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Optimization of the Microgrid Scheduling with Considering Contingencies in an Uncertainty Environment

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Abstract

In this paper, a stochastic two-stage model is offered for optimization of the day-ahead scheduling of the microgrid. System uncertainties including dispatchable distributed generation and energy storage contingencies are considered in the stochastic model. For handling uncertainties, Monte Carlo simulation is employed for generation several scenarios and then a reduction method is used to decrease the number of scenarios. The scenarios are used in second stage of the stochastic model to check the system security. The amount of spinning reserve and energy are optimized in the first stage by minimizing the total cost of operation. A sample microgrid is used to compare the offered stochastic model with the deterministic one.

Keywords: DER uncertainty, Energy storage, Microgrid, Stochastic security constrained unit commitment.

Nomenclatures

Index

n	DDGs and the maingrid index.
t	Time index.
s	Scenario index.
N	Number of DDGs and maingrid.
T	Horizon time.
S	Number of scenarios.

Binary variables

$y_{n,t}$ $(z_{n,t})$	Indicate ON (OFF) state of unit n at time t.
$u_{n,t}$	Indicate the state of committed unit n at time t.
$us_{n,t,s}$	Indicate availability of unit n at time t in scenario s.
$ues_{t,s}$	Indicate availability of energy storage at time t in scenario s.

Parameters

$p_n^{\max}$ $(p_n^{\min})$	Maximum (minimum) capacity of unit n.
R_n^{down} (R_n^{up})	Ramp-down (-up) rate of unit n.
$B_{n,t}$	Operation price of unit n & market price at time t.
SU_n (SD_n)	Start up (Shut down) cost of unit n (DDGs).
$c\pi_{n,t}^U$ $(c\pi_{n,t}^D)$	Capacity cost of up- (down-) spinning reserve of unit n at time t
$e\pi_{n,t}^U$ $(e\pi_{n,t}^D)$	Energy cost of up- (down-) spinning reserve of unit n at time t.
$E_{\min}$ $(E_{\max})$	Minimum (maximum) energy capacity of storage.
$P_{disch,\max}$ $(P_{disch,\min})$	Maximum (minimum) power discharge capacity for storage.
$P_{ch,\max}$ $(P_{ch,\min})$	Maximum (minimum) power charge capacity for storage.
$P_{load,t}$	Forecasted load at time t.
$P_{PV,t}$	Forecasted PV generation at time t.
$P_{WT,t}$	Forecasted WT generation at time t.
η	Efficiency of charge/discharge of storage.
$VOLL_t$	Value of loss of load at time t.
T_n^{on} (T_n^{off})	Minimum on (off) time unit n.

Variables

$P_{n,t}$	Scheduled generation of unit n at time t.
$SR_{n,t}^U$ $(SR_{n,t}^D)$	Up- (down-) spinning reserve of unit n at time t.

E_t	Stored energy in storage at time t .
$P_{ch,t}$ ($P_{disch,t}$)	Power charged (discharged) at time t in storage.
$X_{n,t}^{on}$ ($X_{n,t}^{off}$)	Duration of on (off) time unit n at time t .
$sr_{n,t,s}^{U}$ ($sr_{n,t,s}^{D}$)	Deployed up- (down-) spinning reserve of unit n at time t in scenario s .
$LC_{t,s}$	Forced curtailed load at time t in scenario s .
$\Pr_{t,s}$	Probability of scenario s at time t .

1. Introduction

The microgrid paradigm is a proper solution to address technical, environmental, economical issues of power systems. In fact, suitable operation of microgrid could cause reducing the system losses and emission, minimizing the production costs, balancing the demand and supply, decreasing the effects of critical contingencies and increasing reliability of electricity supply to end users [1].

