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Optimal Scheduling of Microgrids with Multi-Period Islanding Operation Considering Demand-Side Management

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Abstract—**This paper presents a scholastic model for energy management of smart microgrids with demand response (DR) considering demand and supply uncertainties. In this model, responsive loads are modeled by using price elasticity of demand concept and with the aim of minimizing the consumption cost of customers. In the proposed program, the operator tries to schedule energy resources optimally by considering islanding events of microgrids, that may occur due to upstream network disturbances. Therefore, in addition to uncertainties caused by load forecasting, renewable power generation and electricity prices, uncertainties caused by the prediction error of microgrid islanding events are also considered. The proposed approach is implemented using existing commercial software on a typical microgrid and the effects of DR programs on system operation via sensitive analyses. The results show that, when customers participate in DR programs, the amount of mandatory load shedding at islanding duration of microgrid reduces, and the expected profit of operator increases.**

Keywords—demand response (DR), islanding mode, microgrid, renewable energy resources (RESs), scholastic scheduling

NOMENCLATURE

Indices and sets

t, h, N_T	Time intervals.
s, N_S	Scenarios.
i, N_G	DGs.
j, N_J	Load groups.
w, N_W	Wind turbines.
v, N_V	Photovoltaic units.
n, r	Bus number.
$(.)_{:t,s}$	At time *t* in scenario *s*.
$(.)^{\min}, (.)^{\max}$	Minimum (Maximum) value of parameter (.)

Parameters and constants

$G^l, (B^l)$	Conductance (Susceptance) of line *l*.
$c_{1,i}, c_{2,i}$	Factors of operating cost function of DG unit *i*.
$D_{j,t}^{\text{int}}$	Initial values of demand of load *j* at time *t* and scenario *s* (kW).
$\rho_{j,t}^{\text{int}}$	Initial values of electricity price ($).
$D_{j,t,s}^{DR}$	Demand of load *j* after implementing DR programs (kW).
$\rho_{i,t}^{Up} (\rho_{i,t}^{Dn})$	Bid of up (down)-spinning reserve submitted by DG unit *i* at time *t* ($/kWh).
$\rho_{j,t}^{Up} (\rho_{j,t}^{Dn})$	Bid of up (down)-spinning reserve submitted by loads *j* at time *t* ($/kWh).
$\rho_{j,t,s}$	Energy price offered to customers ($/kWh).
$\rho_{w,t}$	Bid of energy submitted by owner of wind turbines *w* ($/kWh).
$\rho_{v,t}$	Bid of energy submitted by owner of solar unit *v* ($/kWh).
$\rho_{i,t}^{Non}$	Bid of non-spinning reserve submitted by DG unit *i* at time *t* ($/MWh).
$E_{t,t}^{j}$	Demand elasticity of customer *j*.
$VOLL$	Value of lost load ($/MWh).
π_s	Occurrence probability of normal scenario *s*.
λ_ω	Occurrence probability of islanding scenario ω .
$CSU_i, (CSD_i)$	Start-up (Shut-down) cost of DG unit *i* ($).

Variables

$P\,(Q)$	Active (reactive) power (kW).
$L_{j,t,s}^{shed} (Q_{j,t,s}^{shed})$	Active (reactive) power of load shedding of *j*th group of customers (kW).
$R_{i,t}^{Up} (R_{i,t}^{Dn})$	Reserve up/down service provided by DG unit *i* (kW).
$R_{j,t}^{Up} (R_{j,t}^{Dn})$	Reserve up/down service provided by customers in group *j* (kW).
$R_{i,t}^{Non}$	Non-spinning reserve provided by DG unit *i* (kW).
$r_{i,t,s}^{Up} (r_{i,t,s}^{Dn})$	Reserve up/down deployed by DG unit *i* (kWh).
$r_{j,t,s}^{Up} (r_{j,t,s}^{Dn})$	Reserve up/down deployed by customers *j* (kWh).
$r_{i,t,s}^{Non}$	Non-spinning employed by DG unit *i* (kWh).
$p_{t,s}^{shed} \; (q_{t,s}^{shed})$	Active (reactive) power of load shedding (kW).
$fl_{(n,r),t,s}^{P}$	Active power flowing between bus *n* and *r* (kW).
$fl_{(n,r),t,s}^{Q}$	Reactive power flowing between bus *n* and *r* (kVar).
$V_{n,t,s}, \; \delta_{n,t,s}$	Voltage magnitude (angle) at bus *n*.
$u_{i,t,s}$	Commitment status of DG unit *i,* {0, 1}.
$y_{i,t,s} (z_{i,t,s})$	Start-up (shut-down) indicator of DG *i,* {0, 1}.

