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

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***Abstract*—The microgrids (MGs) are considered to be a key component of future power systems. The increased integration of distributed energy resources (DER) has led to critical challenges in energy management (EM) such as uncertainty, pricing and optimal dispatch. The need for control of DER, optimal resource allocation and EM, requires interconnection of MGs, leading to formation of multiple-microgrid (MMG). One of the fundamental objective of MMG is to make optimal use of DER's within various MGs for optimal benefits. At a particular instance, some MGs might have excess energy generated, while some other MGs might buy the excess energy to meet local demands and storage requirements. The MMG facilitates energy trading between the grid and MG and amongst the MGs in order to achieve efficient energy sharing. In this paper, we evolve through different EM and scheduling strategies using visual basic for applications (VBA). The system considered has 3 MGs interconnected forming a MMG with each MG equipped with PV system and energy storage system (ESS). The objective of the strategies is to maximize the profits of individual MG while benefiting the whole MMG in total. The costs of implementing the proposed strategies are calculated and an economic analysis of various strategies is presented.**

***Keywords*—Microgrid, Multiple - Microgrids, Energy Market Operator, Energy Scheduling, Energy Trading.**

I. Introduction

Microgrid (MG) is a small active distribution network capable of operating both in a grid-connected as well as isolated mode. An MG consist of ESS, RES and controllable loads with defined electrical boundaries. The MG monitors the distributed energy resources (DER) in a decentralized manner, reducing the grid burden [1]. The variable and intermittent nature of these RES affects the reliability of the system. This introduces a significant challenge for managing demand and supply in MGs.

The recent development of energy sharing among MGs provides a viable solution for their reliable and cost-efficient operations [2]. Increased installation of MGs in the low-voltage (LV) network has led to the interconnection of MGs having different characteristics. All interconnected MGs optimize energy trading by scheduling resources to take advantage of different supply and demand patterns. MGs can minimize operational costs by decreasing network interactions and facilitating interactions between MGs. MMG environment helps in achieving optimal use of RES, increased reliability, reduced transmission losses and maximized profits of MGs with exchange of resources amongst them [3].

In [4], naive auction algorithm is proposed and verified on two cases, it is applicable only when an equal number of buyers and sellers are present in the market. In [5], the Cooperative model is used for energy trading in MMG. It proposes to provide additional information about the adjustable power to the Community energy management system so that it provides additional options in trading energy. In [6], energy trading based on agents for including ESS in local level and global level is proposed. In [7], to maximize the social benefit i.e. profits of the MMGs, by strategical use of RES is developed based on multi-agent system (MAS). In [8], three different scenarios are considered for studying the interaction among energy service provider (ESP) and energy market. A Stackelberg game for EM of MMGs is designed as a bi-level programming technique. In [9], a contribution-based energy trading mechanism is proposed where the existence of Nash equilibrium is verified among consumers for energy allocation. In [10], a novel EM algorithm based on sequential non-cooperative game theory is proposed to satisfy energy trading and power constraints. In [11], [12] a similar approach is proposed, but energy allocation is proposed based on the priority index to different MGs. In [13], a coalitional operation model is constructed to minimize the total operation costs. In [14], trading within an MG, problem is formulated as a non-cooperative game verifying the Nash equilibrium and for trading among the MMGs, a multi-leader multi-follower Stackelberg game model is proposed. In [3], rolling optimization is utilized in the first stage to schedule ESS and the Stackelberg game is used to optimize the internal prices. Particle swarm optimization (PSO) based energy scheduling for MMGs is proposed to minimize the distribution losses and maximize the profits of MGs [15].

Different strategies for combined energy scheduling and energy trade in interconnected and autonomous MGs are studied in this paper. The MG after supplying the local load, can store excess energy in ESS or it can supply this energy to the grid or to the other MGs. Different scenarios in which the

MG can operate are compared and strategies are evolved for energy trading among the MGs and grid. The objective is to improve the revenue of each MG.

The rest of the paper is arranged as: Section II presents System Architecture. In Section III, proposed work is discussed. In Section IV, Results for various scenarios are presented along with the most profitable strategy for MGs. Lastly, Section V, summarizes the Conclusion.