Microgrids are small-scale, low voltage distribution networks consist of variety of Distributed Energy Resources (DERs) like microturbine and fuel cell (as dispatchable distributed generator (DDG)), Photovoltaic (PV) cell and Wind turbine (as renewable energy sources (RES)) beside energy storage and different forms of end users. The maingrid or upstream network, based on market prices, can be operated either as a DDG or a load. The microgrid can be operated in two modes: connected mode and isolated mode. In the connected mode, the microgrid, through a substation transformer, is connected to the maingrid and can trade the energy with the maingird. However, the microgrid can be operated as an autonomous entity in the islanded mode when a fault or a power quality problem in the external grid is occurred. This performance requires suitable control facilities and communication systems; thus, microgrids have some control equipments including: Microgenerator Controller (MC) which controls active and reactive power of distributed generations (DGs), Load controller (LC) which controls loads by shedding when necessary and Central Controller (CC) which determines proper set-point of LC and MC for economic and safe operation [2]. There are two approaches for the microgrid operation: Decentralized control and centralized control [3]. In decentralized control, system is divided to some control levels which have a certain level of autonomy to make own decision with defined goals. However, control levels communicate with each other to achieve optimal operation [4,5]. On the other hand, in centralized control, CC makes final decision for optimal operation of the microgrid with coordination of other controllers i.e. MC and LC. For this, CC needs some information like: power production cost and reserve capacity cost of each DG, market price, value of loss of load, security constraints and weather forecast and etc. [3,6]. In reference [6], with centralized control approach, microgrid operation is optimized in two policies, first minimizing the cost and second maximizing the profit. It is resulted in [7] that, the less the power losses that use of dump loads brings, the less the microgrid power generation is required, so on the cost of operation decreased. Reference [8] considered environment constraint by minimizing some emissions. There are some stochastic variables in the microgrid.

A detailed security studies in the microgrid by assessing the impact of contingencies are required [1]. With some changes, stochastic security-constrained unit commitment (SCUC) in the power system can be considered in the microgrid scheduling. In [9,10], some reliability criteria such as loss-of-load probability (LOLP) and expected load not served (ELNS) is used for stochastic SCUC in the power system. In literature [11] as same used probabilistic reliability criteria with the difference that loads interruption time is calculated in a novel approach to obtain the index of expected energy not supplied (EENS). However, in some studies, outage events are defined as some credible and expected contingencies such as [12], in some others, random disturbances are modeled as scenario trees using Monte Carlo Simulation (MCS) such as[13,14]. Each scenario has a probability which determines weight of each contingency in the scheduling, in spite of deterministic SCUC which possible disturbances are considered a determined one that leads to extra costs to provide unnecessary preventive and corrective actions. [15] is from a few studies that is presented the microgrid scheduling as stochastic SCUC. Authors use single-stage stochastic model for unit commitment while two-stage model as shown in [16] is more accurate, because the optimal allocation of generation and reserve for units are defined in first stage with regard to analyzing contingencies in the second stage. In this paper, a day-ahead scheduling of the microgrid by the centralized control approach is performed. For security assessment, system uncertainties (i.e. outage of DDGs and energy storage (ES)) are considered in a two-stage stochastic model. In this framework MCS is used for adaptive scenario generation to model the stochastic behavior of units based on forced outage rate (FOR). Finally, results of this stochastic SCUC are compared to deterministic one. The rest of this paper is organized as follow: In section 2, deterministic model for generation of RESs and ES beside deterministic SCUC for the microgrid is presented. In section 3, stochastic optimization of microgrid is described. Scenario generation and reduction beside two-stage optimization model are presented. The model is simulated in a sample microgrid in section 4 and numerical results are revealed and finally in section 5 conclusion of this study is presented.