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I. INTRODUCTION

Microgrids, as an important part of a smart grid, are highly regarded for providing local loads during upstream disturbances events [1], [2]. A microgrid usually consists of distributed generation resources (including scheduled several distributed generation (DG) and renewable energy resources (RESs)), responsive loads and energy storage systems (ESSs), which can operate in connected or islanded mode [3]-[5]. In the new smart structure, end-users are able to adjust their consumption by participating in demand response (DR) programs [6]. The problem of microgrid scheduling, especially in the presence of renewable resources and participation of end-users in DR programs was paid attention by many researchers [1], [2].

One of the main ability of microgrids is their islanding capability, that they are able to supply local loads without main grid. The islanding events of microgrids usually occur due to upstream network disturbances or faults [7], [8]. Practically, the occurrence time of islanding durations are completely uncertain and must be estimated using appropriate stochastic methods [9]. This, together with the uncertainties of RESs and random behavior of customers, makes the scheduling problem of microgrids more complex, especially when islanding events are considered.

In [10], an optimization model has been presented to include customer approval in energy scheduling programs. Moreover, in [11], a reliability-constrained problem was provided with DR actions. A stochastic scheduling model of smart distribution systems was suggested in [12]. In an islanded microgrid that is faced by uncertainties of both RESs and loads, the participation of responsive loads can play a significant role in its reliable operation. In [13], a model is presented for minimizing the load curtailment of microgrids. Both normal and islanded operations are modeled as mixed integer linear programming (MILP) problems.

In [14] and [15] two stochastic scheduling methods has been presented for energy management of microgrids, in which the optimal operation of microgrids in islanded modes have been addressed by considering active participation of customers in DR programs. However, in that works, the effects of load uncertainties on the results of the proposed programs have not been studied.

Authors in [16] have proposed methods with the aim of maximizing the economic benefits while DR participants have been considered. In those references, the impact of different DR programs on micro-network security along with economic indicators is investigated.

In addition, authors in [17] have proposed risk-based models for scheduling of autonomous microgrids considering DR actions.

In that work, although the uncertainties of renewable resources, loads and prices have been modeled based on a scenario-based method, the uncertainty of islanding duration of microgrid has not been considered. In [18], a stochastic framework is proposed to minimize load shedding in islanded mode followed by a disturbance event. Although, uncertainty of RESs and loads are considered in that study, the uncertainties of islanding duration are neglected.

This paper presents a stochastic framework for joint energy and reserve scheduling of microgrids considering DR actions and islanding duration uncertainties. The objective is to minimize the expected profit of the microgrid operator over the estimated islanding events. The impact of islanding events on the microgrid scheduling is investigated and different terms are compared in normal and emergency operation cases.

II. ENERGY MANAGEMENT STRATEGY

In the proposed energy management strategy, at first, the amount of RESs output power, load demand and islanding durations of microgrid are estimated and their uncertainties are obtained by using scenario-based approach, such as Monte Carlo simulation (MCS) method. Then, the operator schedules available resources using stochastic optimization model to maximize its expected profit by taking into account the technical constraints in both operating modes.

It should be noted that, scheduling of the microgrid during the islanded mode affects the state of microgrid operation in the connected mode. Therefore, in the proposed model, the microgrid is scheduled for 24-hours a day by considering probability of islanding events at each period.

By considering islanding duration scenarios together with normal ones, the number of scenarios increases drastically, which complicates the optimization. Therefore, scenario reduction techniques are used to reduce the number of scenarios and reduce the time to solve the program [19].

III. PROBLEM FORMULATION

A. Model of DR

In this study, the concept of elasticity [20] is used to model the responsive loads. The benefit of customer *j* after participation in the DR program can be obtained as follow [16]:

$$S(D_{j,t,s}^{DR}) = B(D_{j,t,s}^{DR}) - D_{j,t,s}^{DR}.\rho_{j,t,s} \tag{1}$$

where, $S(D_{j,t,s}^{DR})$ and $B(D_{j,t,s}^{DR})$ represent benefit and income of customer *j* at period *t* after implementing DR programs.

To achieve maximum profit, the derivative of the profit function must be equal to zero.

