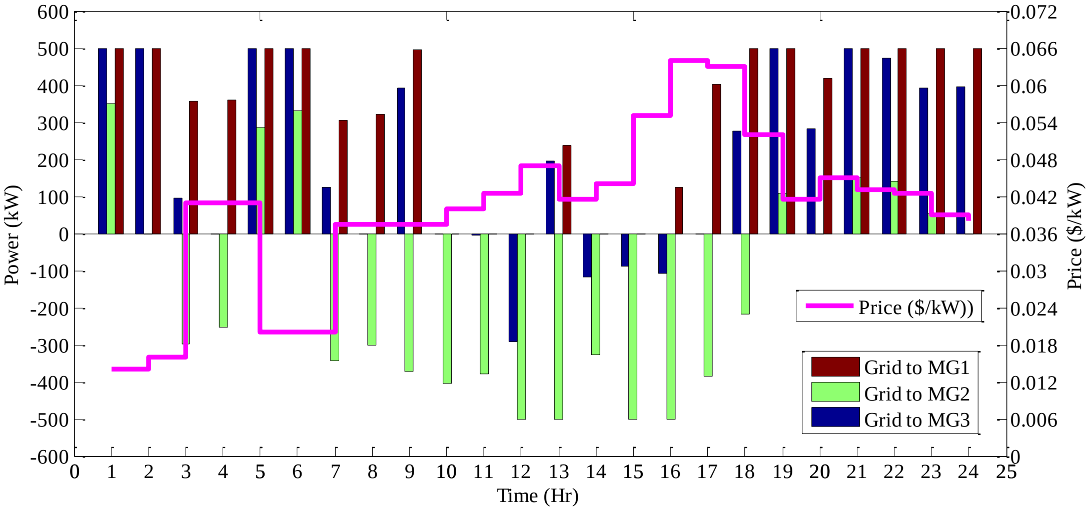

Fig.9 Power exchange between grid and MGs with ESS and price of grid

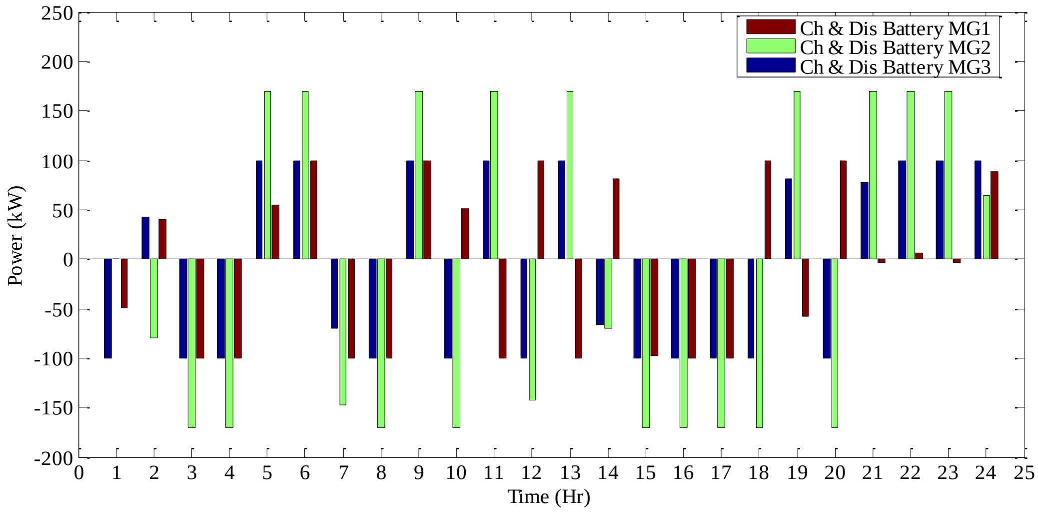

Fig.10 Charging and discharging of each MG's ESS

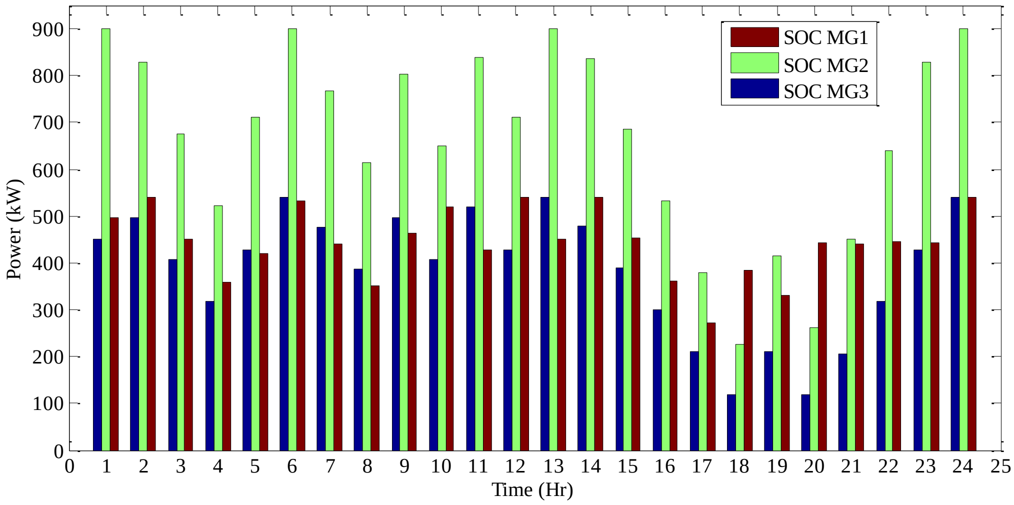

Fig.11 SOC of each MG's ESS

Table 5.

Cost of each MG, emission cost, and total cost of MMG.

	MG1 Cost	MG2 Cost	MG3 Cost	Emission Cost	Total Cost
Case-I	486.673	65.350	527.211	83.962	1163.196
Case-II	498.715	-0.222	513.575	84.414	1096.482

IV. CONCLUSIONS

Currently, several solutions have been proposed to overcome the uncertainty in energy management to increase reliability and improve efficiency. One effective solution is to decentralize the control of distribution networks into a set of small-scale areas, known as MGs. An interconnected network structure of MGs offers numerous benefits, such as the effective use of renewable energy sources (RES), reduced operation costs, and compensation for the low flexibility caused by the high penetration of RES.

However, the most important part of research is utilizing this structure is ensure optimal energy management. This paper proposes an EMS for the optimal operation of MMG systems. The advantage of this approach is that MGs can manage their local resources more effectively, reducing operating costs through power exchanges between themselves and the grid. To demonstrate the effectiveness of the proposed method, an MMG system operating under real conditions and considering all sources of uncertainty was used. Two different cases were investigated in this simulation, and the mentioned advantages were thoroughly analysed. The results confirmed that the operating cost of the connected MMG with an energy storage system is lower than the operating mode without the storage system. The research also prevents unnecessary selling or buying of power in transmission mode, ensuring that such actions do not cause unfair increases or decreases in operating costs and protect the rights of MGs.The simulation results show that a well-designed EMS, which influences advanced optimization techniques and incorporates energy storage can significantly improve the economic and operational performance of MMG systems. From the result, it can be seen that MMG not only enhances the reliability and efficiency of energy management but also ensures fair and optimal use of available resources, ultimately leading to a more resilient and cost-effective power grid.

