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A Flexibility Based Approach on Wind/Load Curtailment Reduction in Presence of BESS

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ABSTRACT: Nowadays, renewables are the first choice option for a modern power system generation scenario. It is due to their high attraction, especially environmental attraction, cost aspects and also availability in almost all over the world. Wind and solar sources are now competitive with conventional sources and command a high percentage of investments in renewable power. The main challenge of using these cheap and clean energies is their output power uncertainty, and their variability may lead to wind/solar power curtailment, or load shedding caused by insufficient spinning and fast reserve. Energy storage systems integrated with renewable energies are a common solution for this challenge. However, they impose extra cost to planning, and operation costs need a suitable economic study for the best location and size of these systems.

In this paper, a flexibility based approach is used to show the role of Battery Energy Storage System (BESS) in the wind/load curtailment reduction. This approach can lead to a suitable economic routine to determine BESS size based on economic trade-off between BESS fixed, variable costs and wind/load curtailment costs. First, the BESS flexibility index is introduced and the suitable State of Charge (SoC) control is presented to use for Dynamic Economic Load Dispatch (DELD) solution based on the wind/load curtailment reduction. The simulation results show the efficient dependency between system flexibility improved by BESS integration, and the wind/load curtailment reduction.

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1- INTRODUCTION

Nowadays Energy Storage Systems (ESS) are widely used in the power system, especially due to wide use of renewable energies. ESS technology improvement and the reduction cost trend of this technology show wider deployment of ESS in the future. As we know, power system flexibility reduces due to the uncertainty and variability in the renewable outpour power. ESS is one of the main tools used to provide sufficient flexibility for the safe and stable operation of power systems integrated by renewable sources. As far as the wind curtailment issue is concerned, power systems should have sufficient flexibility to mitigate short-term fluctuations of wind power as well as the temporal mismatch between the total generation, including the wind power and the load. With the increasingly mature energy storage technology, grid-scale ESS is regarded as a potential solution to provide the required flexibility for accommodating large-scale wind power generation. Flywheel Energy Storage System (FESS) can be used to store the wind energy in the form of kinetic energy when the wind output power or ramp up is more than the desired values. On the other hand, when the wind output power is less or ramp down is more than the specified values, it can release the stored energy. Battery Energy Storage System (BESS) is a conventional and widely used ESS, integrated by the large-scale wind farms. Superconductive Magnetic Energy Storage System (SMESS), Ultra-Capacitors and Compressed Air Energy Storage (CASE) systems are the other types of ESS, used by large-scaled wind farms.

The two inherent specifications of renewable energies output power, uncertainty and variability, are the two main different approaches to use ESS. Smoothing the output power due to the variability specification is the first approach to use ESS, which effects the high ramp up/down conventional generation units yields to more efficiency of the generation system. Fig. 1 shows the performance of ESS for output power smoothing and high ramp rate reduction [1].

The second approach which is the main goal of the current paper, is to reduce unwanted renewable power output or load curtailment caused by output power uncertainty. Curtailment of the renewable output power is an increasing concern in electric power systems. Due to the low effective capacity factor of wind energy, it needs a suitable balance for adequate reserve generation and also wind energy curtailment to achieve the best economic profit. Fig. 2 shows a typical wind generation capacity factor curve.

Energy storage is one of the main options to decrease renewable curtailment and use the most amount of accessible wind energy. Energy storage reduces wind curtailment by increasing grid flexibility [2].

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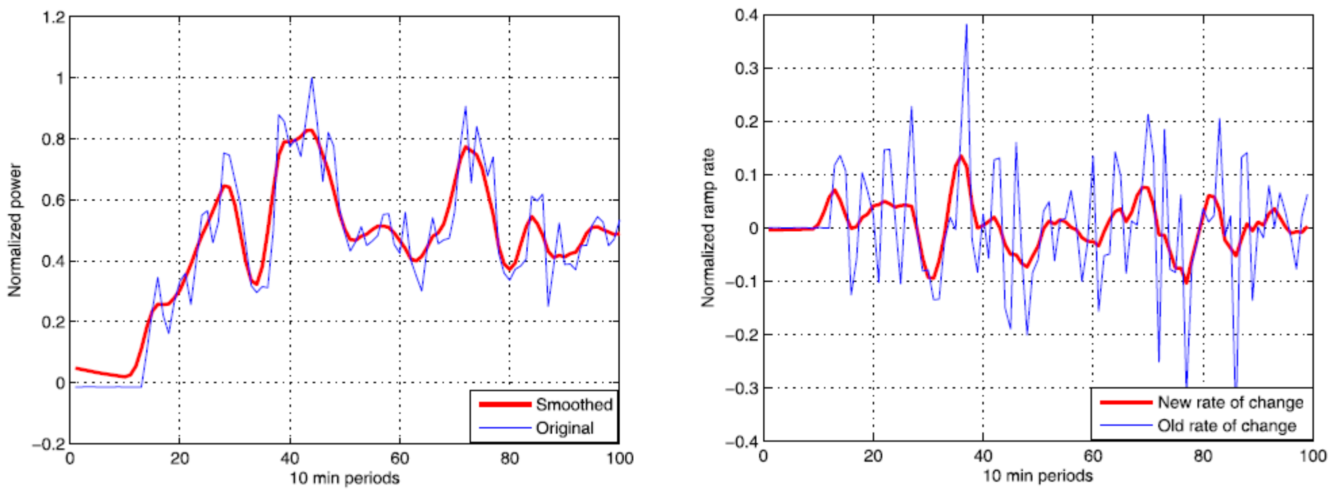

Fig. 1. ESS performance on the output wind power smoothing and ramp rate reduction