Therefore, it can be written as:

$$\frac{\partial S(D_{j,t,s}^{DR})}{\partial D_{j,t,s}^{DR}} = 0 \Rightarrow \frac{\partial B(D_{j,t,s}^{DR})}{\partial D_{j,t,s}^{DR}} = \rho_{j,t,s} \tag{2}$$

The utility of customers *j* is attained as [20]:

$$B(D_{j,t,s}^{DR}) = B_{j,t}^{\text{int}} + \frac{\rho_{j,t}^{\text{int}} D_{j,t,s}^{DR}}{1+(E_{t,t}^{j})^{-1}} \times \left[(\frac{D_{j,t,s}^{DR}}{D_{j,t}^{\text{int}}})^{(E_{t,t}^{j})^{-1}} - 1 \right] \tag{3}$$

Differentiating (3) with respect to $D_{j,t,s}^{DR}$ gives:

$$\begin{aligned} \frac{\partial B(D_{j,t,s}^{DR})}{\partial D_{j,t,s}^{DR}} = {} & \frac{\rho_{j,t}^{\text{int}}}{1+(E_{t,t}^{j})^{-1}} \times \left[(\frac{D_{j,t,s}^{DR}}{D_{j,t}^{\text{int}}})^{(E_{t,t}^{j})^{-1}} - 1 \right] + \\ & \frac{\rho_{j,t}^{\text{int}} .D_{j,t,s}^{DR}}{1+(E_{t,t}^{j})^{-1}} \times \left[(E_{t,t}^{j})^{-1} \times \frac{1}{D_{j,t}^{\text{int}}} (\frac{D_{j,t,s}^{DR}}{D_{j,t}^{\text{int}}})^{(E_{t,t}^{j})^{-1}-1} \right] \end{aligned} \tag{4}$$

Substituting (4) into (2) yields:

$$[1+(E_{t,t}^{j})^{-1}].\frac{\rho_{j,t}^{\text{int}}}{\rho_{j,t,s}}= \\ (\frac{D_{j,t,s}^{DR}}{D_{j,t}^{\text{int}}})^{(E_{t,t}^{j})^{-1}}-1+(E_{t,t}^{j})^{-1}(\frac{D_{j,t,s}^{DR}}{D_{j,t}^{\text{int}}})^{(E_{t,t}^{j})^{-1}} \quad (5)$$

$$\frac{\rho_{j,t,s}}{\rho_{j,t}^{\text{int}}}=(\frac{D_{j,t,s}^{DR}}{D_{j,t}^{\text{int}}})^{(E_{t,t}^{j})^{-1}}-\frac{1}{1+(E_{t,t}^{j})^{-1}} \quad (6)$$

Finally, after mathematical operations and simplification, the complete model of responsive loads is obtained as follows [21]:

$$D_{j,t,s}^{DR}=D_{j,t}^{\text{int}}\exp\sum_{h=1}^{N_T}E_{j,t,h}\ln[\frac{\rho_{j,t}^{\text{int}}}{\rho_{j,h,s}}+\frac{1}{1+(E_{t,h}^{j})^{-1}}] \quad (7)$$

B. *Model of the Uncertainties*

Uncertainties of wind and solar units' output power, electricity price and load demand are extracted based on the wind speed, solar irradiation, electricity price and load forecast errors, respectively. In this regard, related probability density functions (PDFs) are obtained. Forecasting errors of solar power, price and load are modelled using a normal PDF [22]. Weibull PDF is used to model wind power production [17]. Moreover, to model the probability of microgrid islanding durations, normal PDF is used as shown in Fig. 1, which is approximated by seven discrete segments with different probabilities.

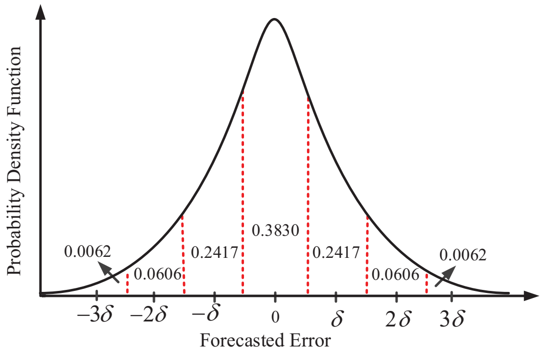


Fig. 1 Normal PDF for prediction islanding errors.

Forecasting error of the islanding durations ($F_N(h)$) is modelled using a normal PDF, which is shown in (8) [20].

$$F_N(h)=\frac{1}{\sqrt{2\pi\sigma}}.e^{-(h-\mu^2)/2\sigma^2} \quad (8)$$

where μ indicates the mean of time duration in which islanding events occur and σ shows indicates standard deviation of time duration. Using the MCS method, a set of random numbers between zero and one for each time (in this study per hour) is generated, which illustrates a scenario for the occurrence of microgrid islanding events.

