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Optimal Sizing of Energy Storage System in A Renewable-Based Microgrid Under Flexible Demand Side Management Considering Reliability and Uncertainties

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Abstract- *Utilization of energy storage system (ESS) in microgrids has turned to be necessary in recent years and now with the improvement of storage technologies, system operators are looking for an exact modeling and calculation for optimal sizing of ESS. In the proposed paper, optimal size of ESS is determined in a microgrid considering demand response program (DRP) and reliability criterion. Both larger and small-scale ESSs have their own problems. A large-scale ESS reduces microgrid operating cost but it includes higher investment costs while a small-scale ESS has less investment cost. The main goal of the proposed paper is find optimal size of ESS in which microgrid investment cost as well as operating cost are minimized. Since the renewable units may not have stable production and also because of the outages that conventional units may have, ESS is utilized and then a reliability index called reliability criterion is obtained. Furthermore, effects of reliability criterion and DRP on optimal sizing of ESS are evaluated. A mixed-integer programing (MIP) is used to model the proposed stochastic ESS optimal sizing problem in a microgrid and GAMS optimization software is used to solve it. Five study cases are studied and the results are presented for comparison.*

Keyword: Demand response program (DRP), Energy storage system (ESS), Renewable-based microgrid, Reliability criterion.

NOMENCLATURE

Indices

h	Hour index
n	Unit index
r	Renewable unit index
t	Day index
s	Scenario index

Parameters

C^0	State of charge at the start of every day
C^{end}	State of charge at the end of every day
$C_B^{\max}$	Maximum storage capacity
CIF_B	Main investment cost of ESS
$DRP^{\max}$	Maximum value of DRP
DT_i	Minimal down time of thermal unit
DR_i	Ramp down rate of thermal unit

Parameters

ICP_B	Installation cost of power rating for ESS
ICE_B	Installation cost of energy rating for ESS
k	Depth of discharge
$LOLE^{Target}$	Predicted value for loss of load expectation
NG	Available conventional units number
NR	Available renewable units number
NH	Hours number
NT	Days number
$P_M^{\max}$	Maximum limitation of power import (export)
$P_i^{\min}$	Minimum output power of thermal unit
$P_i^{\max}$	Maximum output power of thermal unit
$P_{W,th}^s$	Production of wind turbine
P_B^R	Rated power of ESS
$P_{D,th}^s$	The load supplied by microgrid
UT_i	Minimal up time of thermal unit

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UR_i	Ramp up rate of thermal unit
ρ_t	Electricity price
Δ_t	Time pause
Variables	
C^s_{th}	State of charge
C^s_{t1}	State of charge at the start of every day
F_i	Function of generation cost for thermal unit
I^s_{ith}	Unit engagement condition
IC	Microgrid overall investment cost
$I^s_{it(h-1)}$	Unit engagement condition at hour (h-1)
LS^s_{th}	Load reduction
$LOLE$	Loss of load expectation
OC	Overall operating cost of microgrid
$P^s_{M,th}$	Sold (purchased) power to (from) the main grid
P^s_{rth}	Produced power by renewable unit
$P^s_{B,th}$	ESS consumption (production)
P^s_{ith}	Produced power by thermal unit
$P^s_{DRP,th}$	Microgrid new load considering DRP
$P^s_{TOU,th}$	Microgrid new load considering TOU program
SU^s_{ith}	Startup cost of thermal unit
UX^s_{ith}	Outage condition of thermal unit
$UY^s_{M,th}$	Outage condition of line connecting upstream grid to the microgrid
w^s_{th}	Binary variable
y^s_{ith}	Binary variable, 1 if the unit is started up; otherwise it is 0
z^s_{ith}	Binary variable, 1 if the unit is shut down; otherwise it is 0

