Optimal Spinning Reserve Allocation in Presence of Electrical Storage and Renewable Energy Sources

Mohammad Sadegh Javadi
INESC TEC
Porto, Portugal
msjavadi@gmail.com

Mohamed Lotfi
FEUP and INESC TEC
Porto, Portugal
mohd.f.lotfi@gmail.com

Matthew Gough
Instituto Superior Técnico
Lisbon, Portugal
mattgough23@gmail.com

Ali Esmaeel Nezhad
University of Bologna
Bologna, Italy
ali.esmaeelnezhad@gmail.com

Sérgio F. Santos
C-MAST/UBI
Covilhã, Portugal
sdfsantos@gmail.com

João P. S. Catalão
FEUP and INESC TEC
Porto, Portugal
catalao@fe.up.pt

***Abstract*—This paper investigates the optimal allocation of Spinning Reserve (SR) for power systems in the presence of Renewable Energy Sources (RES) and Electrical Energy Storage (EES) devices. This is done in order to reduce the system's dependency on thermal generation units and the decrease total daily operational cost. A Security Constrained Unit Commitment (SCUC) model for a typical power system was used, which includes thermal and renewable generation units and EES devices in the form of batteries. In the proposed model, the hourly operation strategy is determined by adopting a predetermined level of SR. In order to optimize SR requirements, the Independent System Operator (ISO) runs the SCUC problem and determines the minimum SR that should be provided by generation units and EES devices. The simulation results illustrate that by optimizing the operation of batteries, the ISO can effectively reduce the required capacity of thermal units. Therefore, optimal SR allocation under RES uncertainty is determined in this study.**

***Index Terms*—Energy Storage, Renewable Energy Source, Security Constrained Unit Commitment, Spinning Reserve.**

NOMENCLATURE

Sets:

b	Index for buses
d	Index for demand buses
i	Index for thermal power generations
j	Index for renewable power generations
k	Index for electrical energy storages
l	Index for transmission lines
s	Index for scenarios
t	Index for time

Symbols:

Max	Maximum value
Min	Minimum value
$Ch.$	Charging mode
$Disch.$	Discharging mode

Parameters:

$A(b,l)$	Incidence matrix of transmission network
MSR_i	Spinning reserve provision per minuete
P_{sdt}	Demand in scenario s at bus d at time t
P_{jst}	Power generation in scenario s for unit j at time t
$R_{st}^{Spin.}$	Minimum required SR in scenario s at time t
RU_i	Ramp-up for thermal unit i
RD_i	Ramp-down for thermal unit i
XL	Reactance of transmission line l
T_i^{on}	Minimum up time of unit i
T_i^{off}	Minimum down time of unit i
$\alpha_i, \beta_i, \gamma_i$	Coefficient of quadratic cost function for unit i
$\eta_k^{Ch.}$	Efficiency of charging mode of EES
$\eta_k^{Disch.}$	Efficiency of discharging mode of EES
π_s	Occurrence probability of scenario s

Variables:

E_{skt}	Stored energy in scenario s at ESS k at time t
P_{sit}	Power generation in scenario s for unit i at time t
$P_{skt}^{Ch.}$	Hourly charging power in scenario s for ESS k
$P_{skt}^{Disch.}$	Hourly discharging power in scenario s for ESS k
PL_{slt}	Power flow in scenario s through line l at time t
SUC_{sit}	Start-up cost in scenario s of unit i at time t
SDC_{sit}	Shut-down cost in scenario s of unit i at time t
I_{sit}	Binary decision variable of unit commitment
$X_{skt}^{Ch.}$	Binary decision variable of charging mode
$X_{skt}^{Disch.}$	Binary decision variable of discharging mode
δ_{sbt}	Voltage bus angle in scenario s of bus b at time t

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I. INTRODUCTION

With the increase of distributed generation within electricity networks, the development of active grids has become more important than ever in order to increase operational sustainability and security [1]. The intermittent nature of renewable energy sources (RES), especially PV and wind, have made secure operation of power systems more challenging. Increased RES penetration within distribution networks has increased the need for spinning reserves (SR), as well as generators with faster ramping capabilities in order to account for fluctuations in renewable energy output. Battery storage can also assist network operators by being fast response reserves which can be used to satisfy SR requirements [2].