C. *Objective Function*

The objective of the proposed model is the maximization of the expected profit of the microgrid operator, which is obtained by revenue from purchasing electricity energy minus various operating costs of resources, as provided in (8) and (9):

$$OF=Maximaze\{\sum_{t=1}^{N_T}\sum_{t=t_0}^{t_0+h-1}\sum_{s=1}^{N_S}\sum_{j=1}^{N_J}\lambda_\omega\pi_s[\rho_{j,t,s}D_{j,t,s}] \\ -\sum_{t=1}^{N_T}\sum_{i=1}^{N_G}\sum_{t=t_0}^{t_0+h-1}\sum_{s=1}^{N_S}\lambda_\omega\pi_s[(c_{1,i}.u_{i,t,s}+c_{2,i}.P_{i,t,s})+CSU_{i,t,s}+CSD_{i,t,s}] \\ -\sum_{t=1}^{N_T}\sum_{i=1}^{N_G}\sum_{t=t_0}^{t_0+h-1}\sum_{s=1}^{N_S}\lambda_\omega\pi_s[\rho_{i,t}^{Up}r_{i,t,s}^{Up}+\rho_{i,t}^{Non}r_{i,t,s}^{Non}+\rho_{i,t}^{Dn}r_{i,t,s}^{Dn})] \\ -\sum_{t=1}^{N_T}\sum_{i=1}^{N_G}\sum_{t=t_0}^{t_0+h-1}\sum_{s=1}^{N_S}\lambda_\omega\pi_s[\rho_{j,t}^{Up}r_{j,t,s}^{Up}+\rho_{i,t}^{Dn}r_{j,t,s}^{Dn})] \\ -\sum_{t=1}^{N_T}\sum_{t=t_0}^{t_0+h-1}\sum_{s=1}^{N_S}\lambda_\omega\pi_s[\sum_{w=1}^{N_W}\rho_{w,t}P_{w,t,s}+\sum_{v=1}^{N_V}\rho_{v,t}P_{v,t,s}] \\ -\sum_{t=1}^{N_T}\sum_{t=t_0}^{t_0+h-1}\sum_{s=1}^{N_S}\lambda_\omega\pi_s[\sum_{j=1}^{N_J}VOLL\times L_{j,t,s}^{shed}]\} \quad (9)$$

In the above equation, the first line represents the revenue of selling energy to the customers and the second line indicates the cost of DG units and their start-up and shut-down costs. The third and fourth lines implies the cost of reserve services deployed by DG units and responsive loads, respectively. Line 5 states the cost of purchasing energy from renewable wind and solar units. Finally, the line stands for the cost of expected energy not supplied (EENS) by the microgrid during scheduling horizon.

D. *The Constraints of the Problem*

Constraints (10) and (11) impose respectively the active and the reactive power balance in bus n in each time and scenario [14].

$$P_{i,t,s}^{n}+P_{w,t,s}^{n}-D_{j,t,s}^{n}+L_{j,t,s}^{shed}=\sum_{r=1}^{N_B}fl_{(n,r),t,s}^{P} \quad (10)$$

$$Q_{i,t,s}^{n}+Q_{w,t,s}^{n}-Q_{j,t,s}^{n}+Q_{j,t,s}^{shed}=\sum_{r=1}^{N_B}fl_{(n,r),t,s}^{Q} \quad (11)$$

where, $fl_{(n,r),t,s}^{P}$ and $fl_{(n,r),t,s}^{Q}$ are calculated as follows:

$$fl_{(n,r)t,s}^{P}=G_{n,r}^{l}(V_{n,t,s}-V_{n,t,s}-\omega_{n,r,t,s}+1) \quad (12)$$

$$fl_{(n,r)t,s}^{Q}=-B_{n,r}^{l}(V_{n,t,s}-V_{n,t,s}+\omega_{n,r,t,s}+1) \quad (13)$$

The constraints related to the power of DG units are written as follows:

$$P_{i,t}\le(P_i^{\max}u_{i,t}-R_{i,t}^{U}) \quad (14)$$

$$P_{i,t}\ge(P_i^{\min}u_{i,t}+R_{i,t}^{D}) \quad (15)$$

The constraints related to the operation of DGs that are satisfied in the scheduling problem, is provided by start-up cost limit (16), shut down cost limit (17), power capacity limit (18) and ramping up/down limits (19)-(20), [16].