1. INTRODUCTION

Recently, energy storage systems (ESSs) have been widely used in microgrids to control peak load, optimize operation and manage output fluctuation of available renewable energy sources. In addition to utilization, optimal sizing of ESS in microgrids is necessary [1-3]. Microgrid is created as a small power distribution system with local renewable and non-renewable units to supply local loads. A microgrid can be connected to the upstream grid to exchange power with upstream grid. Utilization of ESS in microgrid is important. Therefore, optimal size of ESS should be determined to minimize the investment cost as well as operation cost. A model is proposed for ESS sizing in which the charge and discharge power curves are determined [4]. ESS is used besides wind turbine and photovoltaic system in microgrid to soften the unstable generation of renewable energy sources [5-7]. A practical approach has been utilized in [8] to improve system reliability by employing ESS. The applications and future of ESS has been studied in [9]. A storage system has been employed to manage and control power in [10]. ESS has been integrated with wind generation units in [11] to solve the intermittent behavior problem of these units. Genetic algorithm has been employed to find optimal size of an energy storage system in [12]. Using the alternative direction method of multipliers, energy storage system is optimally sited and sized in [13]. Finally, the optimal capacity and location of battery energy storage system have been found using a heuristic method in [14]. Energy storage system has been employed for coordination of consumption and renewable generation in [15]. Compressed air energy storage system has been employed to handle intermittent generation of wind turbine in [16]. Virtual energy storage system has been utilized in [17] to control and improve frequency response. As a flexible tool, energy storage system has been employed in [18] to handle intermittent output of wind turbine considering economic and technical issues. Uncertainty based operation of distribution systems have been investigated in [19] subject to load and generation uncertainties. Voltage and current harmonics have been tried to be corrected in an on-grid microgrid in [20].

This paper is with line of worthy reference [4]. The effects of DRP and reliability index on optimal ESS sizing problem are not studied in mentioned work. Therefore, in the proposed paper, the same problem is studied in the presence of reliability index and DRP. Also, stochastic model is employed to consider the uncertainty of system components outage, microgrid load and output power of renewable energy source. The objective function of the proposed paper is total cost of microgrid including the investment cost of ESS as well as operation cost of microgrid. The investment cost consists of power rating as well as energy rating costs of ESS while the operation cost includes the operation cost of generation units, cost of purchased power from upstream grid minus the revenue obtained from selling power to the upstream grid. The proposed reliability index is loss of load expectation (LOLE) in this study which is determined based on the expected load curtailment in each scenario. Also, the TOU rates of DRP is proposed to flatten load curve by transferring some percentage of load from peak time periods to other time period which leads to reduction of operation cost. Finally, the MIP model is used to formulate the proposed model for optimal ESS sizing problem in the presence of DRP and reliability index. Based on the given explanation above, the novelty and contributions of this paper are presented as follows:

1. To determine optimal size of ESS in microgrid considering reliability index.
2. To evaluate effects of DRP on the optimal sizing problem of ESS under reliability index.
3. The scenario stochastic model is used to model uncertainty of load, output power of renewable unit and system components outage.

The rest of paper is classified as follows: The stochastic framework model of ESS sizing in a microgrid is provided in Section 2. Mathematical formulations are presented in Section 3. The case studies are presented in Section 4 in which the effects of DRP and reliability index are investigated and the results are presented for comparison. Finally, the conclusion are presented in Section 5.

2. MODEL OUTLINE

Microgrid expected operating cost and ESS investment cost are the main objective of proposed model for optimal ESS sizing problem. In the proposed paper, one of the purposes is to reduce the investment cost of ESS as well as operating cost of microgrid which incorporates the cost of local unit's generation and the cost of power procurement from the upper grid. In recent years, both financial and reliability issues have been significant factors in power system projects and the goal of this paper is to consider the remarked issues and help managers and related decision makers make an appropriate decision on the planning problems. By considering reliability criterion in the proposed model, the financial and security issues will be considered, so a satisfactory edge between supply and energy demand will be obtained and a level of inherent excess will be guaranteed. In simple words, reliability criterion means the amount of unsupplied load in a definite period which has been assessed as far as LOLE in the proposed model.

The reliability of power system can be exactly evaluated based on the probabilistic reliability index. To obtain the expected reliability index, meaningful calculation is needed, so a breakdown approach is necessary to discrete the reliability issues [21]. Monte Carlo simulation (MCS) is used to compute the microgrid reliability. It is been utilized to simulate various unknown conditions during the study period. According to the microgrid components compulsory interruption degree and proper probability dispersion functions, many irregular numbers are created to define the condition of every sector and production of renewable resources during the simulation period. To study how microgrid would operate in a specific inspected condition, many different conditions are simulated. In the utilized technique, each scenario shows a probable condition related to system operation which leads to a large number of scenarios and complicated calculations. Using a scenario reduction strategy, number of scenarios are decreased. Each reduced scenario has a special meaning which reflects the possibility of an unknown condition. The MCS technique is appropriate for such applications since the number of cases is independent from system extent for a definite precision degree [22].