A. Motivation

There is significant potential for battery energy storage systems (BESS) to assist in providing ancillary services. BESS are capable of very fast response times and ramp rates [3], and have low marginal costs during operation [4]. These feautures make BESS, and energy storage systems (ESS) in general, a potentially valuable resource to provide SR services in the day-ahead market. This is especially the case in highly volatile markets with RES generation uncertainty. This work aims to maximize the benefit of a power system operator by investigating optimal utilization of ESS assets in the presence of RES uncertainties.

B. Literature Review

Many works studying the integration and optimization of spinning reserves use security constrained unit commitment (SCUC) or unit commitment (UC) models. These models have been evolving, especially in recent years, due to RES integration in power systems [5], [6] and the need to accommodate associated challenges: namely uncertainty and variability. However, RES uncertainty is not the only one present in the system, as there are also uncertainties arising from the both the demand and energy price fluctuations. One way to respond to this challenge is through the integration of an ESS [7], [8], [10], which can be used during system operation to respond to uncertainties from different sources. In order to incorporate uncertainty into an optimization model for operation, it is necessary to represent it using a suitable mathematical model.

Numerous have addressed the modeling of uncertain behaviour. The degree of uncertainty present in a signal determines the most suitable modelling approach: deterministic [11], stochastic [12–14], robust [15–18], and chance-constrained [19], [20]. Different studies have considered the application of all the aforementioned modeling approaches showing varying degrees of performance, depending on the case study. The authors of [11] implemented a deterministic solution for SCUC with ESS (without considering degradation costs), using mixed-integer programming. In [15], a robust optimization method was developed, modeling flexible uncertainty of wind power generation incorporated in the solution of SCUC. Another study [16] used multistage adaptive robust optimization, which considered the correlation of temporal and spatial uncertainties for both wind and solar power generation. The study validated the proposed approach on the Polish 2736-bus test system. The works of [19] and [20] both used a methodology based on chance constraints. Meanwhile, [19] developed a chance-constrained two-stage stochastic programming model for SCUC which takes into account both load demand and wind power uncertainties. Wang et al. [20] presented anoth chance-constrained and goal programming approach to which accounts for wind generation intermittency in SCUC. In their model, the uncertainties were forecasted by means of non-parametric neural network-based prediction, while Monte Carlo simulations were used to generate scenarios for the stochastic SCUC accounting for wind speed uncertainties. In recent years, stochastic models have gained popularily in modeling uncertainties of power systems. In [13], a which data-driven stochastic optimization was employed to solve SCUC. Blanco and Morales in [12] used scenario-based optimization and clustering scenarios (characterizing probability density functions). In this approach, the conservatism of the algorithm can be adapted, which can be performed by changing the number of divisions segmenting the uncertain variable sample space. Moreover, a stochastic SCUC model in [14] also incorporates non-spinning reserves.

Very few studies take into account ESS presence in a SCUC problem and explore its great potential to provide ancillary services, including SR. The authors of [21] evaluated a variety of ESS systems with different characteristics and capacities to determine the optimal allocation of each ESS to provide both frequency regulation and SR services. A cost-benefit analysis was carried out by [10] to determine the capacity of ESS to provide SR requirements. A novel non-probabilistic model is introduced in [8] to evaluate the uncertainty associated with markets for SR and frequency regulation using robust optimization.

C. Contribution

In this study, a mixed-integer non-linear programming approach is used to determine the optimal reserve margin for a power system with RES and electrical ESS. In the proposed model, two-stage stochastic programming is adopted, in which optimal allocation of SR would be attained by solving the SCUC problem as the main sub-problem. The optimal operation of the ESS devices would be attained by coptimal scheduling of charging/discharging cycles during the defined planning horizon. The required SR is thereby provided by both ESS and thermal generating units. Therefore, the optimization of the operation of such assets is the main solution sought in this study to better cope with RES uncertainties.

D. Paper Organization

This paper is organized as follows: Section II presents an overview of the modelling of ESS in power systems; In Section III, the formulation of the stochastic SCUC problem is provided; In Section IV, the three case studies and simulation results are demonstrated; Finally, the conclusions of this work are highlighted in Section V.