2. Deterministic model for microgrid operation

In this section, first, the forecasted generation of RESs and ES are modeled then the deterministic SCUC for short-term scheduling of a microgrid is formulated

2.1. Generation of PV Cell

PVs consist of several cells that convert solar irradiance energy to electrical energy. Power generation of PV depends on some factors; for instance, the number of cells, the direction of cells, the weather condition including cloudy or sunny and the temperature. Power generation of PV is calculated as follow [17]:

$$P_s = N.FF.V_y.I_y$$
$$FF = \frac{V_{MPP}.I_{MPP}}{V_{oc}.I_{sc}}$$
$$V_y = V_{oc} - k_v.T_c \quad (1)$$
$$I_y = s.\left[I_{sc} + k_c(T_c - 25)\right]$$
$$T_c = T_a + s.\frac{T_N - 20}{0.8}$$

Where V_{MPP}, I_{MPP} are voltage and current at maximum power point and V_{oc}, I_{sc} are open circuit voltage and short circuit current in V, A. T_c, T_a, T_N are the cell temperature, the ambient temperature and nominal operating temperature in $^{\circ}C$. k_v is voltage temperature coefficient in $V/^{\circ}C$ and k_c is current temperature coefficient in $A/^{\circ}C$. N is the number of cells, P_s is the generation of the PV and FF is the fill factor.

3. Generation of Wind Turbine

Wind turbines are used to convert the wind energy to electrical energy. For computation of WT power generation from the wind speed, a linear equation is considered [18].

$$p_w = \begin{cases} 0 & v < v_{ci} \cup v_{co} \le v \\ P_r.\frac{(v - v_{ci})}{(v_r - v_{ci})} & v_{ci} \le v \le v_r \\ P_r & v_r \le v \le v_{co} \end{cases} \quad (2)$$

Where v_{ci}, v_{co}, v_r and P_r are cut-in, cut-out, rated wind speeds and rated power output of WT, respectively. It means that when the wind speed is more than cut-out wind speed of the WT, no power is generated. On the other hand, when the wind speed is between cut-out and rated wind speeds, the highest power of WT is achieved. Power generation is linearly proportional to wind speed, when the wind speed is changed between cut-in and rated wind speed of WT.

4. Energy Storage Model

The ESs are electrochemical devices that store energy from other sources for later use. The power from ES is needed when the DGs and the maingrid are insufficient to supply the load or even the market price is high. On the other hand, the energy is stored when the supply from DGs exceeds the load demand or when the market price is low [8]. ES constraints are as follow:

$$0 \le P_{ch,t} \le P_{ch,\max}$$
$$0 \le P_{disch,t} \le P_{disch,\max} \quad (3)$$
$$E_{\min} \le E_t \le E_{\max} \quad (4)$$
$$E_t = E_{t-1} + \eta.P_{ch,t} - P_{disch,t} / \eta \quad (5)$$

Where (3) is limitation of discharged/charged power and (4) is energy capacity constraint and (5) is state of charge of energy storages. Also energy stored in the storage at the first and last hour of scheduling must be equal ($E_1 = E_T$) [19].

5. Deterministic SCUC of the Microgrid

In deterministic scheduling of the microgrid system uncertainties are not considered but presented set-points are considered for different reserve [20]. Also load shedding is considered. Therefore, the objective function and related constraints of deterministic framework are as follow:

$$\sum_{t=1}^{T} \begin{Bmatrix} \sum_{n=1}^{N} \left(P_{n,t} B_{n,t} + SU_n \times y_{n,t} + SD_n \times z_{n,t} \right) \\ + VOLL_t \times LC_t \end{Bmatrix} \quad (6)$$

$$p_n^{\min}.u_{n,t} \le p_{n,t} \le p_n^{\max}.u_{n,t} \quad (7)$$

$$\sum_{n=1}^{N} p_n^{\max}.u_{n,t} \ge p_{load,t} + R_t - LC_t \quad (8)$$

Reserve constraint is as (8) where R_t is amount of prespecified reserve. Capacity constraints of DDGs and the maingrid is in (7). Other constraints are similar to (13), (14), (15) and (16).

6. Stochastic Model of the Microgrid Operation

For keeping the power balance and procured the required reserves either in connected mode or isolated mode, uncertainties of the microgrid should be considered. The source of uncertainties includes some contingencies like DGs outage. Stochastic programming provides a tool for dealing with microgrid uncertainties to determine the reserve levels. In this paper DGs contingencies which usually are the most severe impact on the microgrid load not served are modeled in stochastic SCUC. For solving this stochastic model a two-stage stochastic method is proposed.