3. PROBLEM FORMULATION

The main purpose of proposed paper is to minimize investment cost as well as operation cost of microgrid. Mathematical form of this sentence is proposed in in Eq. (1).

$$Min \qquad IC + OC \tag{1}$$

$$IC = ICP_B P_B^R + ICE_B C_B^{\max} \tag{2}$$

$$OC = \sum_{s=1}^{Ns} P_s \sum_{t=1}^{Nt} \sum_{h=1}^{Nh} \sum_{i=1}^{Ng} \left[F_i \left(P_{ith}^s \right) I_{ith}^s + SU_{ith}^s \right] + \sum_{s=1}^{Ns} P_s \sum_{t=1}^{Nt} \sum_{h=1}^{Nh} \rho_t P_{M,th}^s \tag{3}$$

As mentioned before, the main goal is to define an optimal point for ESS in which investment cost and operation cost are minimized Eq. (1). The power rating cost and energy rating investment cost are considered in the investment cost Eq. (2). It should be noted that the variable and fixed costs are also added to the power rating cost. The following costs are standardized on a yearly premise and by finding the optimal size for ESS installation, the ESS total cost will be minimized [23].

The second objective of proposed paper is to minimize the microgrid operation cost. Like the investment cost, microgrid operating cost has been also divided into several separate costs as follows: the expenses related to fuel procurement for local units to produce electricity, the expenses related to power procurement (export) from (to) the upper grid and the costs that the units have when starting up and shutting down.

3.1. Microgrid and unit limitations

Equation (4) expresses the power balance between production and energy demand with considering DRP. It can be understood from Eq. (4) that the production of units (both renewable and thermal) inside the microgrid plus the power that ESS produces (uses) and the power sent or purchased to (from) the upper grid should be equal to the energy demand with considering DRP. If energy demand is more than the microgrid and network production, the variable will be affixed to the Eq. (4) to express load shortage. When storage is discharging, ESS power is a positive value and when charging, it is negative and when not charging or discharging, it is zero. If power is purchased from the upper grid, the upper grid power will be considered positive and it will be negative if it is sent to the upper grid and finally it will be zero if microgrid works in islanding operation mode.

The exchanged power between microgrid and upstream grid is limited by equation Eq. (5). Equation (6) is used to provide the load shedding limitation for stable operation.

$$\sum_{i=1}^{N_G} P_{ith}^{s} I_{ith}^{s} + \sum_{r=1}^{N_R} P_{rth}^{s} + P_{B,th}^{s} + P_{M,th}^{s} + LS_{th}^{s} = P_{DRP,th}^{s} \tag{4}$$

$$\left| P_{M,th}^{s} \right| \le P_{M}^{\max} UY_{M,th}^{s} \tag{5}$$

$$0 \le LS_{th}^{s} \le P_{DRP,th}^{s} \tag{6}$$

Limitations on local thermal units inside the microgrid are presented in Eqs. (7)-(11). The lower and upper production limits of units are expressed by Eq. (7). Ramping up and down limits are presented by Eqs. (8) and (9), respectively. The Eqs. (10) and (11) are employed to determine the minimal down and up time limitations of local units.

$$P_i^{\min} I_{ith}^{s} UX_{ith}^{s} \le P_{ith}^{s} \le P_i^{\max} I_{ith}^{s} UX_{ith}^{s} \tag{7}$$

$$P_{ith}^{s} - P_{it(h-1)}^{s} \le UR_i.(1 - y_{ith}^{s}) + P_i^{\min} y_{ith}^{s} \tag{8}$$

$$P_{it(h-1)}^{s} - P_{ith}^{s} \le DR_i.(1 - z_{ith}^{s}) + P_i^{\min} z_{ith}^{s} \tag{9}$$

$$\sum_{k=h}^{h+UT_i-1} I_{ith}^{s} \ge UT_i.y_{ith}^{s} \tag{10}$$

$$\sum_{k=h}^{h+DT_i-1} (1 - I_{ith}^{s}) \ge DT_i.z_{ith}^{s} \tag{11}$$

According to the indexes y and z which are used as unit startup and shut down indexes, the limitations of Eqs. (8)-(11) are determined. According to the unit commitment in Eqs. (12)-(13), the following indexes are determined. If the unit is start up, y will be equal to 1, or else it will be zero. If the unit is shut down, z will be equal to 1, or else it will be zero.