Acknowledgment: The present work has been carried out under the research grant from MHRD vide letter no. 17-11/2015-PN.1 for Design Innovation Centre, at University Institute of Engineering and Technology, Panjab University, Chandigarh, India.

V. REFERENCES

[1] H. Karimi and S. Jadid, “Optimal energy management for multi-microgrid considering demand response programs: A stochastic multi-objective framework,” *Energy*, vol. 195, Mar. 2020, doi: 10.1016/j.energy.2020.116992.

[2] S. A. Mehraban and R. Eslami, “Multi-microgrids energy management in power transmission mode considering different uncertainties,” *Electric Power Systems Research*, vol. 216, Mar. 2023, doi: 10.1016/j.epsr.2022.109071.

[3] Z. Abdmouleh, A. Gastli, L. Ben-Brahim, M. Haouari, and N. A. Al-Emadi, “Review of optimization techniques applied for the integration of distributed generation from renewable energy sources,” 2017, *Elsevier Ltd*. doi: 10.1016/j.renene.2017.05.087.

[4] Y. Huang and L. Söder, “Assessing the impact of incentive regulation on distribution network investment considering distributed generation integration,” *International Journal of Electrical Power and Energy Systems*, vol. 89, pp. 126–135, Jul. 2017, doi: 10.1016/j.ijepes.2017.01.018.

[5] M. Daneshvar, B. Mohammadi-Ivatloo, K. Zare, and S. Asadi, “Two-Stage Robust Stochastic Model Scheduling for Transactive Energy Based Renewable Microgrids,” *IEEE Trans Industr Inform*, vol. 16, no. 11, pp. 6857–6867, Nov. 2020, doi: 10.1109/TII.2020.2973740.

[6] M. A. Taghikhani and B. Zangeneh, “Optimal energy scheduling of micro-grids considering the uncertainty of solar and wind renewable resources,” *Journal of Scheduling*, vol. 25, no. 5, pp. 567–576, Oct. 2022, doi: 10.1007/s10951-022-00739-5.

[7] D. Kumar, S. Dhundhara, Y. P. Verma, and R. Khanna, “Impact of optimal sized pump storage unit on microgrid operating cost and bidding in electricity market,” *J Energy Storage*, vol. 51, Jul. 2022, doi: 10.1016/j.est.2022.104373.