6.1. Random Outage Events

Generators and transmission lines have stochastic nature; therefore, their availability can be considered as an uncertain variable. Availability of components can be defined by failure rate which estimated with historical data. In the microgrid, feeder lines are less important; therefore, in this paper random outage of DDGs, the maingrid and ES are studied. For this purpose, by MCS based on FOR of DDGs, the maingrid and ES several scenarios at each hour are generated. The process of scenario generation for an hour is as follow:

1) Generate uniform random variable u for each scenario.

2) FOR of each unit n (DDGs and the main grid) which is $\frac{\lambda_n}{\lambda_n+\mu_n}$, is compared to generated uniform random variable. If FOR becomes greater than generated uniform random variable, the unit n is unavailable for scenario s at hour $t: us_{n,t,s}=0$, otherwise the unit n is available: $us_{n,t,s}=1$. As the same process is done for determination of the energy storage availability by generating binary variable $ues_{t,s}$.

3) Given the vector of uncertainties for scenario s at each hour t:

$X_{t,s}=[X_{us_{n,t,s}}, X_{ues_{t,s}}]$

Where $X_{us_{n,t,s}}$, $X_{ues_{t,s}}$ is binary variable of random outage events of unit n and the energy storage respectively.

4) Scenarios are reduced to a few scenarios with new probabilities for each t.

Working with a lot of scenarios is required to deal with large volume of computations; therefore, it is important to reduce scenarios with a good approximation. Reduction methods are based on keeping essential features of original scenarios according to probability distances [21]. There are two methods to reduce scenarios in SCENRED2/GAMS including backward method and forward method [22]. The size of stochastic program and required solution accuracy is considered to choose proper method.

6.2. Stochastic SCUC of the Microgrid

For considering the security issues of the microgrid in an uncertainty environment a stochastic two-stage optimization problem is formulated. This short-term stochastic SCUC schedules the unit's energy and spinning reserve simultaneously. Analyzing the generated scenarios is implemented in second stage to provide system security. Decision on unit's commitment state and their optimal generation and reserve thorough minimizing the total operation cost by mixed-integer linear programming (MILP) is made in the first stage. The two-stage model is formulated as follow:

$$Cost=\sum_{t=1}^{T}\Big\{\sum_{n=1}^{N}\Big(P_{n,t}B_{n,t}+SU_n\times y_{n,t}+SD_n\times z_{n,t} + c\pi^U_{n,t}SR^U_{n,t}+c\pi^D_{n,t}SR^D_{n,t}\Big) + \sum_{s=1}^{S}\Pr_{t,s}SC_{t,s}\Big\} \quad (9)$$

$$SC_{t,s}=\sum_{n=1}^{n}(e\pi^U_{n,t}sr^U_{n,t,s}+e\pi^D_{n,t}sr^D_{n,t,s}) + (VOLL_t\times LC_{t,s}) \quad (10)$$

Objective function is in equation (9). Total cost is sum of production cost of DDGs and trading cost with the maingrid, and also start up and shut down cost related to DDGs, procurement cost of up- and down-spinning reserve, and finally expected cost of providing the network security in different scenarios (10). Security cost in the microgrid is sum of spinning reserve procurement cost which provided by DDGs and the maingrid, also reserve procurement cost which provided by loads and forced load curtailment cost in each scenario s. Note that there are two kinds of reserve cost: capacity procurement cost related to deterministic scheduling (first stage) and energy procurement cost related to stochastic scheduling (second stage). The constraints are as follow:

$$\sum_n P_{n,t}+P_{disch,t}-P_{ch,t}+P_{PV,t}+P_{WT.t}=P_{load,t} \quad (11)$$

$$p_n^{\min}.u_{n,t}+SR^D_{n,t}\le p_{n,t}\le p_n^{\max}.u_{n,t}-SR^U_{n,t} \quad (12)$$