$$y_{ith}^{s} - z_{ith}^{s} = I_{ith}^{s} - I_{it(h-1)}^{s} \tag{12}$$

$$y_{ith}^{s} + z_{ith}^{s} \le 1 \tag{13}$$

In the proposed model for optimal ESS sizing problem, both renewable and thermal units are considered. Each renewable unit has a unique production pattern which will be defined by a long-standing estimation. We can employ a definite approach or simulation method to predict the input performance of the production unit. The power curve of wind turbine will be integrated with input performance of the production unit to create the production pattern according to worthy reference [24]. For instance, by utilizing the Weibull probability distribution function, we can model the wind speed dissemination [25]. There are Different approaches for predicting Weibull parameters [26, 27]. The power produced by a wind turbine can be calculated as follows:

$$P_{W,th}^{s} = \left\{ \begin{array}{ll} 0 & V_{th}^{s} < V_{CI} \\ P_W^{\max} \dfrac{V_{th}^{s} - V_{CI}}{V_R - V_{CI}} & V_{CI} \le V_{th}^{s} < V_R \\ P_W^{\max} & V_R \le V_{th}^{s} < V_{CO} \\ 0 & V_{th}^{s} > V_{CO} \end{array} \right\} \tag{14}$$

Since the renewable sources size is proportional with the microgrid size, the reliability of microgrid would be questioned by the combination of sporadic renewable sources, so the extra resources and ESS should be able to provide the energy demand [28].

3.2. ESS constraints

The Eqs. (15)-(20) can be used to design ESS.

$$-P_B^R \le P_{B,th}^{s} \le kP_B^R \tag{15}$$

$$C_{th}^{S} = C_{t(h-1)}^{S} - P_{B,th}^{s} \Delta t \tag{16}$$

$$0 \le C_{th}^{S} \le C_b^{\max} \tag{17}$$

$$C_{t1}^{S} \le C^{0} \tag{18}$$

$$C_{th}^{S} = C^{end} \quad ; \quad (h = N_H) \tag{19}$$

$$ICP_B P_B^R + ICE_B C_B^{\max} \le CIF_B \tag{20}$$

Evaluating ESS from operational status point of view, three statuses will be obtained: island, charging and discharging. The charging/discharging power limits of ESS are constrained by Eq. (15). Equation (16) is used to determine state of charge of ESS which is limited by Eq. (17). Total amount of energy at the present time plus the amount in former hour is equal to the existing energy inside the storage. The time pause is 1 hour, so is considered to be 1. When ESS is charging, has negative value and the amount of existing energy increases. When ESS is in discharge mode, would be considered negative and the amount of existing energy decreases.

In order to obtain how much energy we have at the beginning and end of every day, the Eqs. (18)-(19) are utilized. We need a fundamental fund to set up and exploit the ESS in power system and this fund is constrained by Eq. (20) and as a result, the microgrid size is limited [29].

3.3. Reliability constraint

The reliability is determined in terms of LOLE. Equation (21) expresses the amount of load curtailment in each time and scenario. In the event of load decrease, is equal to 1. Using the load curtailment index, possibility of load curtailment scenarios in LOLE is considered in Eq. (22). As considered in Eq. (23), LOLE predicated value needs to be more than the acquired LOLE value at every year.

$$0 \le LS_{th}^{s} \le M.w_{th}^{s} \quad (21)$$

$$LOLE = \sum_{s=1}^{N_S} P_s \sum_{t=1}^{N_T} \sum_{h=1}^{N_h} w_{th}^{s} \quad (22)$$

$$LOLE \le LOLE^{T\,\mathrm{arg}et} \quad (23)$$

3.4. Demand response program

DRP includes many various features and programs inside itself and time-of-use (TOU) rates of DRP has been used for optimal ESS sizing problem in the proposed paper [30]. The main reason of DRP employment is to shift some amount of load from expensive periods to the cheaper periods to flatten the load curve and reduce the operation costs. Based on TOU, some percentage of load can be shifted from peak periods off-peak periods. This sentence is mathematically expressed by Eq. (24).

$$P_{DRP,th}^{S} = P_{D,th}^{S} + P_{TOU,th}^{S} \quad (24)$$

In the Eq. (24), new load with considering TOU is equal to the primary load plus the variable . This variable can be either positive or negative which means load increase and load decrease, respectively. In other words, due to appearance of intelligent network technology, some amount of load can be transferred from peak periods to off-peak periods which is modeled in Eq. (24). DRP includes some technical limitations which are presented by Eqs. (25) and (26).

$$\left| P_{TOU,th}^{S} \right| \le DRP^{\max} \times P_{D,th}^{S} \quad (25)$$

$$\sum_{h=1}^{Nh} P_{TOU,th}^{S} = 0 \quad (26)$$

It can be understood from Eq. (25) that the amount of increasing or decreasing load in TOU program should not exceed the base load. In the proposed paper, the maximum amount of increased and decreased load has been considered to be 20 %. Furthermore, Eq. (26) expresses that the load is fixed and it is only transferred from peak periods to off-peak periods. It means that the amount of increasing and decreasing loads during a day should be equal.

