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Energy Management of Multi-Microgrids in Joint Energy and Ancillary Service Market Considering Uncertainties of Renewables

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ABSTRACT

In this study, energy management of grid-connected Multi-Microgrid (MMG) is performed through joint optimization of the energy and ancillary service market. The test system comprises the IEEE 30 bus system as the main grid and the 16-bus system as an MMG. The MMG is comprised of dispatchable and non-dispatchable generation and loads. The non-dispatchable generators are based on renewable energy sources (RES) such as solar and wind. The uncertainty modeling for wind and solar is performed by Weibull and beta probability distribution function. The strategic integration of RES helps MMG deliver both energy and ancillary services to the utility grid. This research aims to reduce the total energy cost while reducing reserve cost by maximizing the use of RES under normal operation and during contingency conditions. It is observed that if MMG is incorporated into the system, then the total generation cost, reserve cost, and power losses are reduced to 0.11 %, 0.325 %, and 1.201 %, respectively, in normal operating conditions. Under contingency, when Generator 5 is out of service and the main grid is operating alone, the total generation cost increased significantly from 22118.92 \$ day^{-1} to 22435.68 \$ day^{-1} and the real power loss increased from 233.35 MW day^{-1} to 245.11 MW day^{-1}. However, by interconnecting MMG with the main grid, generation cost and power loss get reduced to 22375.60 \$ day^{-1} and 243.35 MW day^{-1}, respectively. It is analyzed that participation of MMG provides techno-economic benefits during normal operation and contingency conditions.

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1. INTRODUCTION

Competition in the restructured power market is a driving force for price minimization and social benefit maximization. Co-optimization of energy and reserve markets is used by several independent system operators (ISO), including Pennsylvania–Jersey–Maryland (PJM), California ISO, New York ISO (NYISO), New England ISO (ISO-NE), Australian, and New Zealand markets [1, 2]. The ISO coordinates energy and reserve dispatch to reduce total operating costs while meeting load demand and reserve requirements as well as staying within network limits [3]. In this paradigm, ISO considers the overall offered cost to be the market cost, and determine payments for clearing energy and reserve bids using a settlement process. Three price resolution procedures are employed in energy markets: uniform pricing system, pay-as-bid, and LMP-based scheme (Locational Marginal Price). All accepted offers/bids are paid at the uniform market clearing price (MCP) in a uniform pricing scheme. Each accepted offer is paid according to the offer price rather than the MCP in pay-as-bid. Accepted offers are paid based on locational marginal price in the LMP-based technique [4].

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In this paper, LMP-based pricing scheme is used for market price settlement. There are different methods used by ISO for clearing Energy Market (EM) and Ancillary Services Market (ASM) [5]. These are explained below:

Merit Order Dispatch (MOD): This is the basic form of dispatch where the independent stacks of the quantity of the energy and offers are considered for the EM and ASM. The bid blocks are then arranged based on merit. The energy market is then dispatched until the supply is equal to the demand. The same process is repeated for the AS market. This approach is simple and easy to understand when there is a coupling between EM and AS markets. However, this will lead to infeasible results when there is no coupling between products. The coupling means that the sum of energy and reserve dispatch is less than the unit limit.

Sequential dispatch optimization: This is the extension for MOD. Herein, both the energy market and the ASM have the same generation capacity. The EM and ASM are dispatched separately and sequentially. The EM is cleared first, followed by the clearing of the ASM. It is easy to determine the winner because both markets are dispatched separately.

Joint or simultaneous optimization: The goal of this technique is to distribute several indivisible items to a group of bidders while minimizing the collective bid cost of

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delivering energy and ancillary services. It is difficult to justify the schedule and pricing with this mechanism. As compared to MOD and sequential techniques, this technique has a strong coupling between the products.

Authors in [2, 6-10] presented several models for market clearing of joint energy and reserve auctions in which the energy and reserve offer costs were minimized while static and dynamic security criteria, such as the voltage drop and overloading indices, as well as corrected transient energy and voltage stability margins (VSMs) were also taken into account. In Ref. [2], the joint energy and reserve market clearance was performed considering the proposed multi-objective optimization problem, i.e., the payment cost minimization and voltage stability maximization. However, the stochastic nature of RES is not considered in this paper. In Ref. [6], a multi-market paradigm is proposed to facilitate the trading of energy and ancillary services across nano-grids in an islanded microgrid (MG). However, energy management in the grid interconnected mode is not considered in this work. In Ref. [10], simultaneous optimization of energy and reserve market is performed for IEEE 39 bus test system. In this study, wind and solar plant with PSP-based energy storage is integrated with the system, but uncertainty modeling for RES is not performed.

The primary factor contributing to the fast depletion of fossil fuels and rise of the green-house gas (GHG) emissions is the rapid rise in load demand. In order to overcome these issues, the world is moving towards the deployment of renewable-based distributed generation. The integration of these distributed generations (DG) with grid introduces the concept of microgrid [11]. A microgrid is a group of micro sources, loads, and batteries that represents itself as a single entity which can reciprocate the control signals sent by the central control center. MG is a low-voltage intelligent distributed network that is composed of micro sources or distributed generations, energy storage devices (ESD), and loads [12, 13]. In the case of the grid, it is termed as the controlled entity which can be operated as the aggregated load and as a micro source for power and ancillary services. From the consumer side, it is termed as the low-voltage distribution system [14]. Microgrids have a self-healing ability, thus improving the reliability of the distribution network by minimizing the chances of load shedding [15, 16], increasing the power quality, reducing carbon emissions [17, 18], and decreasing the price by optimally scheduling the renewable energy sources [19]. In addition, it supplies energy to remote areas [20]. Though the MG enjoys numerous benefits, the major issue faced by the microgrid central controller (MGCC) is to deal with the uncertainty of Renewable Energy Sources (RES) and to predict the generation from these sources accurately. The inaccuracy in prediction will results in failure of components and blackouts. The authors in [21] maintained that wind and solar were the fastest growing and most attractive RESs for electricity production. They identified wind and solar energy potentiality for four cities of Iran including Ahvaz, Sirjan, Neyshabur, and Tabriz. The results show the comparative analysis of wind and solar power generation potential for four cities. The wind turbine type and solar photovoltaic (PV) panel should be compatible with the geographical location and environmental conditions of the selected site for installation. In [22], the Technique of Order Preference by Similarity to Ideal Solution (TOPSIS) approach was used to determine the most compatible turbine with respect to the geographical and topological characteristics of the location under consideration. In [23], the effect of environmental and turbine parameters on the energy gains from wind farm was investigated. The Artificial Neural Network (ANN) model was developed, which demonstrated how energy gain increased with increase in annual mean wind speed. In [24], multi-group grey wolf optimizer (MG-GWO) was used to retrieve the parameters of a single-diode photovoltaic solar cell module. According to their results, the MG-GWO exhibited its superiority over classical GWO. There are various factors that affect the performance of wind turbine generator and solar PV panel. The output of solar panel depends on the ambient conditions, intensity of solar irradiance falling on it, and module temperature [25, 26]. Solar insolation is affected by the dust accumulating on the panel [27] or by partial shading of solar panel [28]. The performance of a solar PV plant can be improved by cooling technology [29] or shade dispersion technique explained in [30].