$$u_{n,t}-u_{n,t-1}=y_{n,t}-z_{n,t} \qquad y_{n,t}+z_{n,t}\le 1 \quad (13)$$

$$P_{n,t}-P_{n,t-1}\le R_n^{down} \qquad P_{n,t-1}-P_{n,t}\le R_n^{up} \quad (14)$$

$$0\le SR^U_{n,t}\le R_n^{up} \qquad 0\le SR^D_{n,t}\le R_n^{down} \quad (15)$$

$$(X^{on}_{n,t-1}-T^{on}_n).(u_{n,t-1}-u_{n,t})\ge 0 \qquad (X^{off}_{n,t-1}-T^{off}_n).(u_{n,t}-u_{n,t-1})\ge 0 \quad (16)$$

(17)

$$0\le sr^U_{n,t,s}\le us_{n,t,s}.SR^U_{n,t} \qquad 0\le sr^D_{n,t,s}\le us_{n,t,s}.SR^D_{n,t} \quad (18)$$

First stage constraints are as follow: balance between loads and inside generations of the microgrid and import/export power with the maingrid is shown in (11). Upper and lower bound of power of DDGs and the maingrid is in (12). (13) is start up/ shut down state of DDGs. Ramp up/down limitation of DDGs is in (14). Up/down reserve constraints of DDGs and the maingrid are in (15) and Minimum up/down time constraints are in (16). Also constrains of the second stage are (17) which related to balance between loads and inside generations of microgrid and import/export power with the maingrid in scenario s and (18) that is up/down reserve constraints of DDGs and the maingrid in scenario s.

7. Case Study: Obtained Results and Discussion

The microgrid in Fig. 1 is used to analyze the proposed model for operation in a short-term scheduling. The data of DDGs are presented in Table 1. The maingrid can import/export power until 500 KW to/from the microgrid. The microgrid would be operated in isolated mode with rate of 0.0091 f/hr which is failure rate of the main grid and mean time to return connected mode is 30 minutes.

Production cost of DDGs and market clearing price at each hour are given in Fig. 2. Operation cost of RESs and the energy storage are assumed negligible. Capacity and energy cost of Up- and down-spinning reserve are supposed, respectively, 30% and 100% of DDGs production cost and market clearing price.

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Energy capacity of the storage is 180 KWh. Power charge and discharge capacity of the storage is 150 KW with efficiency of 85% for both. Fault rate and repair time of the storage are 0.008 (f/hr) and 60 (min) respectively. Forecasted wind speed, solar irradiance and load demand at 12 hours are given in Fig. 3 and Fig. 4, respectively. Parameters of WT and PV used in this microgrid are presented in Table 2.

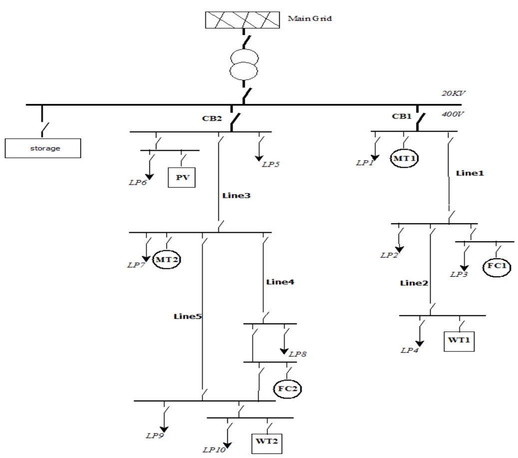

Fig.1.The sample microgrid

Table.1.
DDG data

Solar generator			
Open circuit Voltage (V)	21	Voltage temperature coefficient (V/°C)	0.088
Short circuit Current (A)	3.4	Current temperature coefficient (A/°C)	0.0015
Voltage at maximum power (V)	17.4	Nominal operating temperature(°C)	34
Current at maximum power (A)	3.05	Ambient temperature(°C)	25
Cell number	2		
Wind Turbine			
Cut-in speed (m/s)	3.5	Cut-out speed(m/s)	25
Rated wind speed (m/s)	12	Rated power (KW)	140