[8] G. Liu, M. F. Ferrari, T. B. Ollis, and K. Tomsovic, “An MILP-Based Distributed Energy Management for Coordination of Networked Microgrids,” *Energies (Basel)*, vol. 15, no. 19, Oct. 2022, doi: 10.3390/en15196971.

[9] H. Zou, S. Mao, Y. Wang, F. Zhang, X. Chen, and L. Cheng, “A Survey of Energy Management in Interconnected Multi-Microgrids,” *IEEE Access*, vol. 7, pp. 72158–72169, 2019, doi: 10.1109/ACCESS.2019.2920008.

[10] I. M. Ibrahim, A. Y. Abdelaziz, H. H. Alhelou, and W. A. Omran, “Sizing of Microgrid System Including Multi-Functional Battery Storage and Considering Uncertainties,” *IEEE Access*, 2023, doi: 10.1109/ACCESS.2023.3259459.

[11] D. Han and J. H. Lee, “Two-stage stochastic programming formulation for optimal design and operation of multi-microgrid system using data-based modeling of renewable energy sources,” *Appl Energy*, vol. 291, Jun. 2021, doi: 10.1016/j.apenergy.2021.116830.

[12] M. Marzband, H. Alavi, S. S. Ghazimirsaeid, H. Uppal, and T. Fernando, “Optimal energy management system based on stochastic approach for a home Microgrid with integrated responsive load demand and energy storage,” *Sustain Cities Soc*, vol. 28, pp. 256–264, Jan. 2017, doi: 10.1016/j.scs.2016.09.017.

[13] S. E. Ahmadi and N. Rezaei, “A new isolated renewable based multi microgrid optimal energy management system considering uncertainty and demand response,” *International Journal of Electrical Power and Energy Systems*, vol. 118, Jun. 2020, doi: 10.1016/j.ijepes.2019.105760.

[14] M. Elkazaz, M. Sumner, and D. Thomas, “Energy management system for hybrid PV-wind-battery microgrid using convex programming, model predictive and rolling horizon predictive control with experimental validation,” *International Journal of Electrical Power and Energy Systems*, vol. 115, Feb. 2020, doi: 10.1016/j.ijepes.2019.105483.

[15] A. Nawaz, M. Zhou, J. Wu, and C. Long, “A comprehensive review on energy management, demand response, and coordination schemes utilization in multi-microgrids network,” *Appl Energy*, vol. 323, Oct. 2022, doi: 10.1016/j.apenergy.2022.119596.

[16] N. P. Srinivas and S. Modi, “A Comprehensive Review of Microgrids, Control Strategies, and Microgrid Protection Schemes,” *ECS Trans*, vol. 107, no. 1, p. 13345, Apr. 2022, doi: 10.1149/10701.13345ecst.

[17] A. SoltaniNejad Farsangi, S. Hadayeghparast, M. Mehdinejad, and H. Shayanfar, “A novel stochastic energy management of a microgrid with various types of distributed energy resources in presence of demand response programs,” *Energy*, vol. 160, pp. 257–274, Oct. 2018, doi: 10.1016/j.energy.2018.06.136.

[18] H. Karimi, S. Jadid, and A. Makui, “Stochastic energy scheduling of multi-microgrid systems considering independence performance index and energy storage systems,” *J Energy Storage*, vol. 33, no. April 2020, p. 102083, 2021, doi: 10.1016/j.est.2020.102083.

[19] Y. Zhang, Q. Ai, H. Wang, Z. Li, and K. Huang, “Bi-level distributed day-ahead schedule for islanded multi-microgrids in a carbon trading market,” *Electric Power Systems Research*, vol. 186, Sep. 2020, doi: 10.1016/j.epsr.2020.106412.

[20] S. Ghaemi, J. Salehi, and F. H. Aghdam, “Risk aversion energy management in the networked microgrids with presence of renewable generation using decentralised optimisation approach,” *IET Renewable Power Generation*, vol. 13, no. 7, pp. 1050–1061, 2019, doi: 10.1049/iet-rpg.2018.5573.

[21] H. Afrakhte and P. Bayat, “A contingency based energy management strategy for multi-microgrids considering battery energy storage systems and electric vehicles,” *J Energy Storage*, vol. 27, Feb. 2020, doi: 10.1016/j.est.2019.101087.

[22] E. K. Lee, W. Shi, R. Gadh, and W. Kim, “Design and implementation of a microgrid energy management system,” *Sustainability (Switzerland)*, vol. 8, no. 11, Nov. 2016, doi: 10.3390/su8111143.

[23] Q. Xu, L. Li, X. Chen, Y. Huang, K. Luan, and B. Yang, “Optimal economic dispatch of combined cooling, heating and power-Type multimicrogrids considering interaction power among microgrids,” *IET Smart Grid*, vol. 2, no. 3, pp. 391–398, Sep. 2019, doi: 10.1049/iet-stg.2018.0161.