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Impact of Multiple Battery Energy Storage System Strategies on Energy Loss of Active Distribution Network

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Abstract- The implementation of grid energy storage technologies is essential to maximize the absorption of renewable energy. The operation of distribution network with multiple distributed energy resources is complicated. Therefore, this article proposes different optimal operational strategies for battery energy storage system (BESS) in coordination with wind based distributed generation for distribution network. The BESS charging and discharging schedules for all strategies are subjected to the network operational constraints such as node voltage limit, feeder current limit and nodal power balance etc. The genetic algorithm is developed to evaluate the impact of different operational strategies on the energy loss of distribution network. The validation of economic benefits in terms of operation and electricity consumption cost is also performed. The suggested strategies are investigated on the IEEE 33-bus distribution network. The results indicate that optimal operation of BESS can reduce the energy loss and also increase the economic benefits for the distribution system.

Keywords Battery energy storage, Wind generation, Genetic algorithm, Distribution network, Energy loss.

1. Introduction

With a growing share of renewable energy generation, distribution companies of power sector are facing some new challenges [1]. Despite the environment benefits and sustainability of renewable based energy resources, two main problem arises when it is integrated into distribution network. First, renewable energy production is well-known to be heavily dependent on weather conditions. The intermittent properties of non-dispatchable renewable based energy resources can lead to instability in power system [2]. To address this point, the system operator must provide sufficient reserve to ensure the system safe operation against uncertainty regarding renewable power. In this scenario, standard generation units must have a more regular start and stop, which has important wear and tear effects on these units and can possibly reduce the general system efficiency [3]. Secondly, as renewable energy penetration rises, it is more complicated to absorb the rise in renewable energy generation for conventional distribution network. In [4], it is discussed that over generation of photovoltaic resulted in very small net demand in California at midday, but net demand in another periods was still high when photovoltaics were unable to produce energy. Therefore, when additional photovoltaic is included, this net demand profile would see the net demand through deepen in the center of the day, leading to the so called “Duck-curve”. As a result, with a restricted capacity to accommodate this enormous ramp, it is necessary to curtail solar energy, thus decreasing the financial and environment benefits of inclusion of renewable energy.

One of the potential alternative to the above mentioned problems is to use hybrid renewable based energy systems and incorporating multiple renewables energy resources in an optimal manner [5]. In this respect, periods with low generation resource could obviously be offset by other high energy generation resource [6]. In [7], it is presented by the combination of complementary nature of wind and solar generation resources. Comprehensive literature on the optimal accommodation of distributed generation units [8], energy management and control [9] are available in such hybrid renewable integrations. There has been extensive study of the use of energy storage systems (ESS) to promote the growing penetration of renewable based energy source by absorbing and releasing power in distinct time horizons [10]. Battery energy storage system (BESS) has drawn significant attention from the multiple kinds of ESS technology available, with clear benefits such as rapid response, controllability and geographical autonomy [11]. However, negative effect of high penetration of renewable based distributed generation such as reverse power flow and energy loss can be mitigated through optimal accommodation and operation of BESS [12]. In addition to the above mentioned benefits, BESS also has a wide range of application such as power quality, energy management and voltage improvements etc. In [13], explores the optimal operating state schedule of wind turbine for reducing battery capacity and operational cost. In [14]-[15], proposed the solar generation and BESS hybrid energy management plan for achieving technical and economic benefits. In [16], the exchangeable battery system was suggested and renewable energy can be used effectively to charge that battery system. In [17], arises the issue of embedded generation in the distribution system. In [18], investigate the impact of optimal sizing of BESS on operation cost of micro grid. It is clear from the literature that appropriate use of grid integrated BESS can mitigate the operational challenges of distribution system. Therefore, BESS has great potential for both power utility and consumers but it is done only by adopting optimal operation strategy.

In this paper, comparison of multiple operational strategies of BESS coordinated with wind generation is proposed. The objective for the considered coordinated problem is to minimize the network losses. Genetic algorithm (GA) [19] is used to solve the problem because of its potential to find global and near global optimal solutions. The advantage of the proposed strategy is not only to reduce the network loss and improved voltage profile, but also to maximize the economic benefits of utility in an appropriate manner at the same time.

The reminder of the paper is arranged as follows. Problem formulation and constraints of the considered problem is defined in section 2. Multiple BESS strategies are presented in section 3. In section 4, results outcomes are presented. Section 5 presented the conclusion of the paper.