II. SYSTEM ARCHITECTURE

The MMG system used for analysis in this research work is shown in Fig. 1. The system consists of 3 MGs interconnected to each other and the grid. Each MG consists of PV, ESS and loads with a local EMS [3]. The power flow and energy trading amongst the MGs and with the grid are controlled through the energy market operator (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_{mg}^{b} and selling price P_{mg}^{s} of the MGs as compared to the price of selling P_{g}^{s} or buying power P_{g}^{b} from the grid is given in (1). This condition encourages more trading among MGs and helps the MG to gain more profits from energy sharing with other MGs compared to trading with the power grid.

$$P_{g}^{b} \leq P_{mg}^{b} \leq P_{mg}^{s} \leq P_{g}^{s} \tag{1}$$

Let us assume that there are `N' MGs in a distributed network. This paper considers N=3 for evaluation purposes. Each MG is assumed to be equipped with PV such that it generates energy $PV_{geni}^{h}$ during a certain hour `h' of the day. Each MG is initially required to fulfill its own load demand L_{i}^{h}. In case, if the $PV_{geni}^{h} > L_{i}^{h}$ 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 $PV_{geni}^{h} < L_{i}^{h}$, MG_i is required to buy energy or discharge ESS for meeting the load demand. The set of all MGs which have excess energy will be represented by p. After serving its own load at hour `h', the seller MG will have excess energy given by (2).

$$E_{i,ex}^{h} = PV_{geni}^{h} - L_{i}^{h} \geq 0 \;\forall\, i \in p \tag{2}$$

The amount of energy required for a buyer MG is given in (3) where q represents all buyer MGs.

$$E_{i,req}^{h} = L_{i}^{h} - PV_{geni}^{h} \;\forall\, i \in q \tag{3}$$

Total amount of excess energy in MMG and energy required by MMG is given by (4) and (5), respectively.

$$E_{t,ex}^{h} = \sum_{i=1}^{n} PV_{geni}^{h} - L_{i}^{h} \;where\; i \in p \tag{4}$$

$$E_{t,rq}^{h} = \sum_{i=1}^{n} L_{i}^{h} - PV_{geni}^{h} \;where\; i \in q \tag{5}$$

This information on excess energy and the total amount of energy required by the buyer MGs is provided to the EMO. The EMO then fixes the selling and buying prices for every hour according to (1).

The primary objective of local EMS i.e. microgrid central controller (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 (6).

$$P_{b,i}^{h} - P_{s,i}^{h} = L_{i}^{h} + E_{ch,i}^{h} - PV_{geni}^{h} \tag{6}$$

In (6), $P_{b,i}^{h}$ is the amount of energy bought and $P_{s,i}^{h}$ is the amount of energy sold by MG_i in time slot `h', L_{i}^{h} is the internal load supplied in MG_i, is the amount of energy for charging ESS.

Equation (7) represents the constraint on maximum power flow allowed between an MG and power grid.

$$0 \leq P_{b,i}^{h}, P_{s,i}^{h} \leq P_{f,i}^{max} \tag{7}$$

In addition to the constraints of power flow, a number of constraints with respect to ESS are given in (8) - (11).

$$E_{i}^{h} = E_{ch,i}^{h} - E_{dis,i}^{h} \tag{8}$$

$$0 \leq E_{ch,i}^{h} \leq E_{ch,i}^{max} \tag{9}$$

$$0 \leq E_{dis,i}^{h} \leq E_{dis,i}^{max} \tag{10}$$

$$SOC_{i}^{min} \leq SOC_{i}^{h} \leq SOC_{i}^{max} \tag{11}$$

In (8) - (11), $E_{ch,i}^{h}$, $E_{dis,i}^{h}$ are the charging and discharging energy of ESS in MG_i, $E_{ch,i}^{max}$, $E_{dis,i}^{max}$ are the maximum amount of charge and discharge allowed in ESS and SOC_{i}^{min}, SOC_{i}^{max} 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 prediction algorithm, the internal prices are obtained using Stackelberg game theory [3].