The main feature of MG is that it can be operated in the grid-connected and islanded modes. The decision on the mode of operation is taken by MGCC considering the economic and security constraints. The MG usually operatea in the grid-connected mode for the economic operation of the power system. However, if it is operating in the standalone mode, then it should have sufficient capacity to supply its load during emergency conditions. The MG is isolated from the main grid through switches at the point of common coupling [31]. In the grid-connected mode, MG provides the reserved energy to the main grid in cases of (a) a sudden increase in load demand, (b) reduction in energy generation from Conventional Generators (CGs), or (c) inaccurate load forecast [32]. There is an extensive scope of literature available on optimal scheduling of MG in the grid-connected mode [33-35], but quite a limited literature is available on the islanded operation of MG .The optimal energy management of MG can be done in a centralized or decentralized manner. In the centralized method, all the information regarding the available generation and load is collected for centralized operation and control [36], whereas in the decentralized method, every entity is considered as an agent which is free to take decisions [37]. For the systematic operation of MG in the interconnected mode, it is required that MGCC be coordinated with grid operations. Four different control strategies for energy management in MMGs were explained in Ref. [38]. First is the centralized control, in which all the generation and consumption devices are controlled by the central controller, but it fails to protect the customer privacy. Its main objective is to maximize profit of the whole MMG system. The MMG in this case operates at a very high risk given that the whole system will get affected if the centralized control fails. In decentralized control, individual MG is an autonomous entity that has a local controller (LC) to maximize its profit. The LC manages the MG and determines the operating point of generation and loads. Failure of one LC will not result in the failure of the operation of MMG. However, this method will introduce a competitive environment between the MGs to maximize their profit. In hybrid control, the central controller is at the MMG level and the local controller at the MG level. The LC performs local energy management and informs the central controller about the surplus/deficit of energy. Then, the central controller negotiates with multi-MG for its reliable operation. Thus, it is a two-level controlled strategy. The last one is the nested multi-microgrid energy management system

(MMGEMS). It is a hierarchical structure with multiple levels, and each microgrid constitutes a level of the whole MMG system. The privacy of customers with this control scheme can be preserved due to the multiple-layered privacy structure. The functionalities and operations of MGs were explained in [39]. In this study, the multi-agent system for the operation of the integrated MG was explained. A hierarchical control scheme was utilized for maximizing the production of DG and optimizing the power exchange between MGs and the grid. A novel double-layer coordinated control approach to MG was proposed in [40]. The schedule layer operates on the forecasted data and the dispatch layer provides power for controllable units in real time. The error between the two layers is resolved by their coordinated control.

According to the literature review, it is observed that much of the literature is focused on the islanded operation of the MG. However, a limited scope of the literature has focused on the joint optimization of the energy and ancillary services market of MMG in interconnected operation with the main grid considering the uncertainty of wind and solar. In this study, the uncertainty modeling for wind speed and solar irradiance is done through beta-Weibull probability distribution function (pdf). Also, this work considered the (N-1) contingency analysis. The contingency considered is generator and line outage. The energy management of MMG in the grid interconnected mode is performed by joint optimization of the EM and Reserve Market (RM). Generally, the RES is thought of as the consumer of ramping services due to their variability and intermittent nature. However, when these sources are integrated with fast ramping generators (micro-turbine and energy storage system), they can support the grid by providing reserves in the ASM. Thus, MMG considered in this work is composed of dispatchable and non-dispatchable generators as well as loads.

The rest of the paper is organized as follows. Section II shows the problem formulation and modeling of wind and solar power. Section III outlines the results and discussion. Section IV concludes the paper.

2. PROBLEM FORMULATION AND UNCERTAINTY MODELING

2.1. Objective function

The aim of this study is to minimize the energy and reserve costs by utilizing the energy available with RES in the MMG system. The market model considered in this paper is based on a joint dispatch mechanism. The simplicity and transparency of this mechanism are the main reasons behind the widespread use of this approach. In simultaneous or joint optimization, the ISO task is to match consumer demand with power plant capability in the most cost-effective manner while maintaining system stability and security. The goal is to achieve the following criteria by procuring energy and reserves at the lowest possible cost. In the deregulated power market, generating companies (GenCo) and distribution company (DisCo) submit their bids for the energy and reserve market in day-ahead of actual schedule. In this work, only the generator side bidding for energy is considered. There is no bidding from the consumer side. The cost minimization problem was given in [10], which was modified in this study. The proposed objective function is shown in Eq. 1. The proposed approach and its flowchart are shown in Figure 1 and Figure 2, respectively.

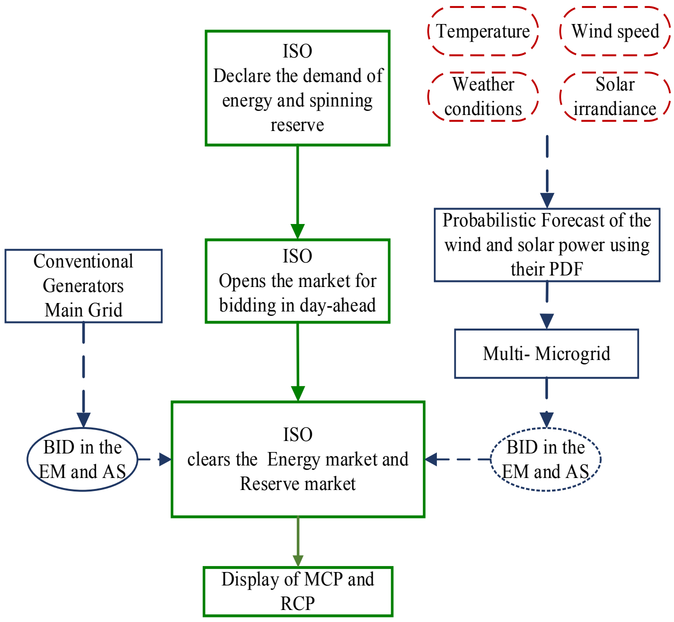

Figure 1. Proposed approach for joint optimization of energy and ancillary market

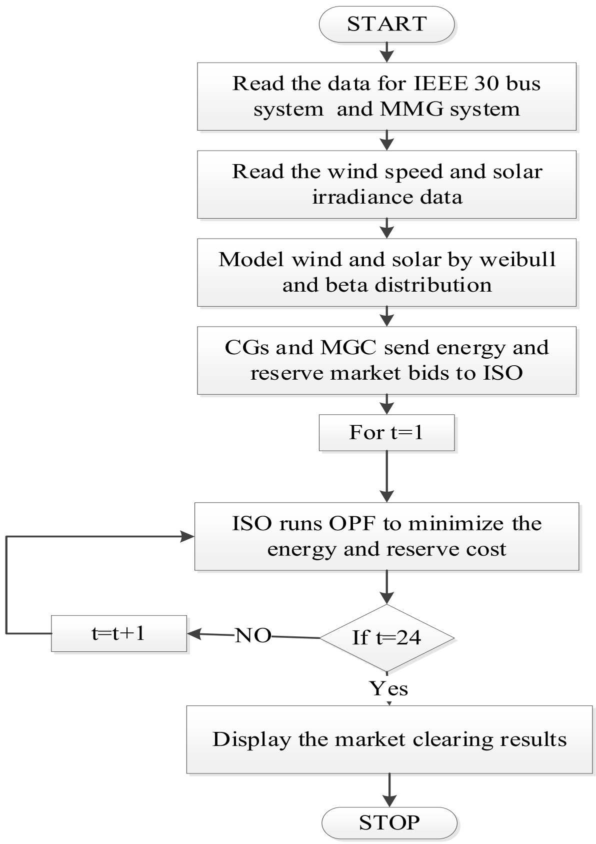

Figure 2. Flowchart of the proposed approach

$$\min TC=\sum_{h=1}^{24}\left(\sum_{i=1}^{N_G}\{CE_i(P_i)+CR_i(R_i)\}+\sum_{j=1}^{N_{MMG}}\{CE_j(P_j)+CR_j(R_j)\}\right) \quad (1)$$