II. ELECTRICAL ENERGY STORAGE SYSTEMS MODELING

Fast response units with fast governors or ESS are necessary for power systems which have significant uncertainties associated with load demand and/or power generation from intermittent renewable energy sources. In general, the model presented in this paper can be used both for hydro pumped-storage units or medium and large-scale battery storage systems, which have experienced an increase in use in recent years. The most important feature of electrical ESS, or EES, is the dynamic nature of the stored energy when taking into consideration the charging/discharging capability. The energy balance equation of such units is:

$$E(t) = E(0) + \int_0^T Q(t)dt \cong E(0) + \Delta E \tag{1}$$

It is obvious that the constraint varies across time and the energy at each instant is a function of the energy available in the previous time period. If the operating state is charging Q would be positive and the stored energy increases. On the other hand, in the discharging mode, Q would be negative and the energy stored in the EES system decreases. The above relation can be rewritten as (2) which takes into account the charging and discharging efficiencies of the EES unit.

$$E_{kt} = E_{k,t-1} + \frac{1}{\eta_k^{Ch.}} P_{kt}^{Ch.} - \eta_k^{Disch.} P_{kt}^{Disch.} \tag{2}$$

The energy stored in the EES unit is constrained through the following limitation, where the superscripts max and min, respectively show the upper and lower limit of the stored energy.

$$E_k^{Min} \leq E_{kt} \leq E_k^{Max} \tag{3}$$

It should be noted that the simultaneous operation of the EES unit in both modes is impossible. Thus, a set of binary variables should be defined to characterize each operating mode. It is obvious that the amount of power delivered/absorbed to/from the grid is limited. To this end, the following constraints are defined:

$$0 \leq P_{kt}^{Ch.} \leq \frac{1}{\eta_k^{Ch.}} P_{kt}^{Max,\,Ch.} X_{kt}^{Ch.} \tag{4}$$

$$0 \leq P_{kt}^{Disch.} \leq \eta_k^{Disch.} P_k^{Max,\,Disch.} X_{kt}^{Disch.} \tag{5}$$

$$0 \leq X_{kt}^{Ch.} + X_{kt}^{Disch.} \leq 1 \tag{6}$$

III. STOCHASTIC SCUC PROBLEM FORMULATION

With regards to the uncertainties of the problem (which are due to the load demand forecast, and wind and solar power generation) a stochastic model is defined for the SCUC problem. Using this framework, the total cost is quantified and minimized as the expected value of the probable scenarios.

This section provides a more complete model for the joint energy generation and the operation of ESS with the capability of handling the uncertainties. The transmission system's constraints have been assigned to the model as well.

In the present context of stochastic optimization, the objective minimization function is expressed as:

$$Min \sum_{s=1}^{NS} \sum_{i=1}^{NG} \sum_{t=1}^{NT} \pi_s [F_{ci}(P_{sit}) I_{sit} + SU_{sit} + SD_{sit}] \tag{7}$$

$$F_{ci}(P_{sit}) = \alpha_i + \beta_i P_{sit} + \gamma_i P_{sit}^2$$

where π_s and NS denote the probability of scenarios s and the number of scenarios, respectively. It is noteworthy that the operating costs of renewable energy technologies and the EES units are negligible compared to the fossil-fuel generating units, thus such costs are excluded in this paper. The expected values of the operating costs, including the fuel cost as well as the start-up and shut-down costs, are considered as the objective function, in which the summation of all the terms is to be minimized. The associated constraints of the SCUC problem stochastic model are as follows:

$$\sum_{i=1}^{NG} P_{sit} + \sum_{j=1}^{NR} P_{sjt} + \sum_{k=1}^{NK} \left[P_{skt}^{Disch.} - P_{skt}^{Ch.}\right] = P_{sdt} \tag{8}$$

$$\sum_{i=1}^{NG} R_{sit}^{Spin.} + \sum_{k=1}^{NK} \left[E_k^{Max} - E_{skt}\right] \geq R_{st}^{Spin.} \tag{9}$$

$$0 \leq R_{st}^{Spin.} \leq \min\{(10 \times MSR_i), (P_i^{Max} - P_{sit})\} \tag{10}$$

$$P_{sit} - P_{si(t-1)} \leq \tag{11}$$
$$[1 - I_{sit}(1 - I_{si(t-1)})]\, RU_i + I_{sit}(1 - I_{si(t-1)}) P_i^{Min}$$

$$P_{si(t-1)} - P_{sit} \leq \tag{12}$$
$$[1 - I_{si(t-1)}(1 - I_{sit})]\, RD_i + I_{si(t-1)}(1 - I_{sit}) P_i^{Min}$$

$$[x_{si(t-1)}^{on} - T_i^{on}] \times [I_{si(t-1)} - I_{sit}] \geq 0 \tag{13}$$

$$[x_{si(t-1)}^{off} - T_i^{off}] \times [I_{sit} - I_{si(t-1)}] \geq 0 \tag{14}$$