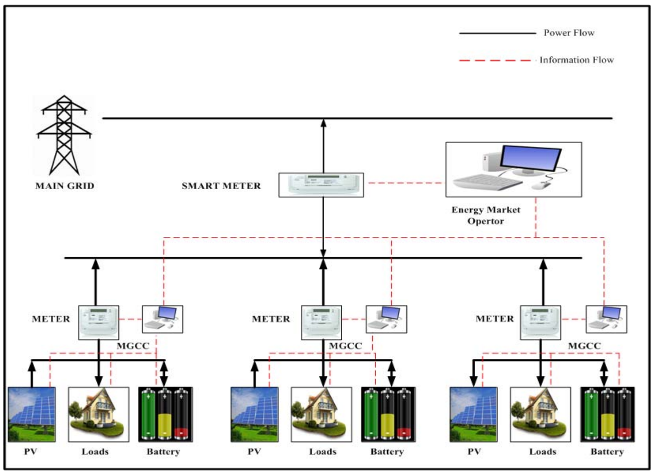

Fig. 1 Structure of MMG system [3]

III. Evolution of Strategies

The objective is to establish an efficient EMS in MMGs to maximize profitability of individual MGs and the EMO, by analyzing 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 (12).

$$\max f(x) = \sum_{h=1}^{24} [\theta \times PV^h_{geni} - P^{sh}_g \times P^h_{bt} + P^{bsh}_{mg} \times P^h_{ld} + P^{bh}_g \times P^h_{ex}] \quad (12)$$

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}_g is the internal buying or selling price of energy within the MMG. It will be positive when the MG sells energy and vice versa. The MG with which the energy is traded by the MG, under consideration, within the MMG is given by P^h_{ld} and P^h_{ex} is the energy sold to the grid. The objective function will be evaluated for each hour `h'.

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 EM strategies used in this analysis are shown through flowchart in Figs. 2 and 3. Fig. 2 shows the flowcharts for the first 4 proposed strategies and Fig. 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.

A. Strategy 1:

In this case, the PV generated (PV^h_{geni}) in each MG_i is self-consumed i.e., supplied to the load L^h_i and remaining energy after supplying to load i.e., excess energy $E^h_{i,ex} = PV^h_{geni} - L^h_i$ is stored in the ESS as shown in (13) by satisfying the constraints in (8) – (11) and (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 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 (15) by complying with the constraints in (6)-(7). The ESS is not scheduled and discharges irrespective of peak period to the local load obeying (14). The amount of cost occurred is calculated using (12). The operation of PV generation, consumption and role of ESS is shown as flowchart in Fig. 2.

$$BC^h_i = BC^{h-1}_i + (PV^h_{geni} - L^h_i) \quad (13)$$

$$BC^{min}_i \leq BC^h_i \leq BC^{max}_i \quad (14)$$

$$P^h_{b,i} = L^h_i - \left(PV^h_{geni} + \left(BC^h_i - BC^{h-1}_i\right)\right) \quad (15)$$

B. Strategy 2:

In an improvement to the previous strategy, in this case the ESS charging and discharging pattern is similar to strategy 1, where the generated PV (PV^h_{geni}) in each MG_i is supplied to the local load L^h_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^h_{geni}) is traded with the grid as shown in Fig. 2. The excess energy supplied to the grid is given by (16) and the amount of energy purchased from the grid is shown in (15).

$$P^h_{s,i} = PV^h_{geni} - \left(L^h_i + \left(BC^h_i - BC^{h-1}_i\right)\right) \quad (16)$$

C. 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 period to supply the local load of the MG as shown in Fig. 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 (15).

D. 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. 2. The excess energy produced by the PV is supplied to the grid according to (16). This strategy is evolved from the earlier strategies.