$$SUC_{i,t}\ge CU_i(u_{i,t}-u_{i,t-1}) \quad (16)$$

$$SDC_{i,t}\ge CD_i(u_{i,t-1}-u_{i,t}) \quad (17)$$

$$\underline{P}_i u_{i,t,s}\le p_{i,t,s}\le\overline{P}_i u_{i,t,s} \quad (18)$$

$$p_{i,t,s}-p_{i,t-1,s}\le RU_i(1-y_{i,t,s})+\underline{P}_i y_{i,t,s} \quad (19)$$

$$p_{i,t-1,s} - p_{i,t,s} \le RD_i(1 - z_{i,t,s}) + \underline{P}_i z_{i,t,s} \qquad (20)$$

The constraints of up, down, non-spinning reserves are represented as follows:

$$0 \le r^{U}_{i,t,s} \le R^{U}_{i,t} \qquad (21)$$

$$0 \le r^{D}_{i,t,s} \le R^{D}_{i,t} \qquad (22)$$

$$0 \le r^{NS}_{i,t,s} \le R^{NS}_{i,t} \qquad (23)$$

Moreover, the constraints of up and down-spinning reserves deployed by responsive loads are written as:

$$0 \le r^{U}_{j,t,s} \le R^{U}_{j,t} \qquad (24)$$

$$0 \le r^{D}_{j,t,s} \le R^{D}_{j,t} \qquad (25)$$

IV. CASE STUDY AND NUMERICAL RESULTS

A. *Case Study Description*

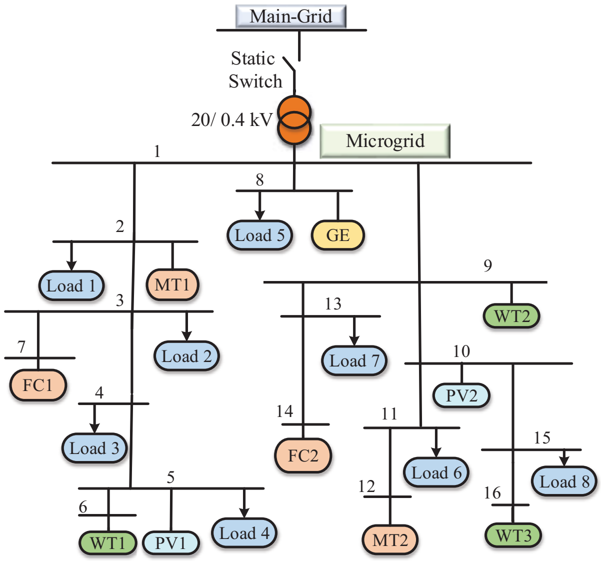


Fig. 2. Scheme of the test microgrid.

Fig. 2 shows one-line diagram of a grid-connected microgrid, which can disconnect via a static switch. Hourly forecasted power of wind and solar units, energy prices, as well as demand loads during the scheduling horizon are given in Table I, [17]. Four DG units are installed in the microgrid, that their related data is given in Table II, [17], [23]. The proposed model is implemented for energy management of the microgrid when encounters an islanding event. The impact of customers' participation in the real-time price-based DR programs is also investigated.

To solve a stochastic optimization problem, a scenario tree is subsequently built based on the generated scenarios of all stochastic variables [24]. To reduce the computational burden, K-means procedure [25] is applied. The proposed optimization problem is solved using the CPLEX commercial solver of GAMS software [26].

B. *Results and Discussions*

In this section, the results of optimization problem are obtained for two cases including both normal and emergency operations.

In the normal operation case, no islanding events occur and the microgrid always is connected to the main grid. In the emergency operation case, the microgrid is often connected but it enters to islanding mode when islanding events occur. The optimal results of the scheduling for two mentioned cases are presented in Table III.

As observed in case of normal operation, total costs of the microgrid including total operating costs of DGs, total costs of deploying reserves and also total costs of EENS are lower than that of their associated values in case of emergency operation. Because, when islanding duration happens, the microgrid is not able to trade energy with the main grid and therefore, it should supply its local loads by expensive local DG units, specifically during peak hours.

In addition, results show the execution of more mandatory load shedding in emergency operation case, and so total cost of EENS increases in this case. Therefore, the expected profit of the operator decreases significantly, when islanding events is considered in the scheduling process. However, the commitment of expensive DGs as well as the amount of mandatory load shedding decrease, and thus, the expected profit increases when DR is implemented.

Table IV illustrates the amount of total reserve deployed by microgrid resources with and without DR in the two cases. It is observed that total reserve in case of emergency operation is higher than that of in normal operation.