$$P_i^{Min} \leq R_{sit} + P_{sit} \leq P_i^{Max} \tag{15}$$

$$P_j^{Min} \leq P_{sjt} \leq P_j^{Max} \tag{16}$$

$$E_{skt} = E_{sk,t-1} + \frac{1}{\eta_k^{Ch.}} P_{skt}^{Ch.} - \eta_k^{Disch.} P_{skt}^{Disch.} \tag{17}$$

$$E_k^{Min} \leq E_{skt} \leq E_k^{Max} \tag{18}$$

$$0 \leq P_{skt}^{Ch.} \leq \frac{1}{\eta_k^{Ch.}} P_{kt}^{Max,\,Ch.} X_{skt}^{Ch.} \tag{19}$$

$$0 \leq P_{skt}^{Disch.} \leq \eta_k^{Disch.} P_k^{Max,\,Disch.} X_{skt}^{Disch.} \tag{20}$$

$$0 \leq X_{skt}^{Ch.} + X_{skt}^{Disch.} \leq 1 \tag{21}$$

$$P_{sit} + P_{sjt} + P_{skt}^{Disch.} - P_{skt}^{Ch.} - P_{sdt} = \tag{22}$$
$$\sum_{l=1}^{NL} A(b,l) PL_{slt}$$

$$\sum_{b=1}^{NB} A^T(b,l) \delta_{sbt} = \sum_{l=1}^{NL} XL^{[Diagonal]} PL_{slt} \tag{23}$$

$$\delta_{sbt} = 0 \quad \forall b = 1 \tag{24}$$

$$-PL_l^{Max} \leq PL_{slt} \leq +PL_l^{Max} \tag{25}$$

Eq. (8) indicates the power balance equation as the most important constraint in power system operation, where fossil-fuel units alongside RES and EES units are expected to supply the total load. P_{sit} and P_{sjt} indicate the power generated by fossil-fuel and RES units, respectively. The total power generated by both is equal to the sum of the uncertain load demand and transmission losses. The total number of EES units is denoted by *NK* while *NR* indicates the total number of RES units (wind and solar). SR requirements have been stated in (9), where only fossil-fuel and EES units are capable of providing this service as such units must be synchronized and in-service. Renewable energy units cannot supply this service as they are intermittent [30]. It is noteworthy that EES units have the capability to deliver/absorb substantial power in emergency conditions. Hence, the available capacity at each time is defined as the difference between the maximum capacity and the energy stored in the unit. Due to the thermal and also the governor's limitations, fossil-fuel units are not able to provide reserve as expressed in (10). The Ramp-Up (RU) and Ramp-Down (RD) constraints of fossil-fuel units are represented in constraint (11) and (12), respectively. Furthermore, constraints (13) and (14) state the Minimum Up-Time (MUT) and Minimum Down-Time (MDT) limitations. Power generated by thermal units is constrained by upper and lower limits as (15). The same constraint is also true for RES while they are not dispatchable but dependent on wind speed and solar irradiation (16). The constraints of EES units in the stochastic framework are represented through (17)-(21).

Transmission system constraints were assumed, since load centers are usually located at distant locations. Therefore, a stochastic SCUC problem with a DC Optimal Power Flow (DCOPF) model was formulated. Utilizing DCOPF, the power losses are generally neglected and only active power flow is considered. In this respect, DCOPF equations are expressed in (22) and (23) using the incidence matrix technique [35], where *NL* and *NB* indicate the total number of transmission lines and buses, respectively. $XL^{[Diagonal]}$ is the reactance matrix and δ_{sbt} is the voltage angle of bus *b* at time *t* and scenario s. Superscripts *l* and *b* illustrate the transmission line number and bus number, respectively. The voltage angle of the slack bus is assigned as zero as (24) and all other voltage angles at the buses are determined with respect to it. Moreover, the power flow in the lines is limited by the capacity of the transmission lines as represented in (25).

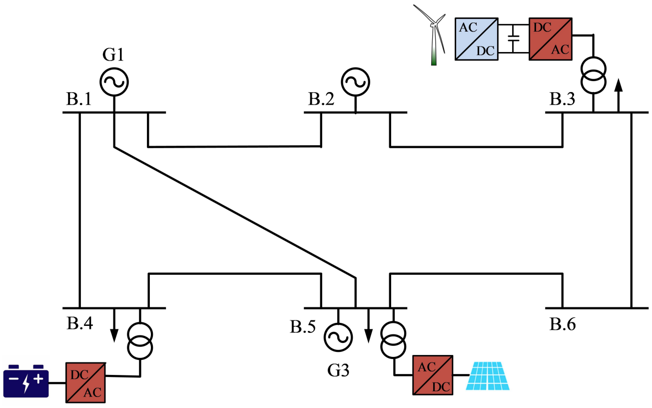

Fig. 1. Single-line diagram of 6-Bus test system [5].