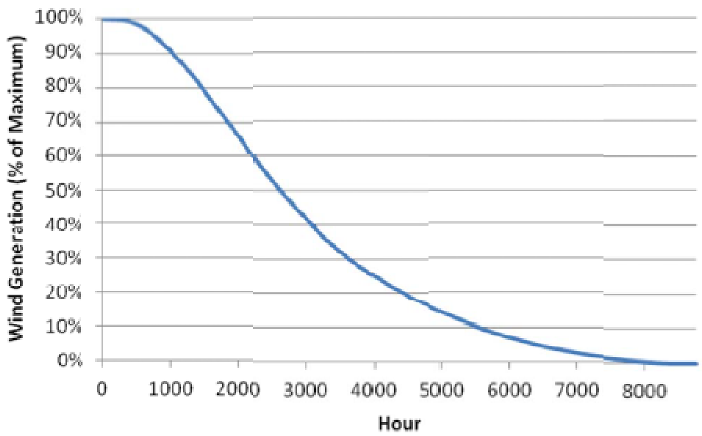

Fig .2. Typical wind generation capacity factor curve

Each of the two mentioned approaches need to coordinate the operation of the wind turbine and ESS, but in different control strategies where a variety of methods and algorithms are developed. Some of the related studies are focused on power smoothing and power ramp control of the wind farm output power. A review of intermittent smoothing approaches for the wind farm output power is illustrated in [3]. On the other hand, the wind/load curtailment reduction is the base of some other researches focused on EES control strategy. As a feasible solution to alleviate wind power curtailment, BESS has been extensively studied in the recent years [4]. Wind curtailment occurs due to the non-correlation between the wind and load profiles during high wind electricity output periods when the load is lower. The term non-correlation refers to the fact that wind or any other renewable generation, which is nature driven, does not follow the load like conventional power plants [5]. In cases where the wind generation is more than the load minus must-run generation, the excess of wind energy needs to be curtailed to keep the balance between demand and supply. A simulation model for maximizing economic profit from coordination of renewable wind and pumped storage with thermal power generation for a GENCO is presented in [6]. The participation in energy and ancillary service markets with considerations for environmental emission and uncertainty associated with the wind power has been included, and a newly heuristic optimization algorithm is developed. An optimal power dispatch scheduling method based on model predictive control (MPC) scheme is proposed in [7] for a wind farm integrated battery energy storage system. The objective of the proposed method is to minimize the energy loss of the wind farm and the battery usage while meeting the grid constraints. Another coordinated control algorithm is proposed in [8] to mitigate the wind power fluctuation by using the coordinated control between the wind turbine and the ESS, considering ESS State of Charge (SoC) and the wind power fluctuation. The main objective of the approach presented in [9] is to obtain the optimal sizing of a hybrid PV-wind-diesel system considering battery energy storage in order to minimize total cost. Annual sun radiation and wind speed are evaluated, and simulation results are presented for two different types of common PV technologies. An optimal control strategy is presented in [10] with an objective of minimizing the probability of violating the limits of the combined output power fluctuations from the cogeneration system. The goal of the study presented in [11] is to solve the optimal bidding strategy problem for a GENCO with coordinated wind-pumped storage-thermal system for maximizing economic profit with participation in day-ahead energy and spinning reserve markets with considerations for CO2 emission and the wind power uncertainty. A dynamical control system is presented in [12] which is based on model predictive control (MPC) in real time, and to make full use of the flexibility and controllability of energy storage to mitigate problems of wind farm variability and intermittency. As can be seen, the common concept in the mentioned articles is the coordinated operation of renewable energy and ESS to maximize the economic profit. The coordinated operation and wind power fluctuation reduction are two key concepts can be found in the mentioned articles.

In [5], a planning tool is proposed for electric utility operators to provide an insight into the sizing and operation of grid-scale energy storage technologies and demand response programs to reduce curtailed wind energy. Wind curtailment challenge can be mitigated by increasing flexible resources in the system, such as energy storage and demand response [13]. It is possible to partially deal with the variable and stochastic generation from renewable sources by cycling intermediate power plants. However, the downside of this strategy is fatigue and has increased the rates of maintenance. Wind curtailment is a serious issue in stand-alone (island) systems with no interconnections for importing or exporting electricity. The economic and dynamic security issues for an island system with high wind energy penetration is discussed in [14]. A two-stage method to determine the optimal power and capacity of BESS in systems including thermal plants, wind farms, and BESS to reduce the wind curtailment is proposed in [15]. In the first stage, the unit commitment of the thermal generators and scheduled wind farm outputs are optimized with AC power flow constraints modeled by second-order cone programming (SOCP). Time series of the wind farm output generated by Monte-Carlo simulations are used for BESS optimization. In the second stage, operational strategies for BESS are designed. An optimization formulation to assess the techno-economic possibility of employing storage from the DSO point of view is presented in [16]. Where the amount of wind curtailment is minimized, and the congestion is avoided. Some control schemes for BESS mainly based on smoothing power output are discussed in [17, 18]. Another scheme which is the main concept of the current paper, is to reduce the renewable energy/load curtailment illustrated in [19, 20]. This scheme can be used for the economic trade-off between flexibility improvement cost and the renewable energy/load curtailment cost (penalty) to obtain the best level of system flexibility.

The goal of the current paper is to relate the reduction in the wind/load curtailment to the system flexibility enhancement due to the wind turbine and BESS coordinated operation. In this way, a generation/load unbalance compensation method is presented which uses the maximum effort of BESS to reduce the generation/load unbalance. This approach can also be used to determine the suitable BESS capacity and ramp up/down specification for the desired wind/load curtailment or to establish the economic trade-off between flexibility improvement cost and the renewable energy/load curtailment cost. Where the flexibility improvement cost is equivalent to use of BESS with suitable capacity and ramp up/down specification.

2- CONTRIBUTION

This paper proposes a flexibility based coordinated wind turbine and BESS operation approach to reduce wind/load curtailment in a power system including the wind farm integrated BESS. As the generation system flexibility index and also BESS flexibility index are introduced by authors in [21] and [22], the contribution of this paper is to establish a control scheme for BESS charge/discharge focusing on reduction of the wind/load curtailment to the minimum feasible amount which leads to total system flexibility improvement. Similar to the approach on upper and lower components of generation unit flexibility index illustrated in [21], this concept is used for BESS flexibility index to introduce upper and lower components [22]. Since the BESS ramp rate is positive when it charges and negative when it discharges, the wind curtailment reduction is obtained by increasing the upper component and lower component. This enhancement causes reduction in the load curtailment, which is despite the generation flexibility components behavior. The investigation of the relation between the wind curtailment and the upper component of BESS flexibility index and also between the load curtailment and the lower component is as another contribution respect to [22].

As the generation unit flexibility index and generation system flexibility index are introduced in [21] with details, their description is avoided in this paper. Hence, in the following, the BESS charge/discharge model is presented. The BESS flexibility index approach is introduced in part 4. Dynamic Economic Load Dispatch (DELD) including the BESS model description and the proposed control scheme for reduction wind/load curtailment is illustrated in part 5. Simulation and analysis are presented in part 6 and finally part 7 contains the conclusion.

3- BATTERY ENERGY STORAGE MODEL

Nowadays energy storage systems are the inseparable parts of the renewable energy plants, especially large-scale wind and solar farms. Fast technology improvement and cost reduction of these systems are the two main reasons for their wide use. Large-scale battery energy storage system is one of the main types of energy storage used for large scale wind and solar farms integration. The main advantage of BESS is its very fast up/down ramp rate with respect to the other types such as pumped storage system and CAES. In Fig. 3, a very simple and schematic view of the wind energy conversion system and BESS integrated to the power system is shown.

The basic power balance can be written as:

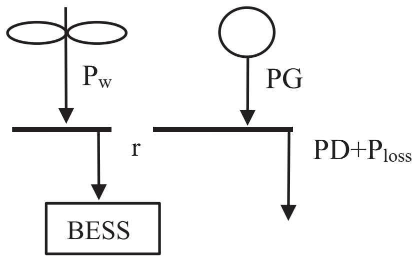

Fig. 3. Simple wind power and BESS integration system schematic

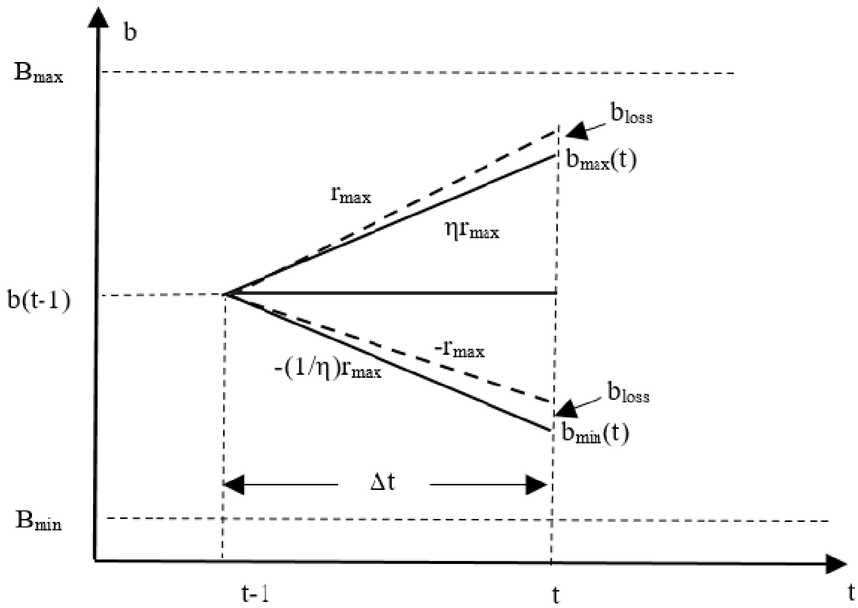

Fig. 4. Battery energy storage model

$$PG + Pw = PD + P_{loss} + r \quad (1)$$

If the battery is in charging mode, r is positive.