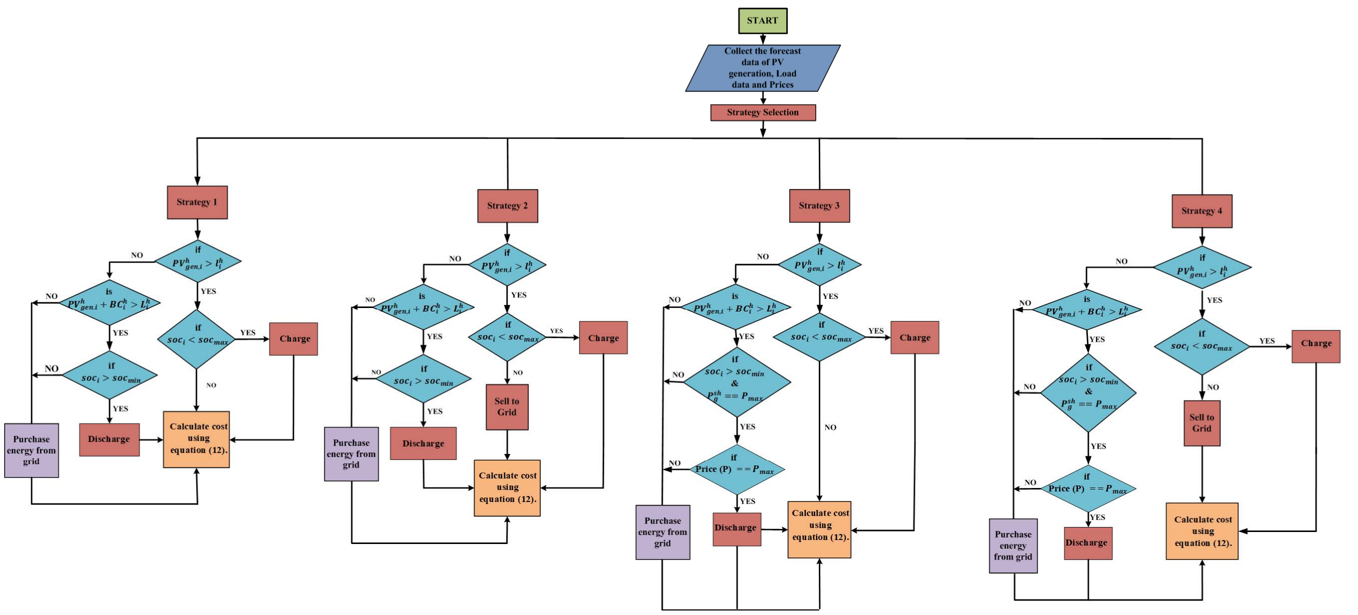

Fig.2 Flowchart for strategies 1-4

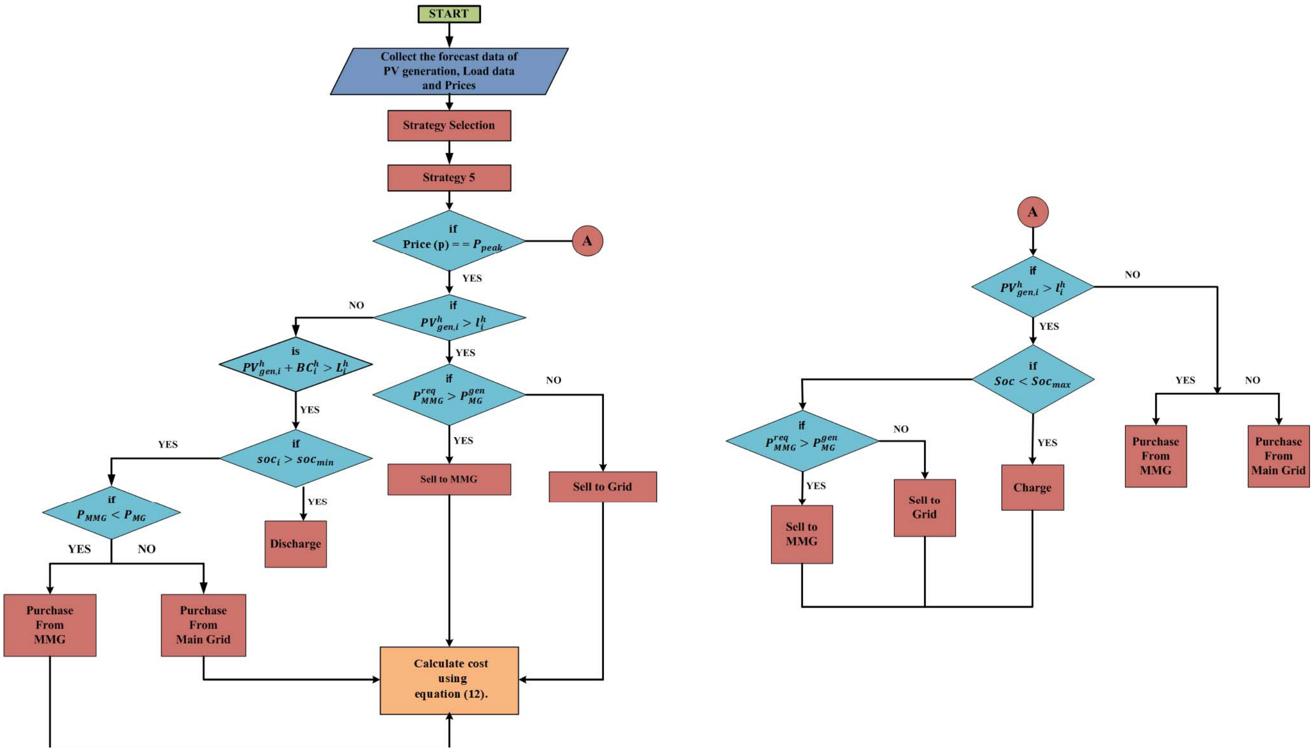

Fig. 3 Flowchart for strategy 5

E. Strategy 5:

Strategy 5 leads us to the threshold of evolution, as we move from strategies 1 to 4. As 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 strategy 3 and 4, discharges during peak time only. The excess energy generated by the PV unit is either sold to the grid or microgrid during peak period. The energy stored in the ESS may also be discharged during peak periods to realize an increase in profits. In case, if the total energy required $E^{h}_{t,rq}$ by other MG's in MMG is zero, the total excess energy $E^{h}_{t,ex}$ is sold to the grid.

IV. Results

To analyze the performance of the proposed EM schemes, an MMG system consisting of 3 interconnected MGs as shown in Fig. 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 a MMG with load satisfaction as its main objective and excess energy is traded with grid in Strategy 2 and 4. In Strategy 5, trading amongst MMG is considered with profit making as the primary objective. Table I 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, Time Of Use (TOU) tariff of different MGs in a day is considered from [3]. The grid selling and buying price and the internal prices for energy consumption in each MG and trading with other MMGs is shown in Fig. 4. The relation between the selling and purchase prices is as shown in (1).

TABLE I. System Data for case study

Parameters	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

A. Strategy 1:

The revenue generated for Strategy 1 is presented in Fig. 6a. The price has both negative and positive values. The negative values indicates that the sum of energy generated by PV and energy stored in ESS are unable to supply the load. This is observed during 1-8 hours and 18-24 hours. The ESS in MG_1 charges till 17^{th} hour, in MG_2 till 15^{th} hour and up to 11^{th} hour in MG_3 to its full capacity, then discharges to support the load as shown in Fig. 5a. The variation in cost incurred for 3 MG's is shown in Fig. 6a.

B. 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. 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. 5a. Fig. 6b, provides the revenue generated by each MG and 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 as – MG_1 - 5606.89 INR, MG_2 - 8407.17 INR and MG_3 - 5993.05 INR in comparison to Strategy 1 as shown in Fig. 6b.