2. Problem Formulation

The optimal coordinated strategies of multiple BESS in presence of wind generation in distribution network is formulated in order to minimize the network losses and also to improve the system node voltage profile. The benefit of BESS depends largely on how best they are scheduled in distribution network.

The objective function is formulated as:

$$\min(F) = \sum_{T=1}^{24} P_L^T \tag{1}$$

where, P_L^T represent the active power loss for time T period.

Equation (2) is used for the calculation of Power loss [12], [20]:

$$P_L^T = \sum_{i=1}^{N}\sum_{j=1}^{N} \alpha_{ij}^T \left(P_i^T P_J^T + Q_i^T Q_J^T\right) + \beta_{ij}^T \left(Q_i^T P_j^T - P_i^T Q_j^T\right) \forall\ T \tag{2}$$

$$\alpha_{ij}^T = r_{ij} \cos\left(\delta_i^T - \delta_j^T\right) / V_i^T V_j^T \tag{3}$$

$$\beta_{ij}^T = r_{ij} \sin(\delta_i^T - \delta_j^T) / V_i^T V_J^T \tag{4}$$

where, $V_i^T, V_j^T, P_i^T, P_j^T, Q_i^T, Q_j^T, r_{ij}$ and δ_i^T represents the node voltage, power delivery loss, active and reactive power, branch resistance and node angle of i^{th} and j^{th} node for the time period of T respectively.

The constraints for the considered problem is follow as:

$$P_B^{\text{Min.}} \le P_{B(C_i/D_i)}^T \le P_B^{\text{Max.}} \quad \forall T, i \tag{5}$$

$$SOC^{\text{Min.}} \le SOC_i^T \le SOC^{\text{Max.}} \quad \forall T, \text{i} \tag{6}$$

$$SOC_i^T = \begin{cases} SOC_i^{T-1} + P_{B(\mathrm{C}_i/\mathrm{D}_i)}^T \eta_c \Delta t / E_B^R & if\ P_{B(\mathrm{C}_i/\mathrm{D}_i)}^T > o \\ SOC_i^{T-1} + P_{B(\mathrm{C}_i/\mathrm{D}_i)}^T \Delta t / \eta_d E_B^R & else \end{cases} \tag{7}$$

$$\sum_{T=1}^{24} \eta_c P_{B(C_i/D_i)}^T + P_{B(C_i/D_i)}^T / \eta_d = 0 \tag{8}$$

where, equation (5) to (8) represents the BESS operation constraints and is taken from [12],[21]. Here, $P_B^{\text{Min.}}, P_B^{\text{Max.}}$ $P_{B(\mathrm{C}_i/D_i)}^T, SOC^{\text{Min.}}, \mathrm{SOC}^{\text{Max.}}, SOC_i^T$ are the maximum and minimum limit of dispatch power of battery, charging and discharging BESS power at a particular time, state of charge (SOC) limits and SOC of node i^{th} for T time period respectively.

The other network constraints are as follow:

$$I_{f,ij}^T \le I_{a,ij}^{\max} \quad \forall T, i, j \tag{9}$$

$$P_i^T = V_i^T \sum_{j=1}^{N} V_j^T Y_{ij} \cos\left(\theta_{ij} + \delta_j^T - \delta_i^T\right) \quad \forall T, i \tag{10}$$

$$Q_i^T = -V_i^T \sum_{j=1}^{N} V_j^T Y_{ij} \sin\left(\theta_{ij} + \delta_j^T - \delta_i^T\right) \forall T, i \tag{11}$$

$$V^{\min} < V < V^{Max} \tag{12}$$

where, equation (9) represents the feeder current limit [22]. Equation (10) and (11) shows the power balance constraints. Node voltage limit constraints are shown in equation (12) [23].

Here, $I_{f,ij}^{T}, I_{a,ij}^{\max}$ are the actual current flow and maximum thermal limit of line between i^{th} and j^{th} nodes. The $P_i^T, Q_i^T, V_i^T, V_j^T, Y_{ij}, \theta_{ij}, \delta_i^T, \delta_i^T$ represents real and reactive power, magnitude of node voltage, Y-bus element, impedance angle, voltage angle of i^{th} and j^{th} nodes at time T.