3.5. Price and demand uncertainty model

In order to model uncertainty of demand and price, the forecast error distribution curves are divided into some intervals with the width of one standard deviation. In uncertainty modeling the inputs are the values used for price and demand in deterministic solution. The percentage of increase or decrease for price and demand is considered to be 10%. Fig. 1 shows a sample discrete form of the predication error probability distribution function. It is essential that for every available scenario 2 values be computed:

1. By integrating the area below the probability distribution curve in every period, each scenario's probability can be achieved.
2. The realized prediction error in each relevant scenario is considered to be the average amount of period.

Table 1 shows the amount and its probability in each relevant scenario.

3.6. Scenario reduction

Utilizing scenario production technique, many various scenarios are acquired. Due to larger size of obtained scenarios, the problem will be complicated and it will take much more time to be solved. So, the number of scenarios should be decreased. In this paper, the most common probability distance used in stochastic optimization is the Kantorovich distance [31], DK(.),defined between two probability distributions Q and Q´ by Eq. (28), where c(s, s´)is a non-negative, continuous, symmetric cost function and the infimum is taken over all joint probability distributions defined on Ω×Ω.

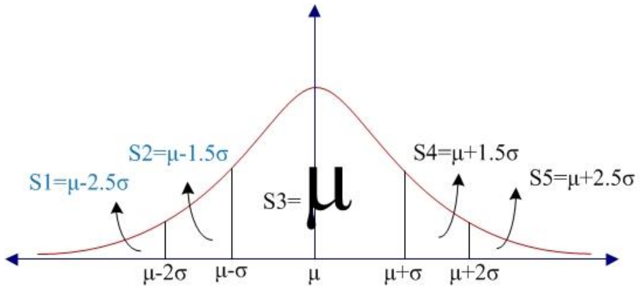

Fig. 1. Probability distribution function for uncertainty parameters.

Table 1. The caption must be shown before the Table.

Scenario number	Value of each relevant scenario	probability of each relevant scenario
S1	$\mu - 2.5\sigma$	0.0123
S2	$\mu - 1.5\sigma$	0.136
S3	μ	0.682
S4	$\mu + 1.5\sigma$	0.136
S5	$\mu + 2.5\sigma$	0.023

$$D_k(Q,Q') = \inf\left\{ \int_{\Omega\times\Omega} c(s,s')\eta(ds,ds') : \int_{\Omega} \eta(.,ds') = Q, \int_{\Omega} \eta(ds,.) = Q' \right\} \quad (27)$$

$$c(s,s') = \left\| s - s' \right\|^{T} \quad (28)$$

The utilized method to reduce the number of scenarios is the fast-forward algorithm [31]. It can be seen from reported results in [31] that the utilized technique is a popular and particle approach.

4. PROBLEM FORMULATION

In order to show the efficiency of the proposed model, different cases are evaluated to show the effects of reliability criterion and DRP on optimal sizing of ESS in a sample microgrid.

4.1. Input data

A microgrid is investigated to show the effectiveness of proposed approach. As expressed in Table 2, this microgrid includes one wind turbine as well as four thermal generation units. ESS includes power investment cost of 40000 $/MW/year and energy investment cost of 11000 $/MWh/year. It is been considered that a 10 MW line connects microgrid to the main grid and constrains the power exchange between the upstream grid and microgrid. In order to simulate component interruptions, wind speed and the microgrid load, 500 scenarios are created. To reduce the time used for calculation because of the problem complication and its considerable size, by applying the scenario reduction technique, number of scenarios are reduced to 5 which probabilities are shown in Table 3. It should be noted that the microgrid peak load is equal to 17 MW and the microgrid load for sample days in spring, summer, autumn, and winter is presented in Figure 2. Also the electricity price in upper grid to which the microgrid is connected is presented in Figure 3. Finally the wind speed in the related scenarios is shown in Figure 4. We can use the scenarios and equation (14) to calculate the output power of wind turbine which is shown in Figure 5. The microgrid load is considered constant for the upcoming years and then the whole schemes are just considered for one year. The reliability criterion is considered 0.1 day/year by microgrid operator which should be satisfied. The proposed approach was carried on a 2.4-GHz PC utilizing CPLEX 11.0 in GAMS optimization package [32].