Now the main characteristics of BESS charge/discharge model is shown in Fig. 4. [23]. Dotted lines for charge/discharge rate show no energy loss situation. It can be formulated as:

$$\frac{b(t) - b(t-1) - b_{loss}}{\Delta t} = r(t) \quad (2)$$

The main constraints are:

$$B_{min} \le b(t) \le B_{max} \quad (3\text{-}1)$$
$$-r_{max} \le r(t) \le r_{max} \quad (3\text{-}2)$$

Where b_{loss} shows the energy dissipated in charge/discharge process and is always positive. b_{loss} is usually considered as a ratio of charged or discharged energy as:

$$b_{loss} = (1-\eta_c)\big(b(t) - b(t-1)\big) \quad \text{charge mode} \quad (4\text{-}1)$$

$$b_{loss} = (1-\eta_d)\big(b(t-1) - b(t)\big) \quad \text{discharge mode} \quad (4\text{-}2)$$

By assumption $\eta_c = \eta_d = \eta$ and substitution (4-1) and (4-2) in (2), we have:

$$\frac{b(t) - b(t-1)}{\Delta t} = \eta r(t) \quad \text{charge mode} \quad (5\text{-}1)$$

$$\frac{b(t) - b(t-1)}{\Delta t} = \frac{1}{\eta} r(t) \quad \text{discharge mode} \quad (5\text{-}2)$$

4- BESS Flexibility Area Index

As mentioned earlier, Flexibility Area Index (FAI) for unit generation and the proposed method for combination of units' flexibility index to obtain system flexibility index are determined in [21] with details. The main concept of flexibility area index for BESS is also described in [22] which is reviewed briefly here. As can be seen in Fig. 4, the triangle as (b(t-1), $b_{min}(t)$, $b_{max}(t)$) is the acceptable charge/discharge BESS State of Charge (SoC) in [t-1,t] time interval. The area of the mentioned triangle, defined as BESS Flexibility Area Index, can be easily calculated as:

$$S_{es} = 0.5 * (\eta + \frac{1}{\eta}) r_{max} \Delta t^2 \triangleq S_{es1} + S_{es2} \tag{6}$$

S_{es1} is the upper area of S_{es} and S_{es2} is the lower area [22]. Where S_{es1} corresponds to the BESS flexibility to cope the sudden wind power rise to avoid wind curtailment and S_{es2} corresponds to the BESS flexibility to cope the sudden wind power fall to avoid load curtailment.

When $b(t\text{-}1)+\eta r_{max}\Delta t > B_{max}$, Se_{s1} will reduce to:

$$S_{es1} = 0.5\eta r_{max}\Delta t^2 - 0.5\eta r_{max} Dt_1^2 \tag{7}$$

Where Dt_1 can be found as:

$$Dt_1 = \Delta t - \frac{B_{max} - b(t-1)}{\eta r_{max}} \tag{8}$$

Similarly if $b(t\text{-}1)-(1/\eta)r_{max}\Delta t < B_{min}$, S_{es2} reduces to:

$$S_{es2} = 0.5\frac{1}{\eta} r_{max}\Delta t^2 - \frac{0.5}{\eta} r_{max} Dt_2^2 \tag{9}$$

Where Dt_2 can be found as:

$$Dt_2 = \Delta t - \frac{\eta(b(t-1) - B_{min})}{r_{max}} \tag{10}$$

As the dimension of generation flexibility index is energy (power*time) [21] but the dimension of BESS flexibility index is energy*time, finally by dividing S_{es} to Δt, the BESS flexibility index has the same dimension and can be compared or combined by generation flexibility index.d

$$flex_{es} = \frac{S_{es}}{\Delta t} \tag{11}$$

5- Proposed BESS power control algorithm

In this part the proposed algorithm for Dynamic Economic Load Dispatch (DELD), incorporating stochastic wind power and suitable strategy for BESS charge/discharge is presented where the main goal is to minimize the wind/load curtailment. It is down by assigning the suitable BESS power absorption/insertion (r) considering all constraints. At first the basic formula for DELD incorporating wind power and BESS is presented. The conventional objective function for DELD incorporated wind power can be written as:

$$Cost = \sum_{t=1}^{T}[\sum_{i=1}^{n}\alpha_i P_i(t)^2 + \beta_i P_i(t) + \gamma_i + \sum_{i=1}^{nw} d_i Pw_i(t)] \tag{12}$$

Subject to:

$$\sum_{i=1}^{n} P_i(t) + \sum_{i=1}^{nw} Pw_i(t) = PD(t) + P_{loss}(t) + r(t) \tag{13-1}$$

$$P_{min,i} \le P_i(t) \le P_{max,i} \tag{13-2}$$

$$|P_i(t) - P_i(t-1)| \le Rampup_i \Delta t \tag{13-3}$$

$$|P_i(t) - P_i(t-1)| \le Rampdn_i \Delta t \tag{13-4}$$

$$0 \le Pw_i(t) \le P_{rated,i} \tag{13-5}$$

$$-r_{max} \le r(t) \le r_{max} \tag{13-6}$$

$$\eta r(t)\Delta t \le B_{max} - b(t-1) \tag{13-7}$$

$$B_{min} - b(t-1) \le \frac{1}{\eta} r(t)\Delta t \tag{13-8}$$

Here only one BESS in the system is considered. The wind power has a stochastic behavior due to the stochastic behavior of the wind speed. The relation of the wind power and the wind speed is determined by the third order polynomial function [24]:

$$\begin{aligned} &0 \quad v\langle v_{cut-in} \;, v\rangle v_{cut-out} \\ &Pw = k_w v^3 \quad v_{cut-in} \le v \le v_{rated} \\ &P_{rated} \quad v_{rated} \le v \le v_{cut-out} \end{aligned} \tag{14}$$

Where k_w is defined as:

$$k_w = 0.5 n_t c_p \eta_w A\rho \tag{15}$$

A common probability distribution function (PDF) for the wind speed is Weibul PDF, used to find the wind speed random variable. Therefore, Pw is also a stochastic variable.