The above objective is subjected to equality and inequality constraints. The equality constraints are binding constraints, whereas inequality constraints may or may not be binding. Here, P_i and R_i are the generations of the i^{th} unit of the main grid in the energy and reserve market, respectively. However, P_j and R_j are the generation of the j^{th} unit of MMG in energy and reserve market, respectively. RR_i is the ramp rate of the i^{th} conventional generator (CG) at the main grid, h is the number of hours, and N_G and N_{MMG} represent the number of generators in the grid and MMG, respectively. Here, $(P_{i,max}-P_i)$ represents the maximum reserve available for CG.

$$\sum P_{G,k} = P_{loss} + P_{D,k} \tag{2}$$

$$\sum Q_{G,k} = Q_{D,k} + Q_{loss} \tag{3}$$

$$P_i + R_i \le P_i \max \tag{4}$$

$$R_i = \min\{(P_{i,max} - P_i), RR_i\} \tag{5}$$

$$P_j + R_j \le P_j \max \tag{6}$$

$$P_{jmin} \le P_j \le P_{jmax} \tag{7}$$

$$P_{imin} \le P_i \le P_{imax} \tag{8}$$

$$P_{ij} \le P_{ijmax} \tag{9}$$

$$V_{imin} \le V_i \le V_{imax} \tag{10}$$

2.2. Uncertainty modeling of RES

2.2.1. Wind speed modeling

The power output of a Wind Turbine Generator (WTG) depends on the wind speed [41]. As the wind speed increases, the power output of the wind energy increases approximately as the cube of the wind speed is shown in Eq. 11 as follows:

$$P_w = \frac{1}{2} \times \rho \times A \times v^3 \tag{11}$$

where Pw is the power generated from WTG, ρ the density of air in kg m^{-3}, A the area of blades in m^2, and ν the wind speed in m s^{-1}. Thus, the power generated from WTG is defined as in Eq. 12.

$$P_{WT} = \begin{cases} 0, v < v_{in}, v > v_{out} \\ P_r \times \dfrac{(v - v_{in})}{v_r - v_{in}}, v_{in} < v < v_r \\ P_r, v_r < v < v_{out} \end{cases} \tag{12}$$

Wind speed is variable and follows a Weibull PDF shown in Eq. 13 [42]:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{\left\{-\left(\frac{v}{c}\right)^k\right\}} \tag{13}$$

For Rayleigh PDF, the value of k is 2. This is the preferred PDF as it has periods of both low and high wind speeds. Hourly mean wind speed and standard deviation of wind are used as the input data to create the pdf for wind speed.

2.2.2. Solar PV modeling

The generated power of the PV module is determined by the site's ambient temperature, solar irradiation, and module features. The beta distribution is used to model the solar irradiations. The solar irradiation follows the bimodal distribution, which is, combination of two unimodal distributions [43].

$$f_{pv}(ir) = \begin{cases} \left(\dfrac{\Gamma(\alpha+\beta)}{\Gamma(\beta)\Gamma(\beta)} \times ir^{\alpha-1} * (1-ir)^{(\beta-1)}, \text{ for } 0 \le ir \le 1, \alpha \ge 0, \beta \ge 0\right. \\ 0, \text{otherwise} \end{cases} \tag{14}$$

The values of alpha and beta can be calculated using Eq. 15:

$$\beta = (1-\mu) \times \left(\frac{\mu \times (1+\mu)}{\sigma^2} - 1\right)$$
$$\alpha = \frac{\mu \times \beta}{1-\mu} \tag{15}$$

From the generated PDF, the output power of the solar is modeled, as shown in Eq. 16 to Eq. 20.

$$P_{pv}(h) = N \times FF \times V(h) \times I(h) \tag{16}$$

$$FF = \frac{V_{MPP} \times I_{MPP}}{V_{oc} \times I_{sc}} \tag{17}$$

$$V(h) = V_{oc} - k_v \times T_c \tag{18}$$

$$I(h) = S_a \times [I_{sc} + k_i(T_c - 25)] \tag{19}$$

$$T_c = T_a + S_a \times \left(\frac{N_{OT} - 20}{0.8}\right) \tag{20}$$

3. RESULTS AND DISCUSSION

In this study, IEEE 30 bus system is considered as the main grid, whereas the 16 bus test system is taken as the MMG system. The IEEE 30 bus system is composed of 6 generators, 41 transmission lines, and 21 loads [44, 45]. The MMG system is comprised of MG1, MG2, and MG3. The MG1 contains 1 wind turbine (WT), 1 micro turbine, 1 photovoltaic (PV), and 1 fuel cell and 5 loads. The MG2 is composed of 1 diesel generator, 1 PV, 1 WT, and 1 load. The MG3 has 2 WT, 1 PV, 1 CHP, and 7 loads. The MMG system data is taken from [46]. Figure 3 shows the system under study, and Figure 4 shows the architecture of the main grid. The data of solar irradiation and wind speed is taken from [47, 48]. The wind and solar power available for a day is shown in Figure 5 and Figure 6, respectively. The load data of MMG shown in Figure 7 is taken from [49] and scaled for the considered test system. The load data for the main grid in the energy market and reserve market are shown in Figure 8, which were taken from [50], and normalized according to the system data. The demand of the reserve market is taken as 10 % of the demand in EM. Table 1 and Table 2 show the generator data and its cost coefficients for the main grid and MMG. The ramp rate is measured at almost 10 % of the maximum power.

Table 1. Generator data in the main grid

No.	Pmax (MW)	Energy price			Reserve price ($ MW^{-1})	RR
		α	β	γ		
G1	200	0.00375	2	0	2.25	15
G2	80	0.0175	1.75	0	2	8
G3	50	0.0625	1	0	1.5	5
G4	35	0.00834	3.25	0	3.5	3
G5	30	0.025	3	0	3.25	3
G6	40	0.025	3	0	3.35	4

Table 2. Dispatchable and non-dispatchable units in MMG

No.	Gen	Pmax (MW)	Energy price ($ MW^{-1})	Reserve price ($ MW^{-1})
MG1	WT1	2	1.5	1.5
	PV1	1	1.5	1.5
	FC	1	2	2.25
	MT	1.5	2.25	2.5
MG2	PV2	1.2	1.5	1.5
	DG	0.8	2.5	2.75
	WT2	1	1.5	1.5
MG3	WT3	1	1.5	1.5
	PV3	1.1	1.5	1.5
	CHP	0.4	2	2.25
	WT4	1	1.5	1.5