Table 2. Characteristics of generating units.

Unit no.	Bus no.	Cost coefficient ($/MWh)	Min capacity (MW)	Max capacity (MW)
1	Gas	27.7	1	5
2	Gas	39.1	1	5
3	Gas	39.1	0.8	3
4	Gas	61.3	0.8	3
5	Wind	65.6	0	1
Unit no.	Min. up time(h)	Min. down time(h)	Ramp up (MW/h)	Ramp down (MW/h)
1	3	3	2.5	2.5
2	3	3	2.5	2.5
3	1	1	3	3
4	1	1	3	3
5	-	-	-	-

Table 3. Probabilities of reduced scenarios.

Scenario	1	2	3	4	5
Probability	0.61	0.12	0.11	0.09	0.07

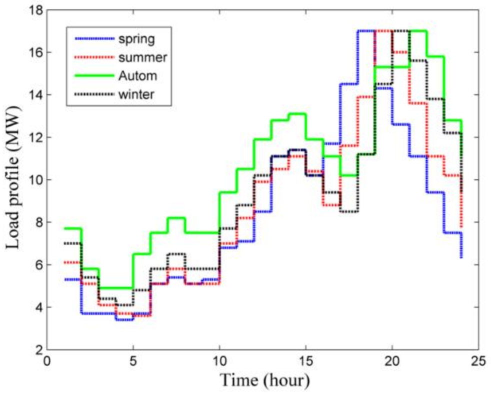

Fig. 2. Load profile for a day in spring, summer, autumn and winter.

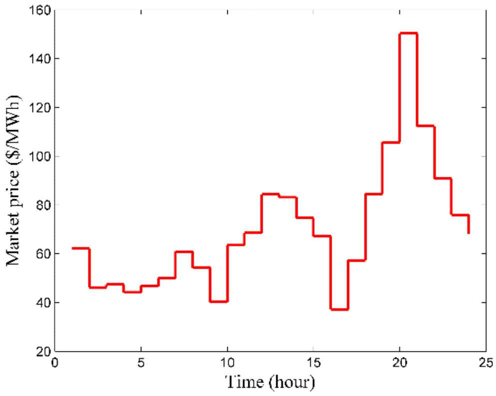

Fig. 3. Forecasted electricity price in upper market.

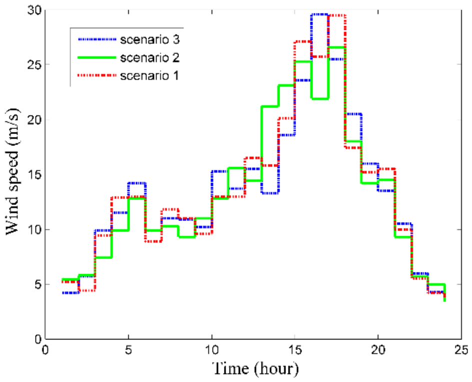

Fig. 4. Wind speed in three scenarios.

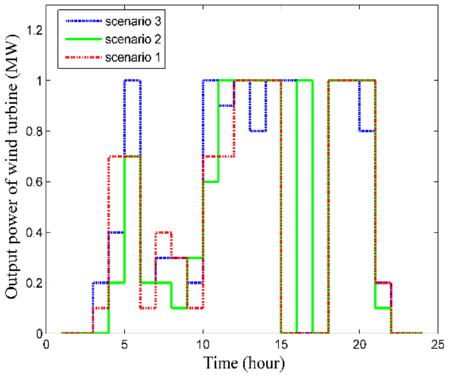

Fig. 5. Output power of wind turbine in three scenarios.

4.2. Results of simulation in different cases

In order to show the efficiency of proposed model, the following items have been considered and the results are presented to compare different cases:

Case 1: base case without ESS.

Case 2: the case 1 to which an ESS, 5 MWh with rated power of 1 MW is added.

Case 3: evaluating the optimal size for ESS to be installed in case 2.

Case 4: evaluating the impact of reliability criterion on cases 1, 2, 3.

Case 5: evaluating the impact of DRP on cases 1, 2, 3.