The power system loss can be found by B loss coefficient method as [25]:

$$P_{loss}(t)=\sum_{i=1}^{n}\sum_{j=1}^{n}P_i(t)B_{ij}P_j(t)+\sum_{i=1}^{n}B0_iP_i(t)+B00 \quad (16)$$

Suitable method to minimize (12) is the Lagrange Multiplier method, since its quadratic form and the linear form for the constraints. Hence, first Lagrange function is formed as:

$$LG=\sum_{t=1}^{T}[\sum_{i=1}^{n}\alpha_iP_i(t)^2+\beta_iP_i(t)+\gamma_i+\sum_{i=1}^{nw}d_iPw_i(t)-\lambda\left(\sum_{i=1}^{n}P_i(t)+\sum_{i=1}^{nw}Pw_i(t)-PD(t)-P_{loss}(t)-r(t)\right)] \quad (17)$$

Partial derivatives of LG respect to $P_i(t)$'s yields to:

$$\frac{\partial LG}{\partial P_i(t)}=2\alpha_iP_i(t)+\beta_i-\lambda\left(1-\frac{\partial P_{loss}(t)}{\partial P_i(t)}\right)=0 \quad (18)$$

Where:

$$\frac{\partial P_{loss}(t)}{\partial P_i(t)}=2B_{ii}P_i(t)+\sum_{j\neq i}B_{ij}P_j(t)+B0_i\triangleq\delta_i(t) \quad (19)$$

So λ_i corresponds to $P_i(t)$ can be found as:

$$\lambda_i=\frac{2\alpha_iP_i(t)+\beta_i}{(1-\delta_i(t))} \quad (20)$$

Now the minimum and maximum of λ_i should be calculated with respect to the unit limitations. The up and down limits of the generation unit i are as:

$$P_{max,i}(t)=\min(P_{max,i},P_i(t)+Rampup_i\Delta t) \quad (21\text{-}1)$$

$$P_{min,i}(t)=\max(P_{min,i},P_i(t)-Rampdn_i\Delta t) \quad (21\text{-}2)$$

So by substitution (21-1) and (21-2) in (20), we have:

$$\lambda_{max,i}=\frac{2\alpha_iP_{max,i}(t)+\beta_i}{(1-\delta_{i,}(t))} \quad (22\text{-}1)$$

$$\lambda_{min,i}=\frac{2\alpha_iP_{min,i}(t)+\beta_i}{(1-\delta_i(t))} \quad (22\text{-}2)$$

Now the proposed control for BESS power absorption/insertion is described. The main concept is based on the minimization of the wind/load curtailment with the minimum BESS charge/discharge operation. First, minimum and maximum of total permissible unit generation constraints at time (t) are defined as:

$$Uplimit(t)=\sum_{i=1}^{n}P_{max,i}(t) \quad (23\text{-}1)$$

$$Dnlimit(t)=\sum_{i=1}^{n}P_{min,i}(t) \quad (23\text{-}2)$$

Obviously, if the net load (gross load plus loss minus wind power) is more than Uplimit, load curtailment is needed, and if the net load is less than Dnlimit, wind curtailment should be performed. Now, in each DELD iteration the net load is compared by the total generation up/down limits. If the net load is more than the Uplimit, then the difference should be compensated by BESS and r(t) is calculated as:

$$r(t)=Uplimit(t)-(PD(t)+P_{loss}(t)-Pw(t)) \quad (24)$$

Clearly, the calculated r(t) is negative. Hence, the battery is in discharge mode. On the other hand, if the net load is less than the Dnlimit, then the difference should be compensated by BESS in charge mode:

$$r(t)=Dnlimit(t)-(PD(t)+P_{loss}(t)-Pw(t)) \quad (25)$$

In each two mentioned cases, we have three main BESS charge/discharge constraints described by (13-6) to (13-8). If the calculated r(t) violates one of the mentioned constraints, then r(t) should be fixed to the corresponding permissible values and the wind or load curtailment will occur.

If calculated r(t) violates (13-6) in the upper limit, it should be fixed at the upper limit and the load curtailment will occur:

$$LC(t)=(PD(t)+P_{loss}(t)-Pw(t))-(Uplimit(t)+r_{max}(t)) \quad (26)$$

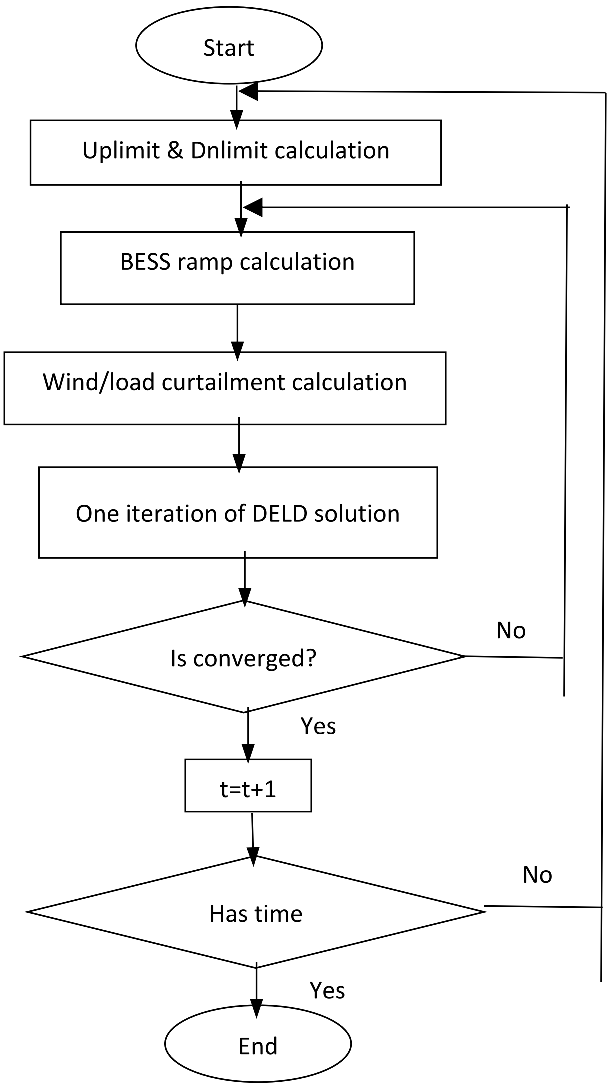

Fig. 5. DELD solution flowchart

Also, if calculated r(t) violates (13-6) in the lower limit, it should be fixed at the lower limit and the wind curtailment will occur:

$$WC(t) = Dnlimit(t) - r_{max}(t) - \left(PD(t) + P_{loss}(t) - Pw(t)\right) \quad (27)$$

If the calculated r(t) violates (13-8), then it should be fixed as:

$$r(t) = \frac{\eta(B_{min} - b(t-1))}{\Delta t} \quad (28)$$

$$LC(t) = Uplimit(t) - r(t) - \left(PD(t) + P_{loss}(t) - Pw(t)\right) \quad (29)$$

Again the load curtailment will occur:

On the other hand, if the calculated r(t) violates (13-7), then it should be fixed as:

$$r(t) = \frac{B_{max} - b(t-1)}{\eta \Delta t} \quad (30)$$

Again the wind curtailment will occur:

$$WC(t) = Dnlimit(t) - r(t) - \left(PD(t) + P_{loss}(t) - Pw(t)\right) \quad (31)$$

It is expected to have minimum wind/load curtailment by the mentioned control charge/discharge scheme and also the minimum operation of BESS charge/discharge. The DELD solution flowchart is shown in Fig. 5.