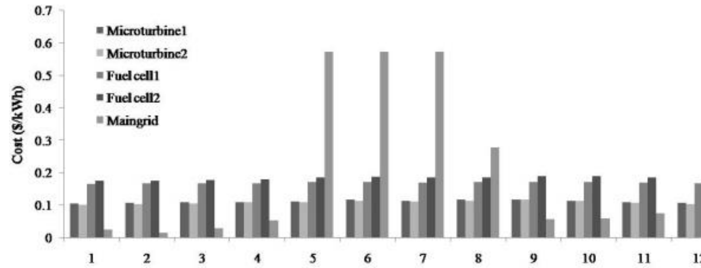

Fig.2.DDGs operation costs and Market-clearing price

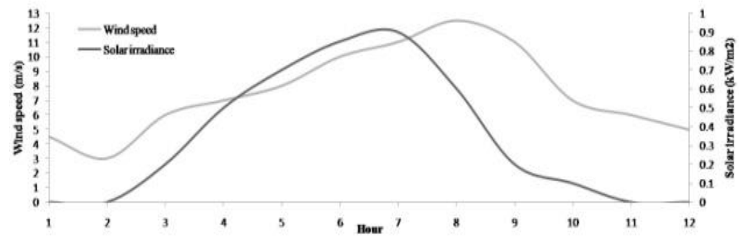

Fig.3.Forecasted wind speed and solar irradiance

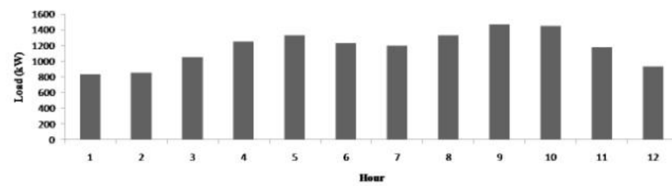

Fig.4.Forecasted load

Table.2.
WT & PV parameters

DG	Min. Power (KW)	Max. Power (KW)	Sup/Sdown cost ($/KWh)	Ramp up	Ramp down	λ(f/hr)	r (min)
MT 1	20	400	0.14	250	350	0.0085	45
MT 2	20	400	0.14	250	350	0.0085	45
FC 1	10	300	0.24	200	250	0.0075	45
FC 2	10	150	0.18	50	100	0.0075	45

Case 1

In the first case, 35% of forecasted hourly peak load assumed as deterministic reserve at each hour. Unit commitment result of first case is revealed in Table 3. As expected, at early and late hours when market price is low, maximum power is bought from the main grid. In contrast, at middle hours when the market price is high, inside productions are used for supplying loads and also selling to the main gird. Also the storage is charged at low market price times and discharged at high market price times. Therefore, the microgrid can be earned by trading off with the maingrid. However, enough reserves are determined at peak load hours of 9 and 10; forced load curtailment is occurred due to the determined reserves cannot be supplied by DGs.

Case 2

In case 2, stochastic SCUC is performed. uncertainties of DDGs, ES, and the maingrid are considered in order to it is generated Ten thousand scenarios with equal probabilities by MCS and Markov chain at each hour. Each scenario consists of a vector with 6 stochastic variables which all of them are binary and related to units' availability. Afterward, scenarios are reduced to 10 scenarios with new probabilities by SCENRED2 solver in GAMS. For declining the response time of the scenario reduction program, Forward reduction method is used. Consequently, Scenario reduction process lasts about 30 seconds for each hour, separately. The scheduling problem is solved in the microgrid optimization module by offered stochastic SCUC model in linear MIP under CPLEX. Unit commitment result is presented in Table 4. In comparison with case 1, the committed units are approximately similar at different hours. Because the main factor to make decision which unit should be committed is operation price of DDGs and market clearing price that is constant in both case 1 and case 2.