TABLE I. HOURLY FORECASTED DEMAND LOADS, POWER OF WIND AND SOLAR UNITS AND ENERGY PRICE

Hours	Load (kW)	Wind power (kW)	Solar power (kW)	Energy price ($/kWh)
1	280	87	0	0.217
2	272	64	0	0.218
3	264	64	0	0.214
4	268	60	0	0.211
5	296	80	0	0.215
6	345	82	0	0.232
7	380	85	0.28	0.236
8	435	92	1.2	0.233
9	488	95	5	0.239
10	545	85	14	0.237
11	579	86	32	0.251
12	614	93	35	0.253
13	620	97	44.5	0.254
14	585	89	48	0.257
15	540	93	52	0.259
16	500	85	56	0.239
17	490	82	46	0.239
18	510	80	34	0.238
19	570	82	18	0.239
20	626	85	6	0.298
21	634	81	2	0.313
22	594	70	0	0.294
23	500	67	0	0.259
24	380	72	0	0.252

TABLE II. TECHNICAL SPECIFICATIONS OF THE SIMULATED MICROGRID INSTALLED DGS

DG unit	$P^{\min}$ (kW)	$P^{\max}$ (kW)	$c_{1,i}$ ($/kWh)	$c_{2,i}$ ($)	SUC ($)	SDC ($)
MT_1	25	150	1.8506	0.0447	0.09	0.08
MT_2	25	150	1.8506	0.1257	0.09	0.08
FC_1	20	100	3.5518	0.0414	0.16	0.09
FC_2	20	100	3.5518	0.1424	0.16	0.09
GE	35	150	3.1200	0.0742	0.12	0.08

Moreover, in case of with DR, a main part of reserve services is provided by the responsive loads. It should be explained that when microgrid operates in islanded mode, DG units must generate more energy during peak periods, and therefore, the amount of reserve allocated by such resources is more expensive at that periods, and thus, more reserve is allocated by DR.

TABLE III. OPTIMAL RESULTS OBTAINED IN DIFFERENT OPERATION CONDITION

Operation condition	State of DR	Expected profit ($)	Cost of DGs ($)	Cost of reserve ($)	Cost of EENS ($)
Normal operation	no DR	444	1985	390	37
	with DR	584	1713	337	2
Emergency operation	no DR	421	2030	417	342
	with DR	557	1812	387	112

TABLE IV. TOTAL SPINNING RESERVE ALLOCATED BY DGS AND DR FOR 24 H

Operation condition	State of DR	Upward reserve of DGs (kWh)	Downward reserve of DGs (kWh)	Upward reserve of DR (kWh)	Downward reserve of DR (kWh)
Normal operation	no DR	1057	1710	0	0
	with DR	1033	1713	171	1148
Emergency operation	no DR	1165	1849	0	0
	with DR	1102	1576	187	1141

It should be noted that, when DR allocate up-spinning reserve, it means that responsive loads are able to reduce their consumption if needed to meet the technical constraints of the system.

Conversely, when DR allocates down-spinning reserve, it means that customers should be able to use more loads if needed and increase their consumption to consume additional energy and maintain power balance.

The operational cost of DGs in different levels of DR participants is shown in Fig. 3. As can be observed, with increasing DR participants, the operation cost of DGs reduces significantly in the two cases because operation of costly DG units mitigates. When islanding events are considered and the main grid is not accessible for some times, the operation cost of DGs augments.

Fig. 4 shows more detail about deployed reserve of DG and DR resources in different levels of DR participants for cases of normal and emergency operations. As can be observed, by increasing DR participants, responsive loads can provide more reserve and as the result, the reserve provided by DG units decreases in both cases.