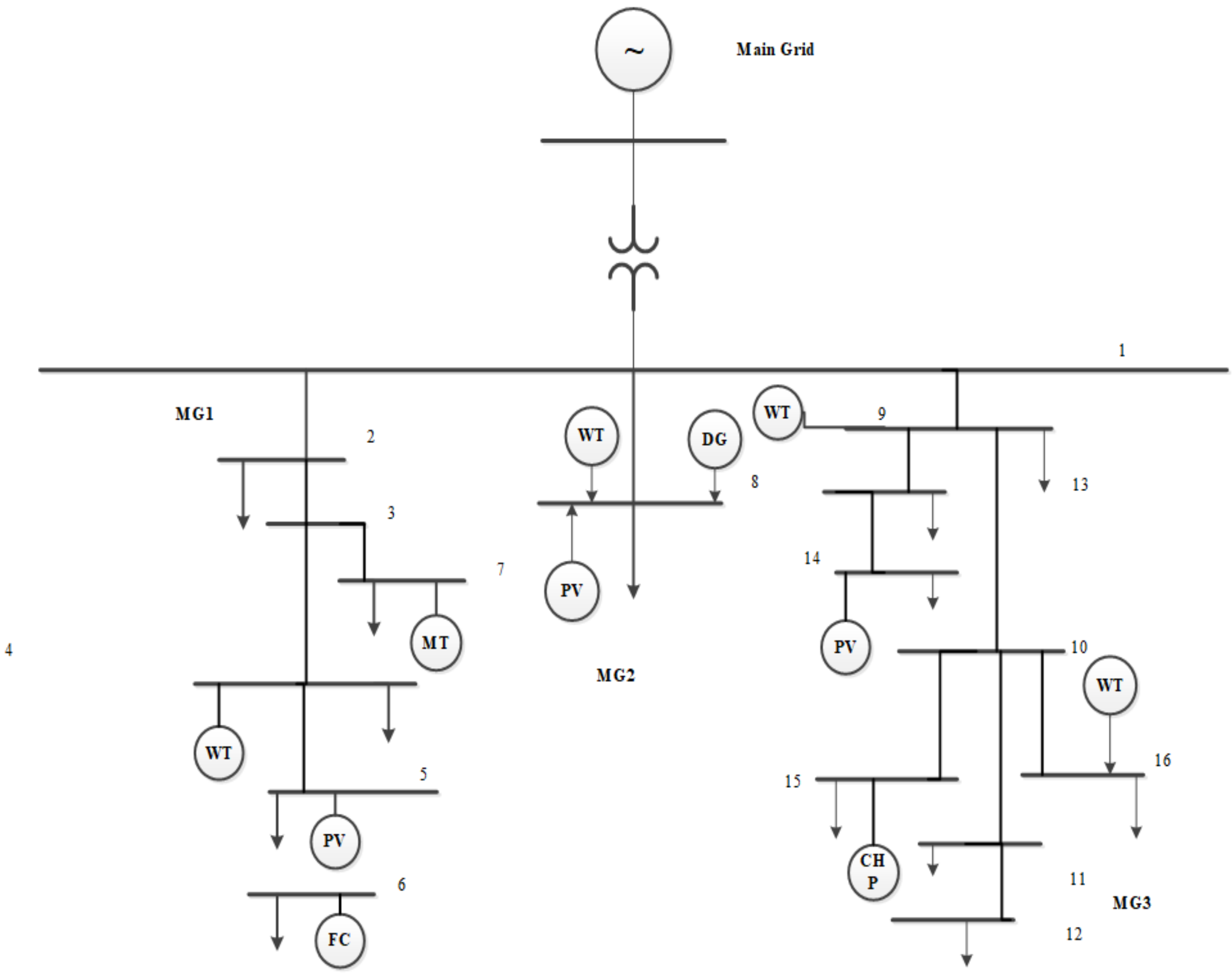

Figure 3. Test system

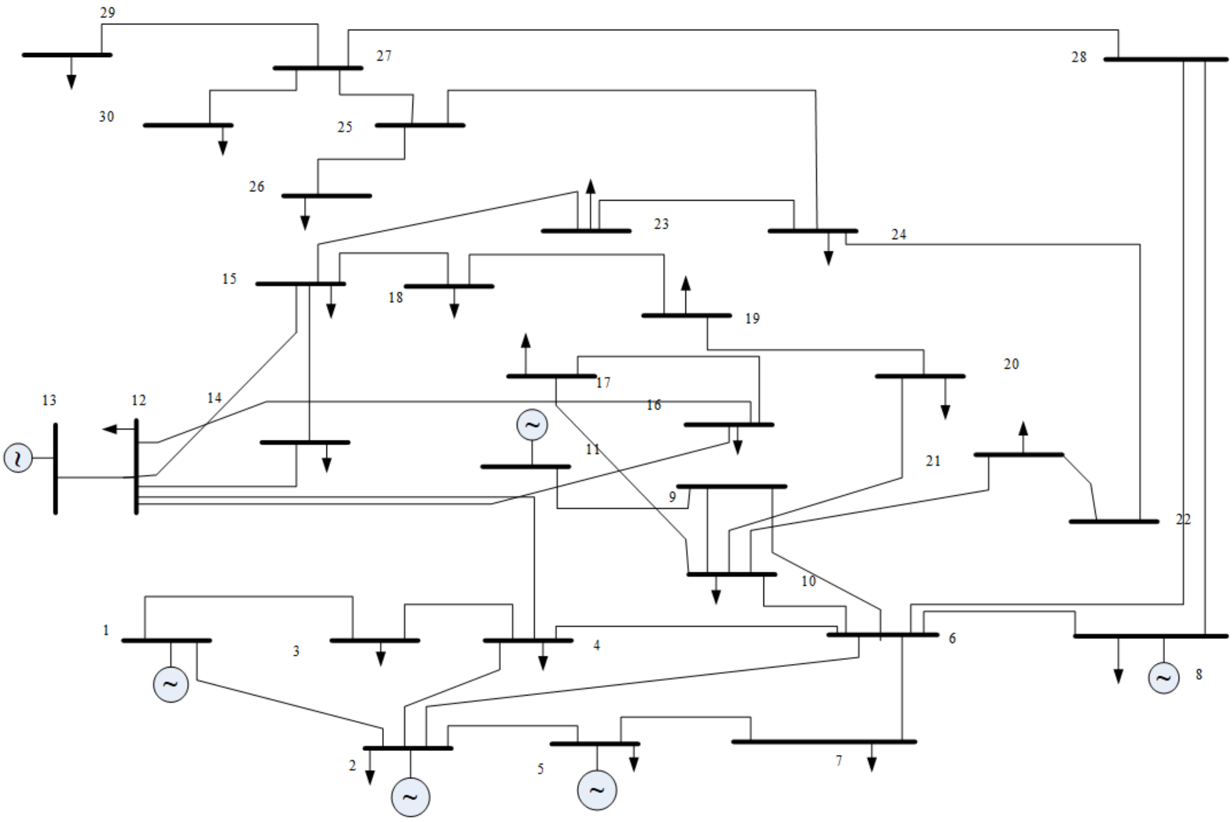

Figure 4. Main Grid (IEEE 30 bus system)