Table 1. Wind farm data

A (m^2)	ρ (Kg/m^3)	Cp	η_w	n_t	d (\$\MW)	V_{cut-in} (m/s)	V_{rated} (m/s)	$V_{cut-out}$ (m/s)	c	k
4000	1.255	0.4	0.8	80	1	4	12	25	8	1

Table 2. Battery energy storage data

Capacity MWh)	B_{max}	B_{min}	r (MW)	$\eta_c=\eta_d=\eta$
200	0.9*Capacity	0.1*Capacity	80	0.9

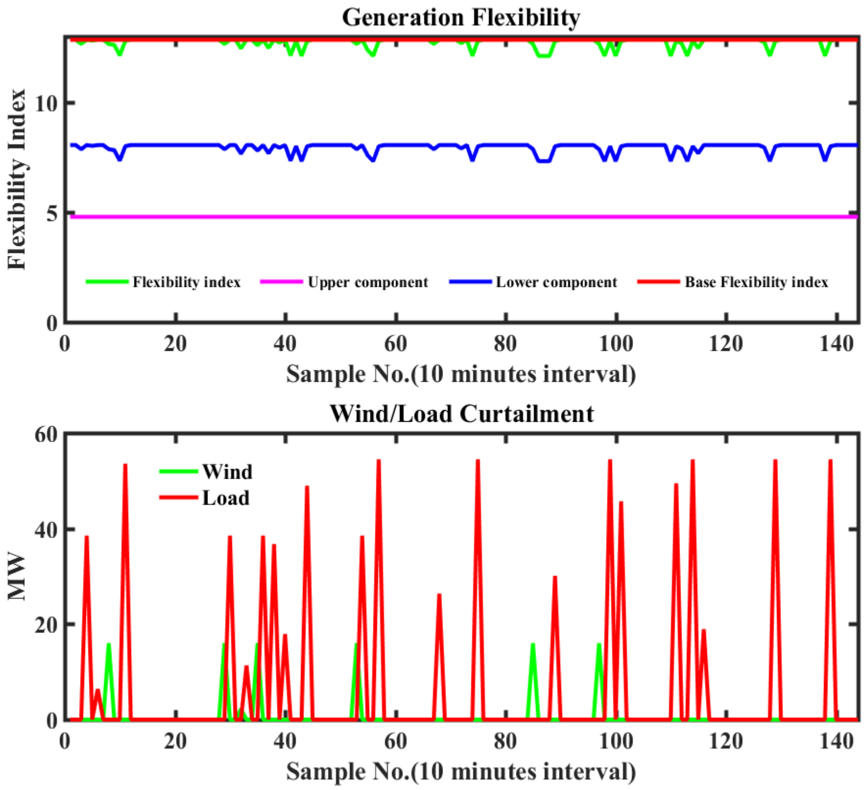

Fig. 6. Simulation results for PD=1200 (MW) (Without BESS)

6- SIMULATION

The six unit generation test system is used for BESS performance simulation and evaluation. The needed data for this test system can be found in [26]. Load demand is assumed as 1200 (MW) in the base case and constant in the whole time interval. It is considered only one wind farm and also one BESS in this system. Wind farm and BESS data are presented in Tables 1 & 2. Here, Δt is considered 10 (min). Where we have 144 samples in 24 hours. A set of 144 stochastic data for the wind speed is generated by Weibull probability distribution function and will be considered fixed in all simulations.

Calculating the generation flexibility index with no wind power and BESS integration, yields to the system flexibility index as 12.8473 (maximum value), and the upper and lower components as 4.7917 and 8.0556 (the system generation flexibility index is not divided by the number of units, can be compared by BESS flexibility index [21]).

The flexibility index of BESS is 13.4074, where the upper and lower components are 6 and 7.4074. It should be noted that if η=1 (b_{loss}=0), the flexibility index reduces to 13.3333, which is less than the real case. The upper and lower components are the same as 6.6667. On the other hand, wind curtailment reduction is expected by decreasing BESS efficiency and increasing loss because of more wind energy dissipation in charging mode which complies the upper component flexibility index in real case (η<1) more than the corresponding component in ideal case (η=1). However, unlike the wind curtailment, load curtailment increases by decreasing the BESS efficiency and increasing the BESS loss. It can be seen that the lower component flexibility index in real case (η<1) is less than the ideal case (η=1). It is also verified by the simulation later.

Now an initial simulation is performed by the wind power integration but without the BESS. It is performed in two cases of system loading as high and low load levels. Fig. 6 shows the generation system flexibility and the wind/load curtailment variations in 24 hours for PD=1200 (MW).

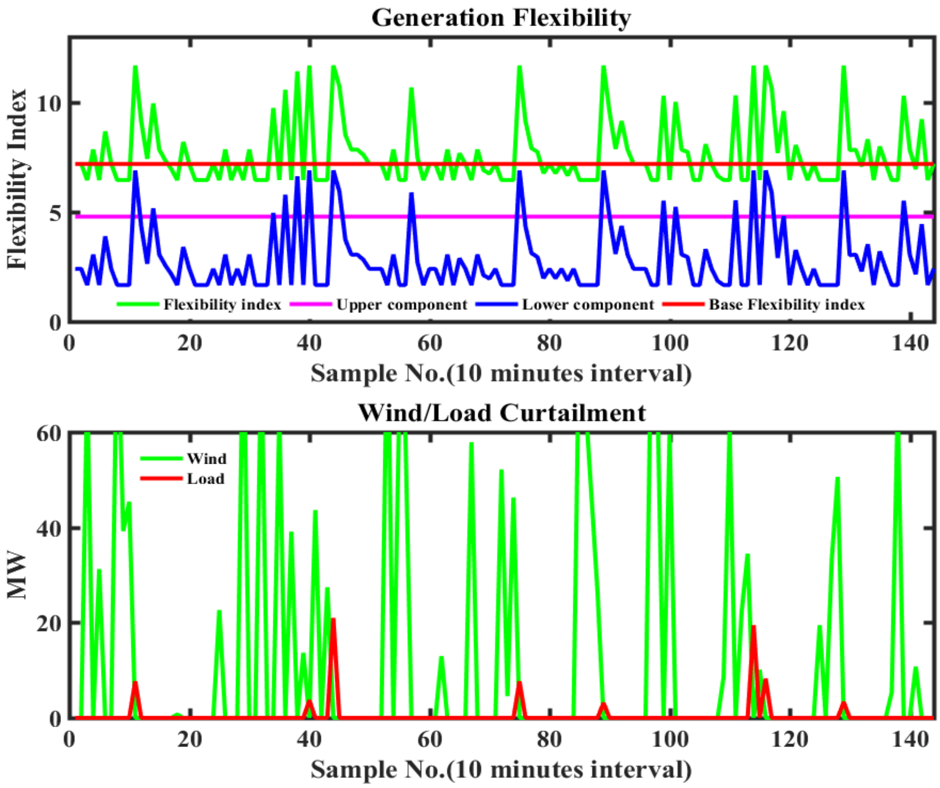

Fig. 7. Simulation results for PD=500 (MW) (Without BESS)

Base flexibility index refers to the generation system flexibility in the base case (without wind power integration). As can be seen, the upper component is constant and has no change, but the lower component varies due to the variation of the wind power. The load curtailment is more than the wind curtailment in the high load level. The average generation flexibility index is 12.7443, which is less than the base case (maximum) flexibility index. The upper and lower components of the average generation flexibility index are 4.7917 and 7.9526. On the other hand, the total load and wind energy curtailments are 137.7030 (MWh) and 16.3512 (MWh), which are % 0.4781 and % 0.0568 of the total needed load energy (PD*24) which verifies the suitable dependency between the load curtailment and flexibility upper component, and also between the wind curtailment and flexibility lower component [21].