4.2.1. Case 1: base case without ESS.

In the cases 1, 2 and 3, it is assumed that the expected reliability criterion from point of microgrid operator is equal to 0.1 day/year. Also in case 1, it is assumed that the microgrid is planned without ESS consideration. The results related to this case are summarized in Table 4. The total cost of microgrid is 2,148,325 $. The total cost of production is 4,563,795 $ and the cost of purchased power is 110,844 $. When the generation of ESS is more than the microgrid demand, the produced power can be sold to the upper grid which results in economic benefits of 2,526,314 $ for the microgrid. Unit 1 is the base unit which operates as full-time unit but whenever unit 1 is not able to supply the microgrid load and it is not able to import power from the upper grid due to high price that the power purchased from upper grid has, other units will be committed. Microgrid will import power from upper grid if the offered electricity by the main network has low price and if the electricity price is high, the power produced by the local units inside the microgrid will supply the load and the extra produced energy will be exported to the upper grid. In this case the amount of LOLE is equal to 0.1 day/year and the amount of unsupplied energy is equal to 38.463 MWh.

4.2.2. Case 2: adding an ESS, 5 MWh with rated power of 1 MW to case 1

In case 2, an ESS with predefined characteristics is added to the microgrid. The added ESS is a 5 MWh ESS with rated power of 1 MW. It takes 5 hours for ESS to be completely charged and attain the maximum SOC. The results of this case are summarized in Table 4. After ESS installation, the expenses related to energy procurement from the upper grid would be equal to 112,308 $ and also the costs related to the production of local units would be 4,563,795 $. The ESS can save 2,637,326 $ by exporting power to the upper grid. It should be mentioned that the cost of ESS installation is equal to 95,000 $. Comparing the obtained results, we can conclude that the total cost related to the microgrid operation is equal to 2,133,777 $. So it can be concluded that total cost has 0.68% reduction in comparison with case 1 which is mainly because of power export to the upper grid. ESS is charged at the times electricity price is low like off-peak hours and it is discharged at the times electricity price is high like peak hours. In peak hours, ESS can use the saved energy to supply the load and gain profit by exporting it to the upper grid. In this case the amount of expected LOLE is equal to 0.1 day/year and the amount of unsupplied energy expected to have is equal to 71.52 MWh.

Table 4. Comparison of summarized results related to cases 1, 2 and 3.

Different parameters	Case1	Case 2	Case3
ESS rated power (MW)	0	1	2.6
ESS rated energy (MWh)	0	5	13
Expected unsupplied energy (MWh)	38.463	71.52	71.52
ESS investment cost ($)	0	95,000	247,000
Microgrid generation cost ($)	4,563,795	4,563,795	4,563,795
Import cost ($)	110,844	112,308	149,319
Benefit from export to grid ($)	2,526,314	2,637,326	2,840,014
Total cost ($)	2,148,325	2,133,777	2,120,100
Total cost reduction (%)	0	0.68 %	1.31 %

4.2.3. Case 3: evaluating the optimal size for ESS to be installed in case 2.

In this case, optimal size of ESS is determined based on the proposed model. So, the calculated optimal size for ESS to be installed in the microgrid is a 13 MWh ESS with rated power of 2.6 MW. The total cost related to the microgrid operation is equal to 2,120,100 $, which incorporates 4,563,795 $ total production cost, 149,319 $ overall expenses related to power purchase, 247,000 $ primary fund to be invested for ESS installation and 2,840,014 $ gained from selling energy to the upper grid. Comparing the results obtained in case 3 with the ones obtained in case 1, it can be concluded that the total cost in case 3 has 1.31% reduction. ESS is charged at the times electricity price is low (off-peak hours) and it is discharged at the times electricity price is high (peak hours). In this case, the amount of expected LOLE is equal to 0.1 day/year and the amount of expected unsupplied energy is equal to 71.52 MWh. The results related to the cases 1, 2 and 3 are summarized in Table 4.

4.2.4. Case 4: evaluating the impact of reliability criterion on cases 1, 2 and 3.

The calculated optimal size of ESS in case 3 can satisfy the microgrid reliability criterion constraint. Considering the LOLE 0.0 day/year and 0.2 day/year compared to 0.1 day/year in cases 1, 2 and 3, ESS planning will have a little change to satisfy the microgrid reliability criterion.