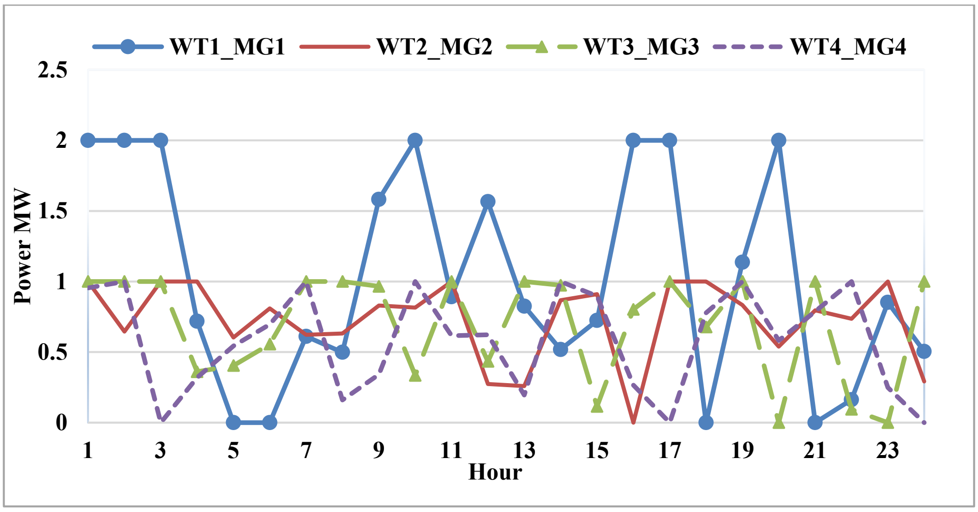

Figure 5. Available wind power in MMG

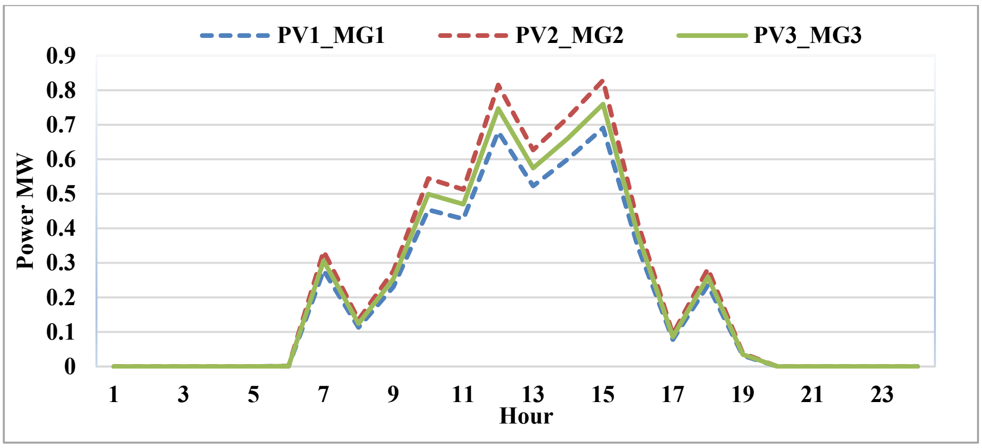

Figure 6. Available solar power in MMG

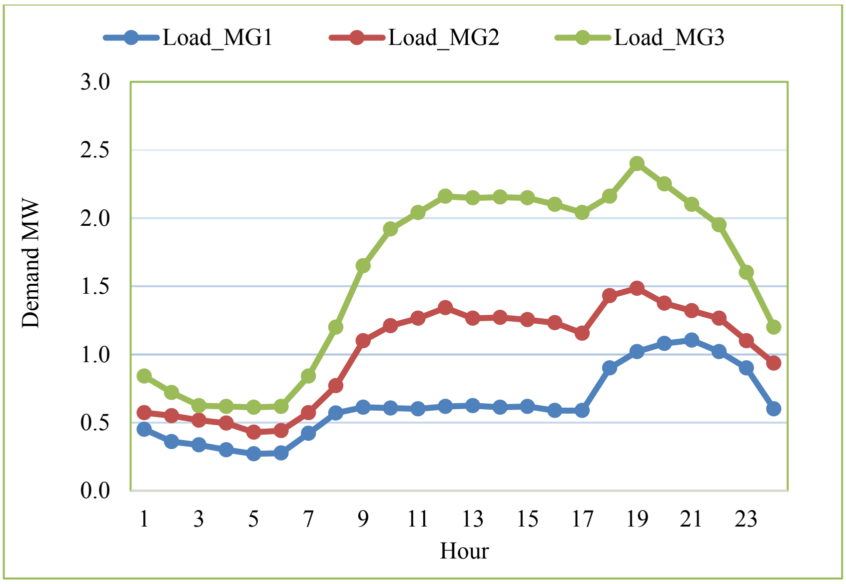

Figure 7. Load data of MMG

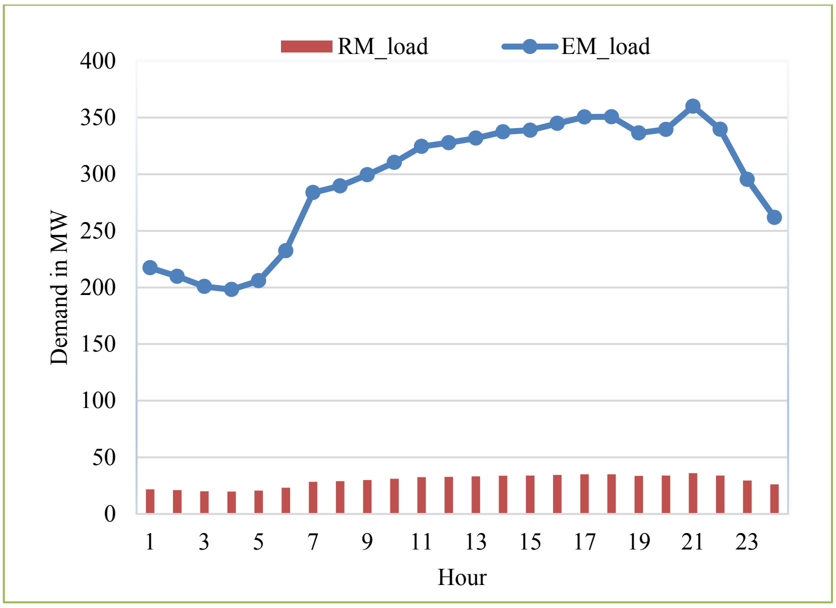

Figure 8. Load demand in EM and RM

The study is divided into three cases. The contingency analysis is also performed for all three cases. The considered contingencies are as follows: conventional generator No. 5 (G5) is out of service, line 3 outage, line 6 outage, and line 8 outage of the main grid (IEEE 30 bus system).

Case 1: When CGs in the main grid participate in EM and ASM.

Case 2: CGs will engage in EM and RM, whereas MMG will participate in EM.

Case 3: When MMG and the main grid both will engage in EM and ASM.

Case 1: When CGs in the main grid participate in EM and ASM

In this case, only CGs will engage in EM and RM. The ramp rate of CGs is taken as almost 10 % of the maximum power of the generator. The maximum reserve of each generator is taken as the maximum capacity minus the power generated at peak load. The CGs will bid energy at a higher price in RM than EM to gain maximum profit in the reserve market. They send their bid of energy and price for both of the markets to the ISO. The ISO will perform simultaneous optimization for both markets according to the bids received from the CGs. The reserve capacity available by each CG is equal to the minimum of maximum reserve bid by the generator and its 10 mins ramp rate. The power generated by generators in EM and RM should always be less than or equal to the maximum power available. The energy dispatched by CGs in the energy and reserve market is shown in Figure 9 and Figure 10, respectively. The hourly generation cost is EM and RM in Case 1 (no outage) is shown in Figure 11. The total cost including energy and reserve for a day is 22118.92 \$ day^{-1}. The total reserve cost and power loss are 1540.299 \$ day^{-1} and 233.3481 MW, respectively. The payment total load is 27534.04 \$ day^{-1}. The Table 3 shows the comparative analysis between Case 1 (no outage case) and different contingency conditions. When compared with Case 1 (no outage), the % increment rates in the generation cost, reserve cost, and power loss in Case 1 with gen outage are 1.43 %, 0.47 %, and 5.04 %, respectively. Similarly, due to the outage of Line 3 of the main grid (the line connecting Buses 2 and 4), The % increment rates in the generation cost and power loss are 0.26 % and 6.01 %. The outage of Line 6 of the main grid (connecting bus 2 and 6) increases the generation cost and power loss by 0.46 % and 10.79 %, respectively. The outage of Line 8 (connecting buses 5 and 7) will increase the generation cost and power loss by 0.019 % and 0.44 %, respectively. From the results, it can be concluded that the outage of the generator has a significant effect on the total generation cost, reserve cost, and active power loss of the system. However, the line outage is not affecting the reserve cost, but has a significant effect on the generation cost and power loss. The reserve cost is the same in all the cases because only three CGs (G1, G2, and G3) are participating in supplying the demand in the reserve market and these line outages are not affecting their generation in each hour.