The second simulation is performed for 500 (MW) as the low load level. It is expected more wind curtailment and less load curtailment. Fig. 7 shows the same results as the previous case for load level 500 (MW).

Base case flexibility index (without wind integration) for PD=500 (MW) is 7.1954, and the average generation flexibility index with wind integration is 7.6235, which both are much less than the maximum flexibility index. The upper and lower components of the latter index are 4.7917 and 2.8318. The upper component is constant and has no change as the previous case. But the lower component has reduction considerably because of the low load level which increases the risk of wind curtailment. Total wind and load energy curtailments are 298.4540 (MWh) and 12.3798 (MWh), which are %2.4871 and %0.1032 of the needed load energy as was expected by the amounts of flexibility index and its upper and lower components.

Now the main simulation is performed again in the presence of BESS for high/low load levels. The initial SoC is considered as 100 (MWh) for both load levels. The simulation results are shown in Fig. 8 and Fig. 9 for PD=1200 (MW) and PD=500 (MW). Wind curtailment is zero but load curtailment is 52.4585 (MWh) as %0.1821 of the needed load energy for load level 1200 (MW), where the load curtailment reduces to about %38 of the corresponding load curtailment in the case without the BESS. The average generation flexibility index and its upper and lower components are the same without the BESS, which shows the same generation dispatch in the whole time of the interval independent of BESS performance. The average BESS flexibility index and its upper and lower components are 10.2645, 6 and 4.2645. Similar to the upper component of generation flexibility index, the upper component of BESS flexibility index is constant with no change in the whole time interval. As can be seen, no load curtailment occurs when BESS flexibility index is constant and lies in its maximum value. It shows enough BESS ramp to compensate wind power variability. However, as the BESS goes to discharge completely, the BESS ramp reduces until it reaches zero when the BESS is completely discharged and the load curtailment

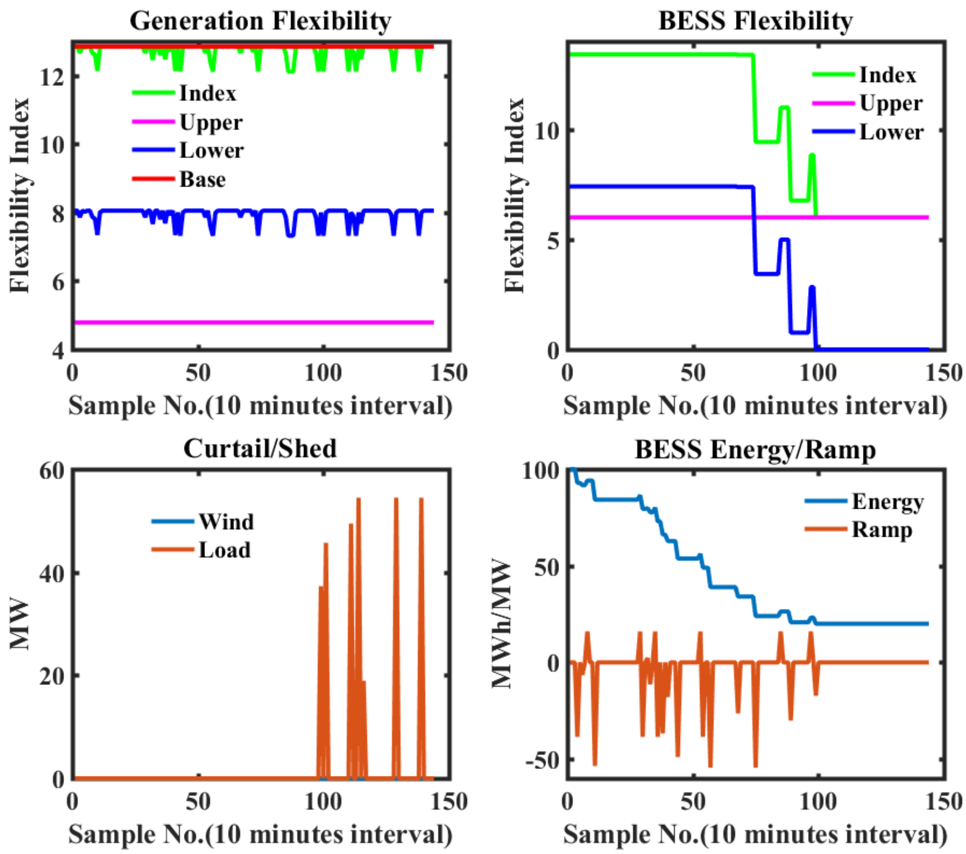

Fig. 8. Simulation results for PD=1200 (MW) (With BESS)

enhances due to zero BESS performance. This is completely verified by the variation of the lower component of BESS flexibility index, where it reaches zero in the beginning of the load curtailment.

In the low load level simulation, the load curtailment is zero but the wind curtailment is 194.2814 (MWh) as % 1.6190 of the needed load energy. It is %64 of the wind curtailment where the BESS is out. The generation flexibility index has no change due to zero BESS case. The BESS flexibility index and its upper and lower components are 9.4804, 2.0730 and 7.4074. Unlike the previous case, the lower component of BESS flexibility index is constant with no change in the whole time interval. However, the upper component is zero at the end of the time interval when the BESS charges completely.

Here two other medium load levels as 700 (MW) and 1000 (MW) are considered to have a bright view of the BESS flexibility effect on the wind/load curtailment. To summarize, only the tabulated results are shown for better view and conclusion. Additionally, the results of the two cases with/without BESS are presented together. Table 3 shows the wind/load curtailment with/without the BESS upper/lower rows, generation and BESS flexibility index. The charged/discharged energy at the end of the time interval is also presented. As expected, wind/load curtailment is totally improved in all load levels with BESS. It should be noted that the generation flexibility index does not differ with/without the BESS in each load level, where the performance of the BESS is independent of the system generation and the generation schedule is fixed with/without the BESS in each load level. (The BESS operates only when the system generation is in up or down limits (Uplimit or Dnlimit), where by BESS operation no change happens in the generation schedule.)

As can be seen, the upper component of the generation flexibility index is constant in all load levels and stays in the maximum value. However, the lower component increases by increase in the load level, where the wind curtailment also decreases simultaneously. It shows a good dependency between the proposed generation flexibility index and improvement in the wind/load curtailment again.

The variations of the upper/lower components of BESS flexibility index are also completely compatible with the wind/load curtailment variations and again shows the good dependency between these components and the wind/load curtailment.