Considering three different values for the microgrid expected reliability criterion, its impact on cases 1, 2 and 3 has been presented in Table 5. It can be understood from Table 5 that less reliability criterion (less outage) can increase microgrid total cost. This is because of that due to less outage, the microgrid load especially in peak load hours should be supplied from market with higher price or from the units inside the microgrid which generation cost is high.

4.2.5. evaluating the impact of DRP on Cases 1, 2 and 3.

In this case the effect of DRP on microgrid development planning and microgrid total cost is studied. It should be noted that in order to only study the effect of DRP, the reliability criterion is fixed to be 0/1 day/year. Some percentage of load can be transferred from peak time periods to other time periods during day. Microgrid operator is responsible for maximum adjustment of this percentage of load .Then comparison results of case 5 for different conditions are presented in Table 6. It can be seen from Table 6 that if the maximum ability of load shifting increases, total microgrid cost during planning period will be reduced. The reason of microgrid total cost reduction is shifting some percentage of loads from peak period to off-peak periods which leads to load profile flattening during the day and minimization of operating cost of microgrid.

4.3. Comparison of results and discussion and its evaluation

By decreasing the load shedding, ESS increases the microgrid reliability criterion and improves the microgrid economic performance by producing power in high price hours and storing it at the times in which the electricity price is low.

Furthermore, implementation of DRP in the microgrid leads to microgrid total cost reduction and controls the microgrid extra investment cost to provide peak load.

5. CONCLUSION

In order to find the optimal size of ESS, an exact and efficient solution is presented in this paper considering reliability criterion and DRP. To consider the costs and expenses related to microgrid operation and ESS investment, development planning problem was utilized. The reliability criterion is computed in a way that dependable operation of microgrid would be guaranteed by fulfilling reliability criterion. Also the impact of DRP on total microgrid cost and optimal sizing of ESS is investigated. In order to compute the reliability criterion in the proposed problem which leads to efficient reliability evaluation of the microgrid, an MIP formulation is presented. The obtained results uncovered that having an appropriate reliability criterion can lead to 1.77 % reduction of total cost. Also, it can be concluded that due to utilization of DRP can lead to 16.59 % reduction of total cost.

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Table 5. Comparison of summarized results related to case 4.

Reliability criterion	0.0 day/year			0.1 day/year			0.2 day/year		
Different parameters	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
ESS rated power (MW)	0	1	2.6	0	1	2.6	0	1	2.6
ESS rated energy (MWh)	0	5	13	0	5	13	0	5	13
Expected unsupplied energy(MWh)	0	0	0	38.463	71.52	71.52	75.036	143.43	143.43
ESS investment cost($)	0	95,000	247,000	0	95,000	247,000	0	95,000	247,000
Generation cost($)	4563795	4563795	4563795	4,563,795	4,563,795	4,563,795	4563795	4563795	4563795
Import cost($)	110844	112308	149319	110,844	112,308	149,319	108859	112308	149319
Benefit from export($)	2520530	2626570	2829259	2,526,314	2,637,326	2,840,014	2529197	2647248	2849936
Total cost($)	2154109	2144533	2130855	2,148,325	2,133,777	2,120,100	2143457	2123855	2110178
Reduction cost (%)	-0.26 %	0.17 %	0.81 %	0	0.68 %	1.31 %	0.21 %	1.13	1.77 %

Table 6. Comparison of summarized results related to case 5.

DRP	$DRP^{\max} = 0$			$DRP^{\max} = 0.1$			$DRP^{\max} = 0.2$		
Different cases	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
ESS rated power (MW)	0	1	2.6	0	1	2.6	0	1	2.6
ESS rated energy (MWh)	0	5	13	0	5	13	0	5	13
Expected unsupplied energy(MWh)	38.463	71.52	71.52	38.463	71.52	71.52	38.463	71.52	71.52
ESS investment Cost ($)	0	95,000	247,000	0	95,000	247,000	0	95,000	247,000
Microgrid generation Cost ($)	4,563,795	4,563,795	4,563,795	4563795	4563795	4563795	4563795	4563795	4563795
Import cost ($)	110,844	112,308	149,319	149226	158708	197165	197740	209564	253676
Benefit from export ($)	2,526,314	2,637,326	2,840,014	2736910	2855636	3058041	2957462	3077790	3280636
Total cost ($)	2,148,325	2,133,777	2,120,100	1976111	1961867	1949919	1804073	1790569	1783835
Reduction cost (%)	0	0.68 %	1.31 %	8.01 %	8.67 %	9.23 %	16.02 %	16.65 %	16.96 %

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