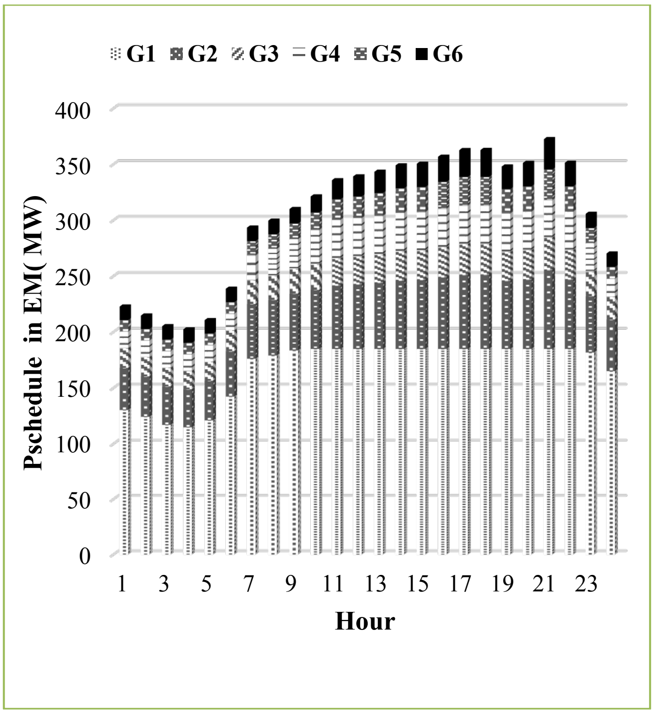

Figure 9. Power scheduled in the energy market in day-ahead market in Case 1 (no outage)

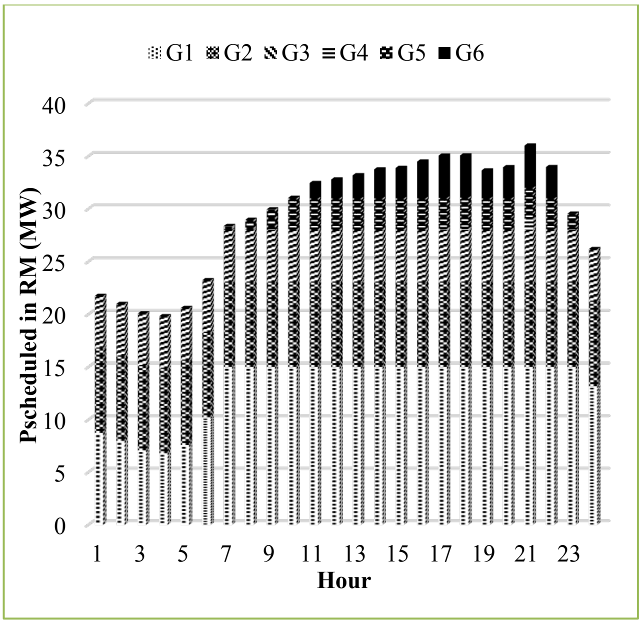

Figure 10. Power scheduled in reserve market in day-ahead market in Case 1 (no outage)

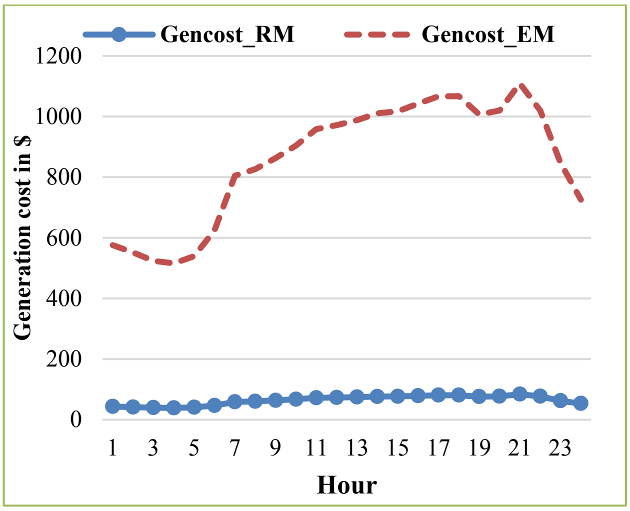

Figure 11. Hourly generation cost in EM and RM market in Case 1 (no outage)

Table 3. Comparative analysis between Case 1 (no outage) and different contingency conditions

Case 1	Generation cost ($ day^{-1})	Reserve cost ($ day^{-1})	Power loss (MW day^{-1})	% increment in gen cost	% increment in reserve cost	% increment in power loss
No outage	22118.92	1540.29	233.35	-	-	-
Gen5 out	22435.68	1547.55	245.11	1.43	0.47	5.04
Line 3 out	22176.43	1540.29	247.37	0.26	0	6.01
Line 6 out	22222.54	1540.3	258.54	0.46	0	10.79
Line 8 out	22123.23	1540.29	234.39	0.019	0	0.44

Case 2: When CGs will engage in EM and RM, MMG will participate in EM

In this case, the MMG will participate in the energy market, but the CGs will engage in both markets. The presence of MMG in EM will affect the dispatch of CGs in EM, whereas the reserve market will be the same as in Case 1. In this case, the RES available in MMG will dispatch to its full limit in energy market. This will reduce the energy cost in EM, because the RES is the cheaper source than the CGs. Maximum energy transferred from MMG to the main grid is 6 MW. The power schedule by MMG in EM, load, and power transfer from MMG to the main grid is shown in Figure 12. From the Figure 12, it is observed that the MMG will first satisfy its load and then, transfer the surplus power to the main grid. The comparative analysis between Case 2 (no outage) and its contingency cases is shown in Table 4. When compared with Case 2 (no outage), the % increments in the generation cost, reserve cost, and power loss in Case 2 with generator outage are 1.36 %, 0.40 %, and 5.16 %, respectively. Similarly, due to the outage of Line 3 of the main grid (a line connecting Buses 2 and 4), the % increment rate in the generation cost and power loss are 0.25 % and 5.88 %. The outage of Line 6 of the main grid (connecting Buses 2 and 6) increases the generation cost and power loss by 0.45 % and 10.47 %, respectively. The outage of Line 8 (connecting Buses 5 and 7) will increase the generation cost and power loss by 0.023 % and 0.55 %, respectively. The outage of Line 8 is having the least impact on the generation cost and the power loss. The Table 5 shows the power dispatch from various sources in MMG in the energy market. In this case, it is also observed that the RES is fully utilized in EM. The power scheduled by CGs in EM is reduced mainly in the valley period, i.e., from hour 1 to hour 10 and shown in Figure 13. In Case 2 (no outage), the total energy cost is 22096.71 \$ day^{-1} and the reserve cost will be the same as in Case 1. The power loss and load payments are 230.593 MW day^{-1} and 27522.61 \$ day^{-1}, respectively.