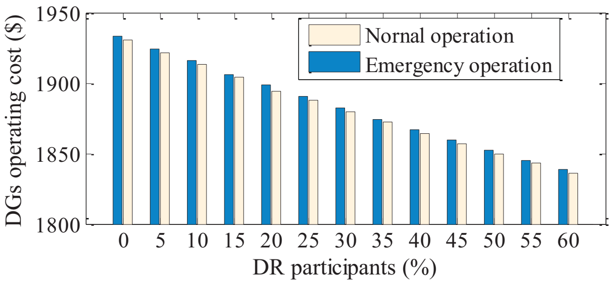
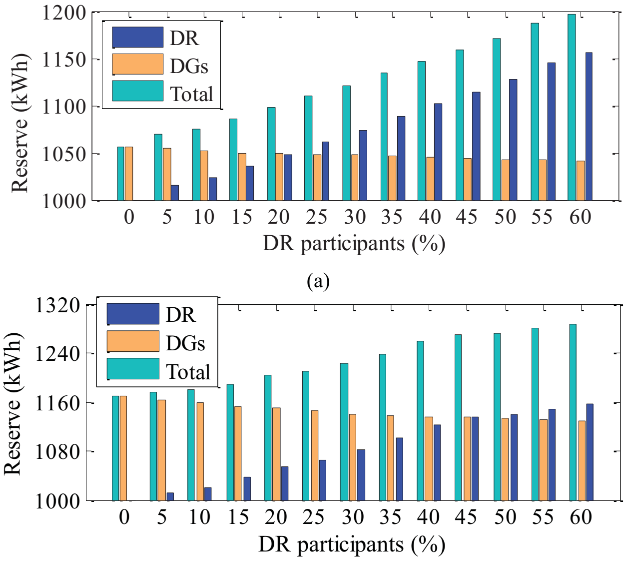


Fig. 3. Total operation cost of DG units versus DR participation in case of normal and emergency operations.



(a)

(b)

Fig. 4. Total upward reserve deployed by DGs and DR versus DR participation (a) case of normal operation, (b) case of considering emergency operation.

Moreover, when emergency operation is considered in the scheduling, the total deployed reserve increases since the microgrid encounters with more uncertainties in islanding duration. Also, DR provides more reserve during islanding periods when reserve allocated by DG units is costly.

V. CONCLUSIONS

In this paper, a stochastic model was presented for scheduling of microgrid considering uncertainty of islanding events. In addition to the uncertainty of islanding duration, the uncertainties associated with demand, RESs power and electricity prices are modeled by using MCS and scenario reduction methods. Numerical results in normal and considering emergency operation were compared in both cases with and without applying DR programs. The impact of consideration islanding events as well as the effect of DR on the expected profit, optimal energy and storage and the amount of EENS was investigated. The results showed that involvement of the customers in DR brings higher profit and lower EENS in both operation conditions, while EENS decreases when islanding events are considered in the scheduling process.

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REFERENCES

[1] K. Kopsidays, and M. Abogaleela, “Utilizing Demand Response to Improve Network Reliability and Ageing Resilience,” *IEEE Trans. Power Syst.,* Vol. 34, no. 3, pp. 2216–2227, 2019.

[2] Y. Wang, S. Mao and R. M. Nelms, "On hierarchical power scheduling for the macrogrid and cooperative microgrids," *IEEE Trans. Ind. Informat.,* vol. 11, no. 6, pp. 1574-1584, Dec. 2015.

[3] X. Lu, K. Li, H. Xu, F. Wang, Z. Zhou and Y. Zhang, “Fundamentals and business model for resource aggregator of demand response in electricity markets,” *Energy*, vol. 204, p. 117885, Aug. 2020.

[4] F. Wang, B. Xiang, K. Li, X. Ge, H. Lu, J. Lai, and P. Dehghanian, “Smart households’ aggregated capacity forecasting for load aggregators under incentive-based demand response programs,” *IEEE Trans. Ind. Appl.*, vol. 56, no. 2, pp. 1086-1097, Mar.-Apr. 2020.

[5] Z. Xuan, X. Gao, K. Li, F. Wang, X. Ge, and Y. Hou, “PV-Load Decoupling Based Demand Response Baseline Load Estimation Approach for Residential Customer with Distributed PV System,” *IEEE Trans. Ind. Appl.*, vol. 56, no. 6, pp. 6128-6137, Nov.-Dec. 2020. DOI: 10.1109/TIA.2020.3014575.

[6] H. Rashidizadeh-Kermani, M. Vahedipour-Dahraie, A. Anvari-Moghaddam, J. M. Guerrero, “Stochastic risk-constrained decision-making approach for a retailer in a competitive environment with flexible demand side resources,” *Int Trans Electr Energ Syst.* vol. 29, no. 2, pp. 1-21, 2018.

[7] F. Wang, X. Ge, P. Yang, K. Li, Z. Mi, P. Siano and N. Duić, “Day-ahead optimal bidding and scheduling strategies for DER aggregator considering responsive uncertainty under real-time pricing,” *Energy*, vol. 213, p. 118765, Dec. 2020.

[8] K. Li, F. Wang, Z. Mi, M. Fotuhi-Firuzabad, N. Dui, and T. Wang, "Capacity and output power estimation approach of individual behind-the-meter distributed photovoltaic system for demand response baseline estimation," *Appl. Energy*, vol. 253, p. 113595, Nov. 2019.