TABLE I
DATA OF TRANSMISSION LINES

Line	From	To	XL	PL^{Max}
L1	1	2	0.170	65
L2	1	4	0.258	70
L3	2	4	0.197	40
L4	5	6	0.140	40
L5	3	6	0.018	75
L6	2	3	0.037	80
L7	4	5	0.037	65

TABLE II
GENERATION UNIT DATA

Unit	α	β	γ	P^{Max}	P^{Min}
$G1$	211.4	6.589	0.099	220	100
$G2$	217.4	7.629	0.203	160	10
$G3$	102.8	10.07	0.494	100	10
Unit	MUT	MDT	RD, RU	SU	SD
$G1$	4	3	55	100	100
$G2$	3	2	50	200	10
$G3$	4	3	20	80	10

TABLE III
GENERATION UNIT DATA

$E(0)$	$E(24)$	$P^{Ch.}$	$P^{Disch.}$
40 MWh	40 MWh	15 MW	15 MW
$\eta^{Ch.}$	$\eta^{Disch.}$	E^{Max}	E^{Min}
100 %	100 %	80 MWh	20 MWh

IV. SIMULATION RESULTS

The presented model is simulated on a 6-bus test system with seven transmission lines and three generation buses with fossil-fuel units. The loads are located at three buses. RES and EES units have been connected to buses 3, 4, and 5. Fig. 1 shows the single-line diagram of the network. Tables I-III list all the data corresponding to the transmission lines, thermal generating units and the EES unit, respectively. Fig. 2 depicts the load demand of the system where the contribution of buses 3 and 4 is 35 each and 30 % of the load demand is located at bus 5. In this regard, three different case studies were considered in this study.

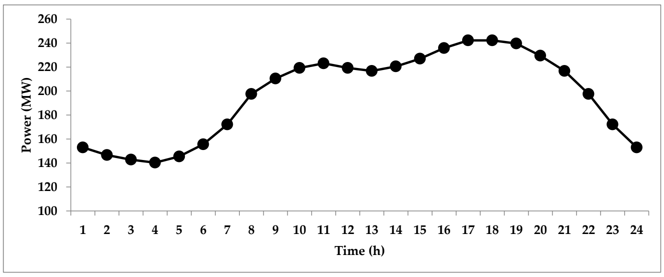

Fig. 2. The hourly load demand of the test system.

TABLE IV
HOURLY UNITS COMMITMENT - BASE CASE SCUC

Unit	$Hours(1-24)$
$G1$	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
$G2$	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
$G3$	0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

TABLE V
HOURLY UNITS COMMITMENT - STOCHASTIC SCUC

Unit	$Hours(1-24)$
$G1$	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
$G2$	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
$G3$	0 0 **1 1** 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

A. First Case Study: SCUC Base Case

First, the SCUC is solved disregarding RES and EES units (only thermal generation). The optimal generation schedule is shown in Table IV, where is it observed that units G1 and G2 are committed over the entire 24-hour period. Unit G3 is committed from hour 5 to the end due to the increase in load demand and the incremental generation costs of the other two units. Note that SR requirements have been considered in this scenario in which in-service units can provide the reserve requirements. The total operating cost was $ 124069.71. By assigning the largest generating unit as the SR, the schedule and total operating cost are unchanged. Meanwhile, assigning the largest unit and 10 % of the load demand as the SR would be infeasible since the peak load demand is 242.3 MW and the total reserve margin is 237.7 MW. As a result, taking into account the capacity of the largest unit and 10 % of the peak load demand, which is 24.23 MW, the SR requirement is 244.23 MW which would be impossible to supply. Note that the total installed generation capacity is 480 MW, so providing the system with the required SR is not possible.