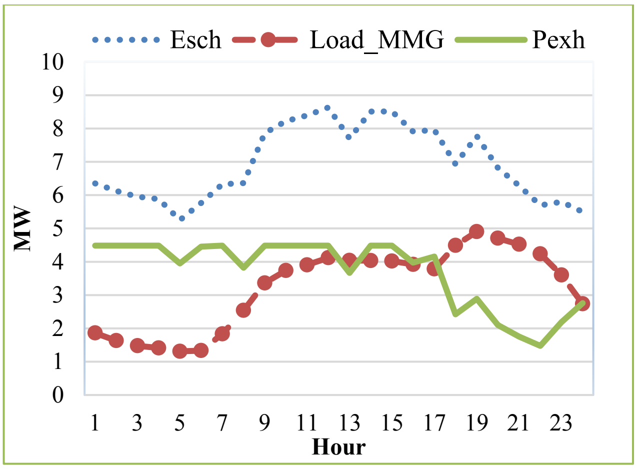

Figure 12. Energy scheduled, load, and Pexh in MMG

Table 4. Comparative analysis between Case 2 (no outage) and different contingency conditions

Case 2	Generation cost (\$ day^{-1})	Reserve cost (\$ day^{-1})	Power loss (MW day^{-1})	% increment in gen cost	% increment in reserve cost	% increment in power loss
No outage	22096.71	1540.29	230.59	-	-	-
Gen5 out	22396.13	1546.49	242.48	1.36	0.40	5.16
Line 3 out	22151.79	1540.29	244.16	0.25	0	5.88
Line 6 out	22195.44	1540.29	254.74	0.45	0	10.47
Line 8 out	22101.81	1540.30	231.85	0.023	0	0.55

Table 5. Power dispatch (MW) in MMG

No.	WT1 MG1	PV1 MG1	FC MG1	MT MG1	PV2 MG2	DG MG2	WT MG2	WT1 MG3	PV3 MG3	CHP MG3	WT2 MG3
1	2.00	0.00	1.00	0.00	0.00	0.00	1.00	1.00	0.00	0.40	0.95
2	2.00	0.00	1.00	0.08	0.00	0.00	0.64	1.00	0.00	0.40	1.00
3	2.00	0.00	1.00	0.55	0.00	0.00	1.00	1.00	0.00	0.40	0.00
4	0.72	0.00	1.00	1.50	0.00	0.58	1.00	0.36	0.00	0.40	0.32
5	0.00	0.00	1.00	1.50	0.00	0.80	0.60	0.40	0.00	0.40	0.54
6	0.00	0.00	1.00	1.50	0.00	0.80	0.81	0.56	0.00	0.40	0.70
7	0.61	0.28	1.00	0.78	0.33	0.00	0.62	1.00	0.31	0.40	1.00
8	0.50	0.11	1.00	1.50	0.14	0.80	0.63	1.00	0.12	0.40	0.16
9	1.58	0.23	1.00	1.50	0.28	0.48	0.83	0.97	0.25	0.40	0.34
10	2.00	0.45	1.00	1.17	0.54	0.00	0.82	0.33	0.50	0.40	1.00
11	0.89	0.43	1.00	1.50	0.51	0.57	1.00	1.00	0.47	0.40	0.62
12	1.57	0.68	1.00	1.50	0.82	0.59	0.27	0.43	0.75	0.40	0.62
13	0.82	0.52	1.00	1.50	0.63	0.80	0.26	1.00	0.57	0.40	0.20
14	0.52	0.60	1.00	1.50	0.72	0.27	0.87	0.97	0.66	0.40	1.00
15	0.72	0.69	1.00	1.50	0.83	0.69	0.91	0.12	0.76	0.40	0.90
16	2.00	0.35	1.00	1.50	0.41	0.80	0.00	0.80	0.38	0.40	0.27
17	2.00	0.08	1.00	1.50	0.09	0.80	1.00	1.00	0.09	0.40	0.00
18	0.00	0.24	1.00	1.50	0.28	0.80	1.00	0.68	0.26	0.40	0.78
19	1.14	0.03	1.00	1.50	0.04	0.80	0.83	1.00	0.04	0.40	1.00
20	2.00	0.00	1.00	1.50	0.00	0.80	0.54	0.00	0.00	0.40	0.58
21	0.00	0.00	1.00	1.50	0.00	0.80	0.80	1.00	0.00	0.40	0.79
22	0.16	0.00	1.00	1.50	0.00	0.80	0.74	0.09	0.00	0.40	1.00
23	0.85	0.00	1.00	1.50	0.00	0.80	1.00	0.00	0.00	0.40	0.25
24	0.50	0.00	1.00	1.50	0.00	0.80	0.29	1.00	0.00	0.40	0.00

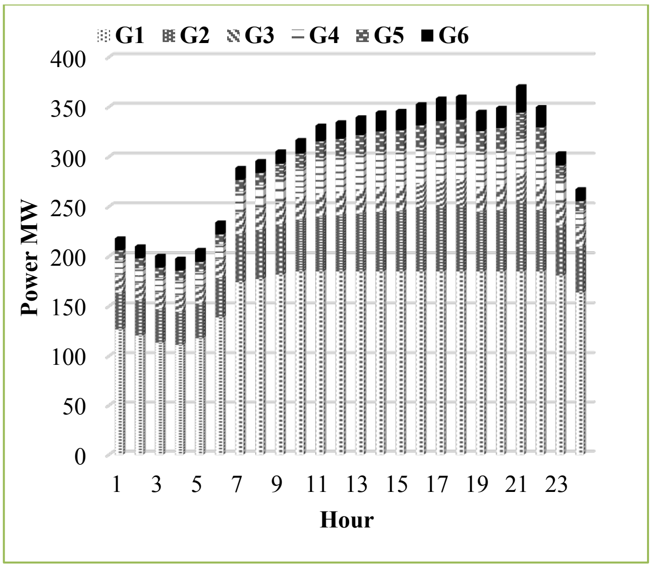

Figure 13. Power schedule by CGs in EM in Case 2 (no outage)

Case 3: When MMG and the main grid both will engage in EM and ASM

In this case, the conventional as well as the DGs in MMG will participate in both markets. This will affect the dispatch of CGs in the reserve market. As in the previous case, they are dispatched in RM though they have a higher cost. The maximum reserve of DGs in MMG is taken as 50 % of the installed capacity. The dispatch of DGs in RM is shown in Figure 14. From Figure 14, it is observed that all dispatchable DGs are either dispatched in EM or result from their high cost not dispatched in RM. The total energy cost and reserve cost in this case are 22094.30 \$ MW^{-1} and 1534.86 \$ MW^{-1}, respectively. The power loss and total load payment are 230.58 \$ MW^{-1} and 27542.5 \$ day^{-1}. The comparative analysis between Case 3 (no outage) and contingency cases is shown in Table 6. Compared to Case 3 (no outage), the percentage of increase in generating cost, reserve cost, and power loss is 1.27 %, 0.49 %, and 5.53 %, respectively, in Case 3 with generator outage. Similarly, owing to the outage of Line 3 of the main grid (the line linking Buses 2 and 4), the generation cost and power loss increased by 0.25 % and 5.89 %, respectively. The failure of Line 6 of the main grid (which connects Buses 2 and 6) increases the generating cost by 0.46 % and the power loss by 10.47 %. The loss of Line 8 (which connects Buses 5 and 7) will raise the cost of generation by 0.023 % and the power loss by 0.54 %. The summary of all the cases with no contingency is shown in Table 7. It is observed that in case of the generator outage (G5 out) in the main grid, the total generation cost increased significantly from 22118.92 \$ day^{-1} to 22435.68 \$ day^{-1} and the real power loss increased from 233.35 MW day^{-1} to 245.11 MW day^{-1}. However, due to the participation of MMG, generation cost and power loss are reduced to 22375.60 \$ day^{-1} and 243.35 MW day^{-1}, respectively. Similarly, if we consider the case of Line 3 outage, when only CGs of the main grid are contributing to EM and RM in Case 1, the generation cost and power losses are 22176.43 \$ day^{-1} and 247.377 MW day^{-1}, respectively. However, in case of the same contingency of Line 3 outage, if we take Case 3 when MMG is contributing to the EM and RM, generation cost and power loss are reduced to 22149.38 \$ day^{-1} and 244.165 MW day^{-1}, respectively. From the results, it can be concluded that the participation of MMG in EM and RM will not only bring about economic and technical benefits to the power system during normal conditions but also support the main grid during contingency conditions.