Table.3.
Scheduling results in case1

Hour	*MT1 (KW)*	*MT2 (KW)*	*FC1 (KW)*	*FC2 (KW)*	*Maingrid (KW)*	*ES (KW)*	*Curtailed load (KW)*
1	47.06	250	0	0	500	0	0
2	100	400	0	0	500	-150	0
3	20	400	0	50	500	-20.9	0
4	150	280.98	100	100	500	-40.9	0
5	400	400	300	150	-129.02	0	45.5
6	400	400	300	150	-456.42	150	0
7	400	400	300	150	-376.078	3	0
8	400	400	300	150	-252.81	0	45.5
9	211.76	400	50	50	500	-7.4	234.5
10	400	400	10	10	500	5.32	207.5
11	187.65	400	10	0	500	0	0
12	20	360.59	0	0	500	0	0

The difference of scheduled generation of DDGs and the maingrid in case 2 with respect to case 1 is due to considering stochastic nature availability of DDGs, ES and the maingrid through various scenarios in the second stage in order to calculate the optimum scheduling in the first stage.

Considering the stochastic nature of uncertain variables through scenarios has positive effects on scheduling of spinning reserve. According to Table 5, however the scheduled spinning reserve is less than deterministic reserve in the most scheduling hours, the scheduled level of reserve is more reliable for supplying loads. For example, according to Table 3, loads are curtailed 4 times in the horizon time especially in peak loads hours (i.e. hour 8 and 9), while in case 2 there is no forced load curtailment. As a result, in case 2 in comparison with case 1, due to scheduling of the optimal reserve level is performed according to the network security requirements along with limitation of units' capacity, not only generation and reserve of DDGs and also the maingrid are changed but also forced load curtailment is dropped. In fact, the decrease in forced load curtailment would be more; the decrease in total operation cost would be more; therefore, operation cost of the microgrid in case 2 according to Table 6 reduced.

8. Conclusion

In this paper, simultaneous scheduling of energy and reserve in microgrid is studied based on stochastic two-stage optimization model using MIP formulation. The stochastic nature of the microgrid including DDG and ES contingencies are considered to study security aspects of the microgrid. This paper has shown the economic benefits of the proposed stochastic model in compared with deterministic one. Therefore, it is resulted that stochastic approach can lead to a more efficient utilization of energy and reserve resources. This research work is under way in order to incorporate more stochastic variables of the microgrid including random outage and generation of RES as well as load uncertainty.

Table.4.
Scheduling result of case 2

Hour	*MT1 (KW)*	*MT2 (KW)*	*FC1 (KW)*	*FC2 (KW)*	*Maingrid (KW)*	*ES (KW)*
1	56.6	240.46	0	0	500	0
2	150	258.4	0	0	500	-58.4
3	150	299.1	0	0	500	0
4	191.2	400	100	50	498.91	-150
5	400	400	300	100	-229.019	150
6	400	379.58	300	150	-286	0
7	400	355.22	300	150	-328.869	0.569
8	400	340.19	300	114.3	-126.87	-30.4
9	163	400	100	100	447.1	-5.7
10	306.8	400	100	0	492.42	26.1
11	187.6	400	10	0	500	0
12	140.8	239.79	0	0	500	0

Table.5.
Scheduled up-spinning reserve in case 2 and comparison with case 1 reserve

Hour	*MT1 (KW)*	*MT2 (KW)*	*FC1 (KW)*	*FC2 (KW)*	*Maingrid (KW)*	Total Case2	Predefined case1
1	250	105.241	0	0	0	355.241	290.5
2	250	141.6	0	0	0	391.6	297.5
3	250	100.89	0	0	0	350.89	367.5
4	208.8	0	162	0	1.0886	371.88	437.5
5	0	0	0	50	266.519	316.51	465.5
6	0	20.417	0	0	395.5	415.91	430.5
7	0	44.777	0	0	259.2	303.97	420
8	0	59.807	0	35.7	410.6	506.10	465.5
9	237	0	200	50	52.8984	539.89	514.5
10	93.2	0	200	0	7.58019	300.78	507.5
11	128.8	0	199	0	0	328.45	413
12	250	151.21	0	0	0	401.21	325.5

Table.6.
Total cost of cases

	Case1	*Case2*
Operation Cost ($)	3417.2	1265.3

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