B. SCUC with ESS Unit

This case investigates the impact of the EES unit on the provision of the required spinning reserve. It is expected that the EES unit facilitates the secure and economic operation of the power system taking into consideration the spinning reserve requirements of the system. This case does not consider renewable energy units. The simulation results verify that installing the EES unit at bus 4 as a load bus would substantially reduce the operating costs. The optimal operating cost, in this case, disregarding the reserve requirements is $ 121096.84 which is lower than Base Case by $ 2972.87. Taking into account the capacity of the largest unit as the spinning reserve requirements criterion and also the largest unit along with 10 % of the load demand, the system operation would not encounter any challenge. The lowest amount of the spinning reserve, in this case, occurs at hour 15 and it is equal to 273 MW. With respect to the load demand at this hour which is 227 MW, the spinning reserve is 242.7 MW which can be easily met. The EES unit provides 20 MW of the 273 MW spinning reserve and the remaining is supplied by thermal units.

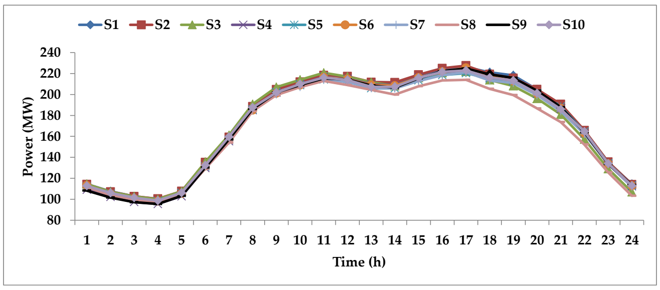

Fig. 3. Scenarios of the load demand.

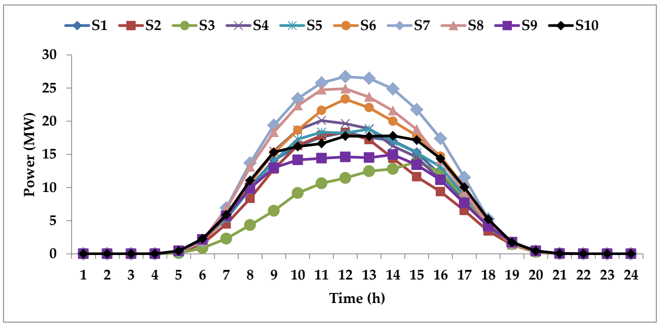

Fig. 4. Scenarios of the solar power generation.

C. SCUC with ESS Unit and RES

This case discusses the stochastic SCUC problem considering the uncertainties due to the load demand forecast and renewable power generation. Due to such uncertainties, the expected value of the total operating costs and the commitment status of units would be different from the base case. Figs. (3)-(5) show the generated scenarios for characterizing the uncertainties of the load demand, solar power, and the wind power generation, respectively. Besides, Table V represents the commitment status of the generating units in this case.

The simulation results show that unit G3 must be committed for two more hours compared to the base case in order to sup-

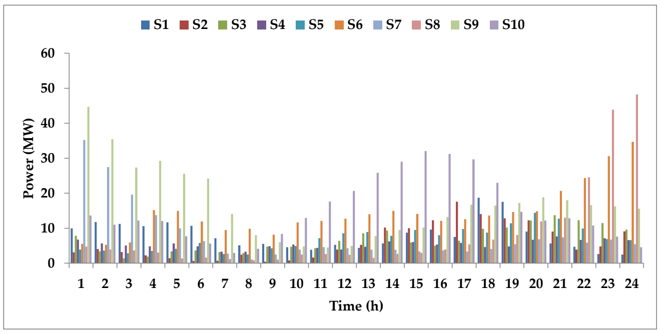

Fig. 5. Scenarios of the wind power generation.

ply the required reserve considering the capacity of the largest unit along with 10 % of the load demand as the criterion. This issue is mainly due to the fluctuations of the wind power generation over the beginning hours. The expected value of the total operating cost is \$ 87551.54. This cost reduction is due to the renewable power generation with negligible generation cost. The EES unit would enable the system operator to provide the required reserve and manage the uncertainties of the load demand and renewable energies. Thus, it is expected that the operating cost reduces substantially.

V. CONCLUSION

In this study, an approach to optimize the reserve margin of spinning reserves, incorporating EES and RES, was proposed, implemented, and validated. The model was based on a two-stage, stochastic, security-constraint unit-commitment (SCUC) problem formulation. Three case studies were cosidered: SCUC with only conventional generation (base case), SCUC with EES, and SCUC with ESS and renewable generation (both wind and PV). The uncertainties associated with load demand and renewable generation were modeled by considering a stochastic model in which 10 possible scenarios for each source of uncertainty are constructed and combined. A mixed-integer programming optimization model was used to solve the SCUC problem for each case. The results demonstrate the the operating costs are reduced significantly by applying the proposed SCUC approach by incorporating EES, especially in the presence of renewable generation.

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