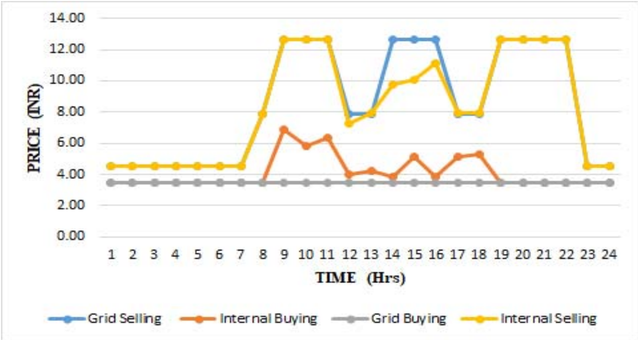

Fig. 4. Time Of Use Prices

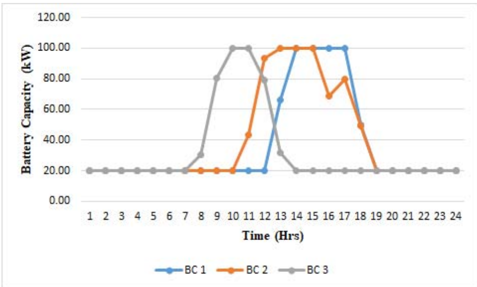

Fig. 5a. Strategy 1 and 2

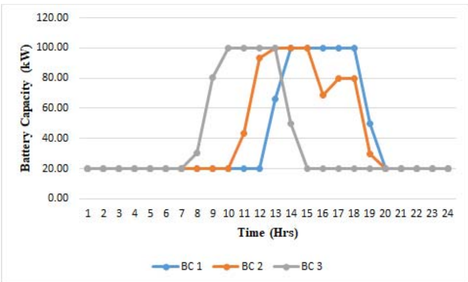

Fig. 5b. Strategy 3 and 4

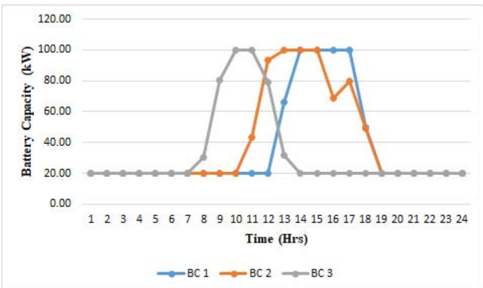

Fig. 5c. Strategy 5

Fig. 5. ESS charging and discharging for strategies 1-5.

C. *Strategy 3:*

In this strategy, each MG profits by discharging ESS only during the peak demand hour's i.e. 9-11, 14-16 and 19-22 hours as shown in Fig. 4. The battery charging and discharging patterns is shown in Fig. 5b. Under this strategy, the excess energy is not utilized as in Strategy 1. The results of revenue generated by each MG and combined revenue of all MGs are shown in Fig. 6c. The revenue of MGs in this strategy are MG_1 - 5459.49 INR, MG_2 - 8133.65 INR and MG_3 - 6390.10 INR.

D. *Strategy 4:*

It is identical to Strategy 3, but trades excess energy generated by PV similar to Strategy 2 as shown in Fig. 7.