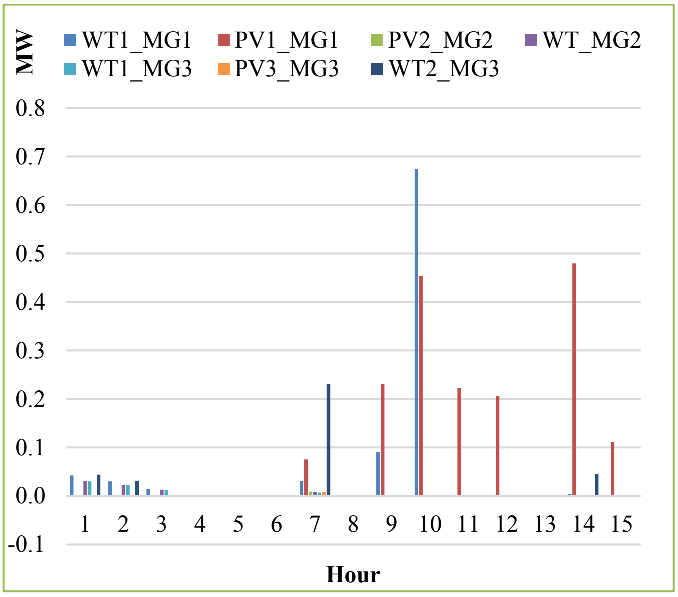

Figure 14. Dispatch of RES-based DG in MMG in the RM

Table 6. Comparative analysis between Case 3 (no outage) and different contingency conditions

Case3	Generation cost (\$ day^{-1})	Reserve cost (\$ day^{-1})	Power loss (MW day^{-1})	% increment in gen cost	% increment in reserve cost	% increment in power loss
No outage	22094.3	1534.86	230.58	-	-	-
Gen5 out	22375.61	1542.52	243.35	1.27	0.49	5.53
Line 3 out	22149.38	1534.86	244.17	0.25	0	5.89
Line 6 out	22193.02	1534.86	254.73	0.46	0	10.47
Line 8 out	22099.39	1534.86	231.83	0.023	0	0.54

Table 7. Comparison between base cases in case of no outage

No. outage cases	Total Gencost (\$ day^{-1})	Total reserve cost (\$ day^{-1})	Power loss MW day^{-1}	% reduction in Gencost	% reduction in Rcost	% reduction in Ploss
Case1	22118.92	1540.29	233.35	-	-	-
Case2	22096.71	1540.29	230.593	0.104	-	1.181
Case3	22094.3	1534.86	230.58	0.111	0.352	1.201

4. CONCLUSIONS

In this study, the energy management of multi-microgrids was performed in the joint energy and ancillary service market. The MMG was composed of dispatchable and non-dispatchable DGs and loads. The RES was considered as the consumers of ramping services due to its volatile nature. However, when they are strategically placed in integration with other sources, they can provide energy in both the energy market and ancillary services market. In this study, the MMG strategically contributed to both the energy and ancillary services market by effectively utilizing all its resources. In Case 1, when there were only CGs, the energy and reserve cost was high and power loss was also high. However, through the participation of MMG in the energy and reserve market, the total generation cost, reserve cost, and power loss were reduced to 0.11 %, 0.325 %, and 1.201 %, respectively. In this study, the system was subjected to N-1 contingency and it was observed that MMG would support the grid in not only normal operation but also contingency conditions. During contingency, the contribution of MMG to EM and RM would reduce the generation cost, reserve cost, and power loss as compared to the case when only CGs would be present in the system. This study can be further extended by the placement of energy storage for effectively utilizing the surplus RES available.

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NOMENCLATURE

TC	Total cost ($/MW)
$CE_i(P_i)$	Energy cost of ith CG of main grid ($/MW)
$CR_i(R_i)$	Reserve cost of i^{th} generator of main grid ($/MW)
P_i	Active power dispatch by i^{th} CG of main grid (MW)
R_i	Reserve power available with i^{th} CG (MW)
$CE_j(P_j)$	Energy cost of j^{th} generator of MMG ($/MW)
$CR_j(R_j)$	Reserve cost of j^{th} generator of MMG ($/MW)
P_j	Active power dispatch by j^{th} generator of MMG (MW)
R_j	Reserve power available j^{th} generator of MMG (MW)
i	Generator number in main grid
j	Generator number in MMG
N_G	Total number of CGs in main grid
N_{MMG}	Total number of generators in MMG
h	Hour (1 to 24)
RR_i	Ramp rate of i^{th} CG in main grid (MW/min)
V(h)	Voltage of PV cell at h hour (volts)
V_{OC}	Open circuit voltage
I_{SC}	Short circuit current
V_{MPP}	Voltage at maximum power point
P_{pv}	Power generated by PV module
α	Cost coefficient ($/MW^{2}h)
γ	Cost coefficient ($/MW)
$P_{i,max}$	Maximum power available with i^{th} generator
V_{min}	Minimum voltage
V_{max}	Maximum voltage
P_{WT}	Power generated by WTG (MW)
P_r	Rated wind power (MW)
v_i	Actual wind speed (m/sec)
S_a	Solar irradiation in (kW/m^2)
v_{in}	Cut-in wind speed (m/sec)
v_{out}	Cut-out velocity (m/sec)
k	Shape factor
c	Scale factor
σ	Standard deviation
μ	mean
N	Number of PV modules
FF	Fill factor
I(h)	Current of PV cell at h hour (amps)
I_{MPP}	Current at maximum power point
N_{OT}	Nominal operating temperature (°C)
T_a	Ambient temperature (°C)
T_c	Cell temperature (°C)
β	Cost coefficient ($/MWh)

Abbreviation

ASM	Ancillary Services Market
CHP	Combined Heat Power
DER	Distributed Energy Sources
DG	Distributed Generation
Disco	Distribution Company
Ecost	Energy Cost
EM	Energy Market
FC	Fuel Cell
Genco	Generating Company
Gencost	Generation Cost
GHG	Green House Gas
ISO	Independent System Operator
LC	Local Controller
LMP	Locational Marginal Price
MCP	Market Clearing Price
MGCC	Microgrid Central Controller
MMG	Multi-Microgrid
MMGEMS	Multi-Microgrid Energy Management System
MT	Micro-Turbine
PDF	Probability Distribution Function
Ploss	Power Loss
PV	Photo Voltaic
Rcost	Reserve Cost
RES	Renewable Energy Sources
RM	Reserve Market
WTG	Wind Turbine Generator

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