The last simulation is performed by the reduction of the BESS efficiency. As stated before, by reduction of the BESS efficiency, more energy dissipation is expected which leads to less wind curtailment and more load curtailment. Here the BESS efficiency is reduced to %85, which are the same results as Table 3, but by ignoring the wind/load curtailment

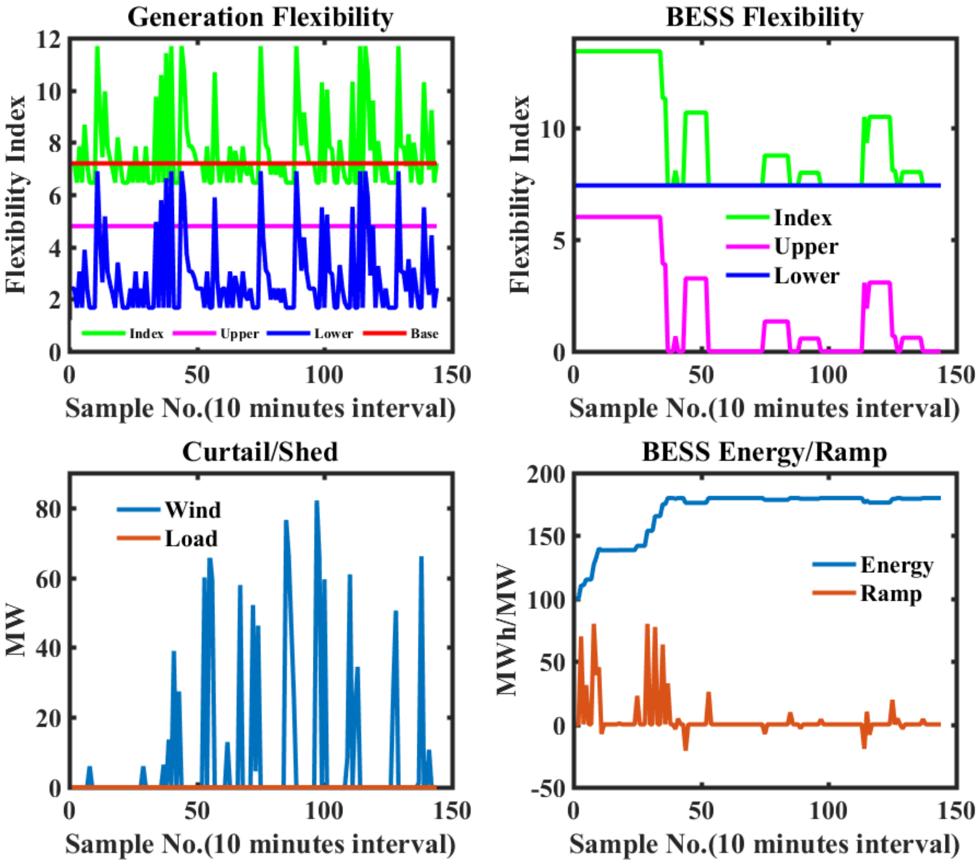

Fig. 9. Simulation results for PD=500 (MW) (With BESS)

Table 3. Wind/load curtailment analysis in the presence of BESS (η=۰٫۹)

PD(MW)	500	700	1000	1200
Wind Curtailment (%)	2.4871 1.6190	0.5962 0	0.1540 0	0.0568 0
Load Curtailment (%)	0.1032 0	0.5309 0	0.5214 0.0967	0.4781 0.1821
Flex_Gen (without/with BESS)	7.6235	9.8074	11.7790	12.7442
Upper Component	4.7917	4.7917	4.7917	4.7917
Lower Component	2.8318	5.0157	6.9873	7.9526
Flex_ES	9.4804	13.4074	11.7787	10.2645
Upper Component	2.0730	6	6	6
Lower Component	7.4074	7.4074	5.7787	4.2645
Charge/Discharge (MWh)	80	-8.9507	-80	-80

without BESS and generation flexibility index results which remain as the same, are presented in Table 4.

The (+) and (-) signs show the increase/decrease of BESS flexibility index respect to the previous case. As expected, BESS efficiency reduction has two different effects. It reduces the wind curtailment and also because of more dissipation of surplus wind energy in the low load levels, it increases the BESS flexibility index. However, the load curtailment increases by reduction in BESS efficiency in the high load levels due to more energy loss necessitates more load curtailment. It also complies with BESS flexibility index upper/lower components variations.

Table 3. Wind/load curtailment analysis in the presence of BESS (η=۰٫۹)

PD(MW)	500	700	1000	1200
Wind Curtailment (%)	2.4871	0.5962	0.1540	0.0568
	1.6190	0	0	0
Load Curtailment (%)	0.1032	0.5309	0.5214	0.4781
	0	0	0.0967	0.1821
Flex_Gen (without/with BESS)	7.6235	9.8074	11.7790	12.7442
Upper Component	4.7917	4.7917	4.7917	4.7917
Lower Component	2.8318	5.0157	6.9873	7.9526
Flex_ES	9.4804	13.4074	11.7787	10.2645
Upper Component	2.0730	6	6	6
Lower Component	7.4074	7.4074	5.7787	4.2645
Charge/Discharge (MWh)	80	-8.9507	-80	-80

Table 4. Wind/load curtailment analysis in the presence of BESS (η=0.85)

PD(MW)	500	700	1000	1200
Wind Curtailment (%)	1.5600	0	0	0
Load Curtailment (%)	0	0	0.1268	0.2010
Flex_ES	9.9629(+)	13.5098(+)	11.5723(-)	9.7107(-)
Upper Component	2.1197(+)	5.6667(-)	5.6667(-)	5.6667(-)
Lower Component	7.8431(+)	7.8431(+)	5.9056(+)	4.0441(-)
Charge/Discharge (MWh)	80	-19.7888	-80	-80

7- CONCLUSION

Rapid growing of uncertainty and variability in power generation system due to the high penetration of the wind and solar energies necessitates the suitable tools to overcome the challenge of generation/load unbalance. Energy storage systems are the important solution widely used to compensate the uncertain and variable output power related to the wind and solar farms. High ramp rate characteristic of battery energy storage system is a good advantage to minimize the wind/load curtailment for the wind farms integrated to the power system. In other words, BESS increases system flexibility for better performance and to overcome the uncertain rise/fall in the wind power output.

In this paper, a control scheme for BESS charge/discharge process based on the system flexibility improvement was introduced to minimize the wind/load curtailment in the wind power integrated power system, where by adding BESS to the power system, total system flexibility index increases and the wind/load curtailment reduces subsequently. This approach also can be used to determine the suitable capacity and ramp rate specification of BESS based on the desired wind/load curtailment using a stochastic method for DELD analysis such as Monte-Carlo simulation to deal all scenarios for the wind power outputs. It can lead to an economic trade-off between BESS cost (fixed and variable) and the wind/load curtailment cost to obtain the best size of BESS.

Improving the concept of the current paper and as the new contribution to the proposed method, the BESS flexibility index and the system generation flexibility index can be combined in a similar approach described in [21] to obtain the BESS/generation system hybrid flexibility index.