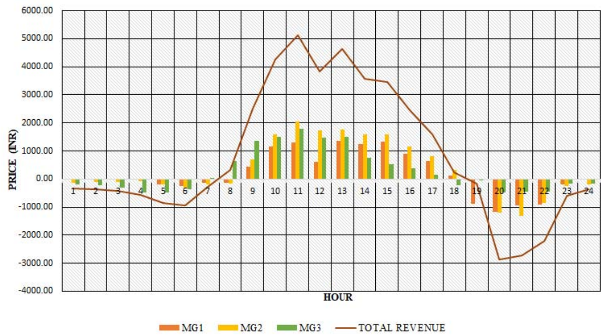

Fig. 6a Strategy 1

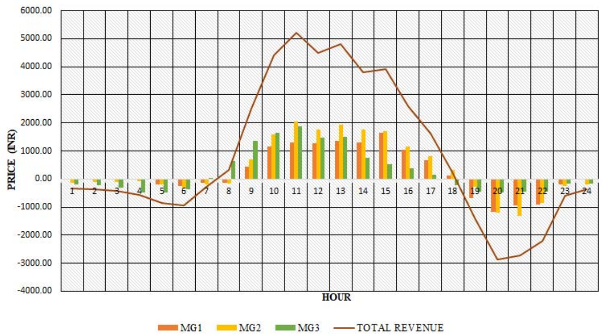

Fig. 6b Strategy 2

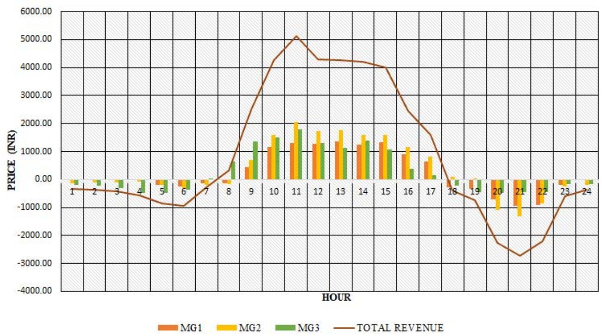

Fig. 6c Strategy 3

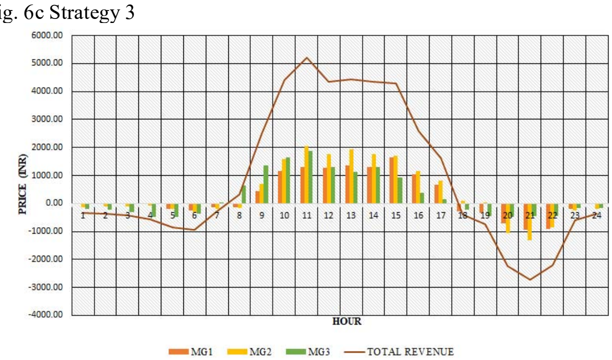

Fig. 6d Strategy 4

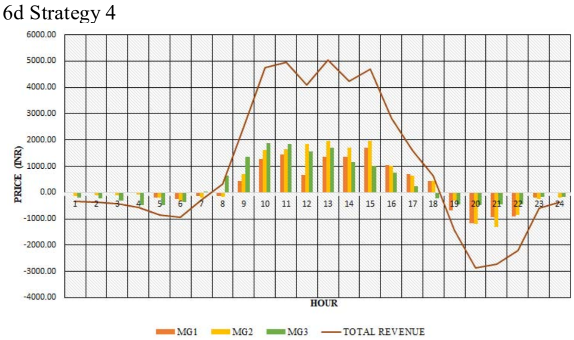

Fig. 6e Strategy 5

Fig. 6 Revenue of Different Strategies

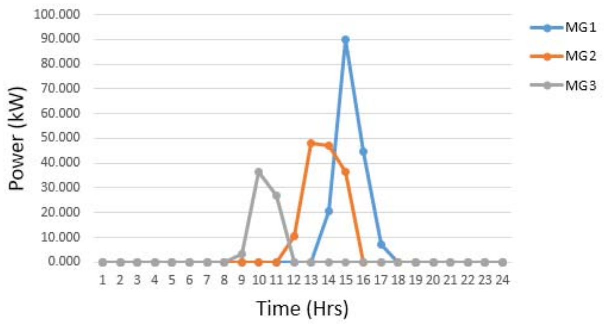

Fig. 7 Excess energy sold in Strategy 2 and Strategy 4

The charging and discharging of ESS is shown in Fig. 5b, while the revenue obtained by each MG and total revenue of all MGs is shown in Fig. 6d. The revenue of MGs in this strategy are MG_1- 6019.14 INR, MG_2 - 8657.97 INR and MG_3 - 6389.90 INR.

E. Strategy 5:

In this strategy, the excess generated energy is traded amongst the MGs or with the grid. The role of each microgrid during each hour is given in Table II. The energy trading between MGs is done in between the 9^{th} and 17^{th} hour. The ESS charging and discharging pattern is shown in Fig. 5c and revenue generated is shown in Fig. 6e.

MMG trading improves the combined revenue of all MGs as compared to individual MG operation as shown in Fig. 8.