[9] B. Zhao, X. Dong, and J. Bornemann, "Service restoration for a renewable-powered microgrid in unscheduled island mode," *IEEE Trans. Smart Grid,* vol. 6, pp. 1128-1136, 2015.

[10] M. Rastegar, “Impacts of Residential Energy Management on Reliability of Distribution Systems Considering Customer Satisfaction Model,” *IEEE Trans. Power Syst.*, Vol. 33 , no. 6, pp. 6062-6073, 2018.

[11] E. Mahboubi-Moghaddam, et al., “Reliability constrained decision model for energy service provider incorporating demand response programs,” *Applied Energy,* Vol. 183, pp. 552–565, 2016.

[12] G. Li, Y. Huang, and Z. Bie, “Reliability Evaluation of Smart Distribution Systems Considering Load Rebound Characteristics,” *IEEE Trans. Sust. Energy,* Vol. 9, no. 4, pp. 1713-1721, 2018.

[13] A. Khodaei, “Resiliency-oriented microgrid optimal scheduling,” IEEE *Trans. Smart Grid,* VOL. 5, NO. 4, pp. 1584–1591, 2014.

[14] N. Rezaei, and M. Kalantar, “Smart microgrid hierarchical frequency control ancillary service provision based on virtual inertia concept: An integrated demand response and droop controlled distributed generation framework,” *Energy Conversion and Management,* Vol. 92, pp 287-301, 2015.

[15] M. Bayat, et al., “Coordination of Distributed Energy Resources and Demand Response for Voltage and Frequency Support of MV Microgrids,” *IEEE Trans. Power Syst.,* vol. 31, no. 1, pp 506-516, 2016.

[16] M. Vahedipour-Dahraie, et al., “Stochastic Security and Risk-Constrained Scheduling for an Autonomous Microgrid with Demand Response and Renewable Energy Resources,” *IET Renew. Power Gener.,* vol. 11, no. 14, pp. 1812-1821, 2017.

[17] M. Vahedipour-Dahraie, A. Anvari-Moghaddam, and J. M., Guerrero, “Evaluation of Reliability in Risk-Constrained Scheduling of Autonomous Microgrids with Demand Response and Renewable Resources,” *IET Renew. Power Gener.,* vol. 12, no. 6, pp. 657-667, 2018.

[18] K. Balasubramaniam, S. Parimal, H. Ramtin, “Energy management system for enhanced resiliency of microgrids during islanded operation,” *Electr. Power Syst. Res.,* 2016, 137, pp. 133–141.

[19] H. Rashidizadeh-Kermani et al., “A bi-level risk-constrained offering strategy of a wind power producer considering demand side resources,” *Int. J. Elec. Power & Energy Syst.,* vol. 104, pp. 562-574, 2019.

[20] M. Vahedipour-Dahraei, et al., “Security-constrained unit commitment in AC microgrids considering stochastic price-based demand response and renewable generation,” *Int. J. Elec. Power & Energy Syst.,* vol. 28, no. 9, pp. 1-26, 2018.

[21] H. Rashidizadeh-Kermani, et al., “Stochastic programming model for scheduling demand response aggregators considering uncertain market prices and demands,” *Int. J. Elec. Power & Energy Syst.,* vol. 113, pp. 528–538, 2019.

[22] D. T. Nguyen, and L. B. Le, “Risk-Constrained Profit Maximization for Microgrid Aggregators with Demand Response,” *IEEE Trans. Smart Grid,* Vol. 6, no.1, pp. 135-146, 2015.

[23] M. Vahedipour-Dahraie, H.R. Najafi, A. Anvari-Moghaddam, and J.M. Guerrero, “Study of the Effect of Time-Based Rate Demand Response Programs on Stochastic Day-Ahead Energy and Reserve Scheduling in Islanded Residential Microgrids”, *Appl. Sci.,* vol. 7, pp 1-19, 2017.

[24] M. Vahedipour-Dahraie, et al., “Stochastic Frequency-Security Constrained Scheduling of a Microgrid Considering Price-Driven Demand Response,” *International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, 20-22 June 2018, Amalfi, Italy, pp. 716-721, 2018.

[25] D. Arthur, and S. Vassilvitskii, “K-means++: The advantages of careful seeding,” in Proc. 18th Annu. ACM-SIAM Symp Discrete Algorithms (SODA ‘07), New Orleans, LA, USA, pp. 1027-1035, 2007.

[26] “The General Algebraic Modeling System (GAMS) Software,” online available at: http://www.gams.com.