NOMENCLATURE

A: turbine area (m^2)
b: BESS energy level (MWh)
b_{loss}: BESS energy loss (MWh)
B_{min}: minimum BESS energy level (MWh)
B_{max}: maximum BESS energy level (MWh)
B, B0, B00: power loss coefficients
c: scale factor of Weibull function
Cost: total cost function ($)
c_p: power coefficient for wind turbine
d: wind power operation cost ($/MW)
$flex_{es}$: BESS flexibility index
k: shape factor of Weibull function
LC: load curtailment (MWh)
P: thermal unit generation (MW)
P_{max}: maximum unit generation (MW)
P_{min}: minimum unit generation (MW)
P_{loss}: system loss (MW)
PD: load demand (MW)
PG: total thermal units generation (MW)
Pw: wind farm generation (MW)
P_{rated}: wind farm nominal power (MW)
r: BESS charge/discharge ramp rate (MW)
r_{max}: BESS charge/discharge maximum ramp rate (MW)
Rampup: unit ramp up rate constraint (MW/h)
Rampdn: unit ramp down rate constraint (MW/h)
S: area corresponds to generation flexibility
S_{ex}: area corresponds to BESS flexibility
v: wind speed (m/s)
$v_{cut\text{-}in}$: starting wind speed (m/s)
$v_{cut\text{-}out}$: shut down wind speed (m/s)

v_{rated}: nominal wind speed (m/s)
WC: wind curtailment (MWh)

Greek symbols

α, β , γ: thermal unit operation cost coefficients, \$/MW^2,\$/MW,\$
η_w: wind turbine-generator efficiency
η_c: BESS efficiency-charging mode
η_d: BESS efficiency- discharging mode
ρ: air density
Δt: time interval (s)

Indices

i: counter
t: time
n: number of thermal units
n_t: number of wind turbines in a wind farm
nw: number of wind farms

REFERENCES

[1] P. Denholm, "Energy storage to reduce renewable energy curtailment", IEEE Power and Energy Society General Meeting, 2012, pp. 1-4

[2] M. Khalid, A.V. Savkin, "Minimization and control of battery energy storage for wind power smoothing: Aggregated, distributed and semi-distributed storage", Renewable Energy, Volume 64, 2014, pp 105-112

[3] Jabir, M.; Azil Illias, H.; Raza, S.; Mokhlis, H., "Intermittent smoothing approaches for wind power output: A review", Energies 2017, 10, 1572.

[4] Hu, Xiaosong, et al., "Technological developments in batteries: A survey of principal roles, types, and management needs", IEEE Power and Energy Magazine 15.5, 2017: pp. 20-31.

[5] H. Bitaraf and S. Rahman, "Reducing curtailed wind energy through energy storage and demand response", IEEE Transactions on Sustainable Energy, vol. 9, no. 1, Jan. 2018, pp. 228-236

[6] Nazari, ME, Ardehali, MM. "Optimal coordination of renewable wind and pumped storage with thermal power generation for maximizing economic profit with considerations for environmental emission based on newly developed heuristic optimization algorithm", J Renew Sustain Energy. 2016; 8, pp. 1-30

[7] Farahmand MZ, Nazari ME, Shamlou S. "Optimal sizing of an autonomous hybrid PV-wind system considering battery and diesel generator" 25th Iranian Conf Electr Eng (ICEE) 2017, pp. 1048-1053

[8] C. Kim, E. Muljadi and C. C. Chung, "Coordinated control of wind turbine and energy storage system for reducing wind power fluctuation", 56th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE), 2017, pp. 1485-1489,

[9] M. Z. Farahmand, M. E. Nazari and S. Shamlou, "Optimal sizing of an autonomous hybrid PV-wind system considering battery and diesel generator" 25th Iranian Conference on Electrical Engineering (ICEE), 2017, pp. 1048-1053

[10] Xiaolei Wang, Lei Sun, Fushuan Wen, M. A. Salam and S. P. Ang, "Control strategies of battery energy storage systems for smoothing wind power fluctuations", 10th International Conference on Advances in Power System Control, Operation & Management (APSCOM 2015), 2015, pp. 1-4

[11] Nazari ME, Ardehali MM. "Optimal bidding strategy for a GENCO in day-ahead energy and spinning reserve markets with considerations for coordinated wind-pumped storage-thermal system and CO2 emission", Energy Strategy Reviews. 2019; 26, pp. 1-18.

[12] Gwabavu, M., Raji, A. "Dynamic control of integrated wind farm battery energy storage systems for grid connection", Sustainability, 2021, 13, 3112

[13] J. Devlin, K. Li, P. Higgins, and A. Foley, "System flexibility provision using short term grid scale storage," IET Gener., Transm. Distrib. vol. 10, no. 3, Feb. 2016. pp. 697–703

[14] N. Hatziargyriou et al., "Security and economic impacts of high wind power penetration in island systems", Proc. 2004 CIGRE Conf., Paris, 2004, pp. 1–9.

[15] X. Dui, G. Zhu and L. Yao, "Two-stage optimization of battery energy storage capacity to decrease wind power curtailment in grid-connected wind farms", IEEE Transactions on Power Systems, vol. 33, no. 3, May 2018, pp. 3296-3305

[16] M. Moradzadeh, J. Van de Vyver and L. Vandevelde, "Optimal energy storage sizing based on wind curtailment reduction", International Conference on Renewable Energy Research and Application (ICRERA), Milwaukee, WI, USA, 2014, pp. 331-335

[17] L. Shao et al., "Coordinated operation strategy of storage battery SOC and smoothing wind power fluctuation"', Electr. Power Construct., vol. 38, no. 1, 2017, pp. 3296-3305

[18] T. Kim, H.-J. Moon, D.-H. Kwon, S.-I. Moon, "A smoothing method for wind power fluctuation using hybrid energy storage", Proc. IEEE Power Energy Conf. Illinois (PECI), Champaign, IL, USA, Feb. 2015, pp. 1-6

[19] A. Alanazi and A. Khodaei, "Optimal battery energy storage sizing for reducing wind generation curtailment", IEEE Power & Energy Society General Meeting, Chicago, IL, USA, 2017, pp. 1-5

[20] B. Wang, M. Zhou, B. Xin, X. Zhao, J. Watada, "Analysis of operation cost and wind curtailment using multi-objective unit commitment with battery energy storage", Energy, vol.178, 2019, pp. 101-114

[21] H. Berahmandpour, S. Monraser Kuhsari, H. Rastegar, "A new approach on development of power system operational flexibility ndex by combination generation unit flexibility indices", AUT Journal of Electrical Engineering, vol. 53, issue 1, 2021

[22] H. Berahmandpour, S. Monraser Kuhsari, H. Rastegar, "Development the flexibility metric incorporating wind power in the presence of energy storage", 34th Power System Conference (PSC) Tehran, Iran, Dec. 2019, pp. 548-556

[23] A. Maei, D. Meola, G. Maraoti, G. Palmieri, L. Iannelli, G. Mathiseny, E. Bjerkan, L. Glielmo, "Optimal power flow model with energy storage, an extension towards large integration of renewable energy sources",

Proceedings of the 19th World Congress. International Federation of Automatic Control, Cape Town, South Africa. vol. 47, issue 3, 2014, pp. 9456-9461

[24] H. Berahmandpour, S. Monraser Kuhsari, H. Rastegar, "A new flexibility index in real time operation incorporating wind farms" 27th Iranian Conference on Electrical Engineering (ICEE), 2019, pp. 549-553

[25] T. L. Baldwin and E. B. Makram, "Economic dispatch of electric power systems with line losses", IEEE, The Twenty-First Southeastern Symposium on System Theory, 1989, pp. 13-17

[26] N. Singh and Y. Kumar, "Economic Load Dispatch Using MRPSO with Generator Ramp Rate Limits Constraint", The Fourth International Conference on Computational Intelligence and Communication Networks, Mathura, 20e12, pp. 632-637

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