TABLE II. ROLES OF MG IN ENERGY TRADING

Hour	MG_1	MG_2	MG_3
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

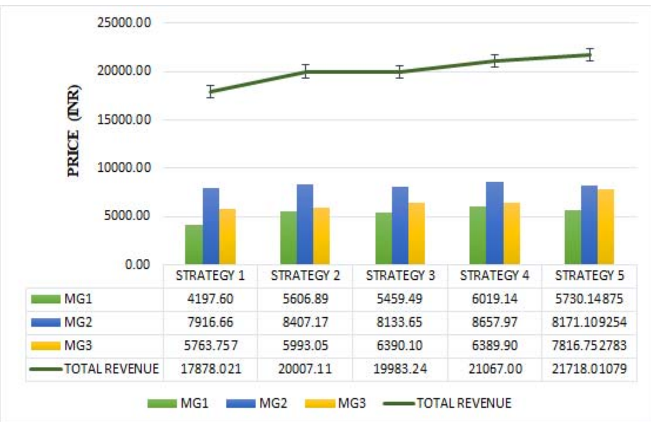

Fig. 8 Total Revenue of each MG

V. CONCLUSION

Various strategies are formulated based on optimum utilization 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 combined revenue of MGs increase by 11.90%, 11.77%, 17.84%, and 21.57% for respective MMG trading strategies. The committed energy trading strategy (5), generates more revenues in comparison to other strategies.

VI. REFERENCES

[1] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, "Microgrids," *IEEE power and energy magazine*, vol. 5, no. 4, pp. 78–94, 2007.

[2] W. Saad, Z. Han, H. V. Poor, and T. Basar, "Game theoretic methods for the smart grid," *arXiv preprint arXiv*:1202.0452, 2012.

[3] T. Rui, G. Li, Q. Wang, C. Hu, W. Shen, and B. Xu, "Hierarchical optimization method for energy scheduling of multiple microgrids," *Applied Sciences*, vol. 9, no. 4, p. 624, 2019.

[4] H. K. Nunna and S. Doolla, "Multiagent-based distributed-energy-resource management for intelligent microgrids," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1678–1687, 2012.

[5] V.-H. Bui, A. Hussain, and H.-M. Kim, "A multiagent-based hierarchical energy management strategy for multi-microgrids considering adjustable power and demand response," *IEEE Transactions on Smart Grid*, vol. 9,no. 2, pp. 1323–1333, 2016.

[6] H. K. Nunna, A. Sesetti, A. K. Rathore, and S. Doolla, "Multi-agent based energy trading platform for energy storage systems in distribution systems with inter-connected microgrids," *IEEE Transactions on Industry Applications*, 2020.

[7] J. Kaur, Y. R. Sood, and R. Shrivastava, "Optimal resource utilization ina multi-microgrid network for tamil nadu state in india," *IETE Journal of Research*, pp. 1–11, 2019.

[8] G. E. Asimakopoulou, A. L. Dimeas, and N. D. Hatziargyriou, "Leader-follower strategies for energy management of multi-microgrids," *IEEE transactions on smart grid*, vol. 4, no. 4, pp. 1909–1916, 2013.

[9] S. Park, J. Lee, S. Bae, G. Hwang, and J. K. Choi, "Contribution-based energy-trading mechanism in microgrids for future smart grid: A game theoretic approach," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 7, pp. 4255–4265, 2016.

[10] Y. Zhang, T. Zhang, R. Wang, Y. Liu, and B. Guo, "An innovative real-time price based distributed optimal energy management of multi-microgrids in a smart distribution system," in *2016 IEEE Innovative Smart Grid Technologies-Asia (ISGT-Asia)*. IEEE, 2016, pp. 341–346.

[11] A. M. Jadhav and N. R. Patne, "Priority-based energy scheduling in a smart distributed network with multiple microgrids," *IEEE Transactions on Industrial Informatics*, vol. 13, no. 6, pp. 3134–3143, 2017.

[12] A. M. Jadhav, N. R. Patne, and J. M. Guerrero, "A novel approach to neighborhood fair energy trading in a distribution network of multiple microgrid clusters," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 2, pp. 1520–1531, 2018.

[13] Y. Du, Z. Wang, G. Liu, X. Chen, H. Yuan, Y. Wei, and F. Li, "A cooperative game approach for coordinating multi-microgrid operation within distribution systems," *Applied Energy*, vol. 222, pp. 383–395, 2018.

[14] W. Zhou, J. Wu, W. Zhong, H. Zhang, L. Shu, and R. Yu, "Optimal and elastic energy trading for green microgrids: a two-layer game approach," *Mobile Networks and Applications*, vol. 24, no. 3, pp. 950–961, 2019.

[15] R. Lahon, C. P. Gupta, and E. Fernandez, "Optimal power scheduling of cooperative microgrids in electricity market environment," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 7, pp. 4152–4163, 2018.