3. Coordination of BESS strategies with wind generation

The suggested operational strategies and algorithm for optimal BESS coordination with wind generation in distribution network has been discussed in this section. The operational problem of distribution system formulated in section 2 is a mixed-integer, non-linear and non-convex optimization problem. Such problems can be solved by any evolutionary algorithm. Ref [24] carried out a survey of recent papers of DG integration in distribution system. The survey shows that artificial intelligence (AI) techniques have been widely used (more than 25 %) in optimal operational planning of DGs. The survey shows that artificial intelligence based computational techniques, especially GA is more suitable than any other techniques. Therefore, GA has been used as optimization tool. GA is a popular meta-heuristic technique based on evolutionary concept and is defined as a free-population derivative stochastic optimization system inspired by the principle of evolutionary process and natural selection. GA is initialized by updating generations with a probabilistic population selection based on their fitness and searches for optima by updating generations. The crossover is the primary operator of the GA and mutation is the secondary operator. Elitism is used to retain the elite child means the best fitness individuals in the present generation. The individuals for the developed GA is hourly dispatch of BESS power. In this paper, forward-backward sweep load flow method is used for the load flow analysis. Load flow analysis provides real power loss, reactive power losses, voltage magnitudes and angle at different nodes of the system. The steps of developed algorithm for the proposed operational strategy can be summarized as follows:

Step 1: Read the system data.

Step 2: Update the power generation based on the wind location and size.

Step 3: Dispatch the BESS power as per the following strategies of BESS.

Step 4: Determine the network loss considering the associated network and BESS constraints.

Step 5: Once the initial size of population is established, its fitness is assessed using Backward/Forward sweep based method [25].

Step 6: The crossover operator than allows various candidate solutions to share genetic information. The concept is that the new individuals that appear in the population contribute to increasing diversity, allowing the exploration space to discover new levels. Multipoint crossover concept is used in the developed algorithm [26] to produce offspring. Two parents out of which one is selected using Roulettte wheel selection and another parent is selected randomly from the population. The crossover rate is fixed to 80%.

Step 7: To explore new search space with reduced probability of local optima, mutation operator is used. One component of chromosome is selected randomly for mutation in the developed GA and its replacement is driven by guidance of considered constraints. After that, fitness of mutated chromosome is determined. Generally, the fixed mutation rate between 10 to 20% is used. However, in this study mutation rate is not considered to be constant. It is considered to be decrease linearly and is taken care by initial and final mutation rate and its step size.

Step 8: Stop, when the number of generations exceeds the value of predefined total generations.

In this paper, three different possible operational strategies of BESS in presence of wind generation are developed and compared.

Considered BESS strategies are as follows:

Strategy 1:

In this strategy, the operation of BESS depends on the pattern of demand consumption only. BESS is motivated for the charging at period of low demand and discharge at a period of peak demand. The average demand of complete day is the decision making factor in this operation strategy and is expressed as

$$P_{B(C_i,D_i)}^{T} = \begin{cases} P_{B(C_i)}^{T} & if\ P_{D,i}^{T} < \bar{P}_{D,i} \\ P_{B(D_i)}^{T} & if\ P_{D,i}^{T} > \bar{P}_{D,i} \end{cases} \tag{11}$$

$$\text{where, } \bar{P}_{D,i} = \frac{\sum_{i=1}^{N}\sum_{T=1}^{24} P_{D,i}^{T}}{T} \tag{12}$$

Strategy 2:

The decision of BESS charging and discharging depends on the forecasted value of availability of renewable energy. Figure 1 shows the considered load factor and wind profile. It is shown in this figure that availability of wind is higher in the starting periods from 1 to 13 hours and comparatively low in the duration of peak demand hours. Therefore, BESS charging is initiated during starting periods depending on the availability of wind and discharging during low wind periods with high demand consumption periods.

$$P_{B(C_i,D_i)}^{T} = \begin{cases} P_{B(C_i)}^{T} & if\ 1 \le T \le 13 \\ P_{B(D_i)}^{T} & else \end{cases} \tag{13}$$

Strategy 3:

In this strategy, BESS operation fully depends on the objective function and optimization algorithm. The SOC balance constraints and dispatched power is taken care by the operation of BESS as explained in equation (2) to (6). The chromosome structure of GA will consider the BESS dispatch power.

The flow chart of the proposed methodology is presented in Figure 2.

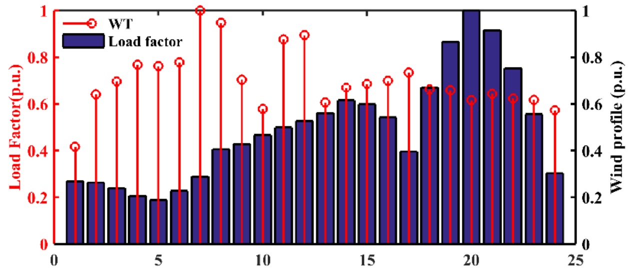

Figure 1. Load factor and wind profile

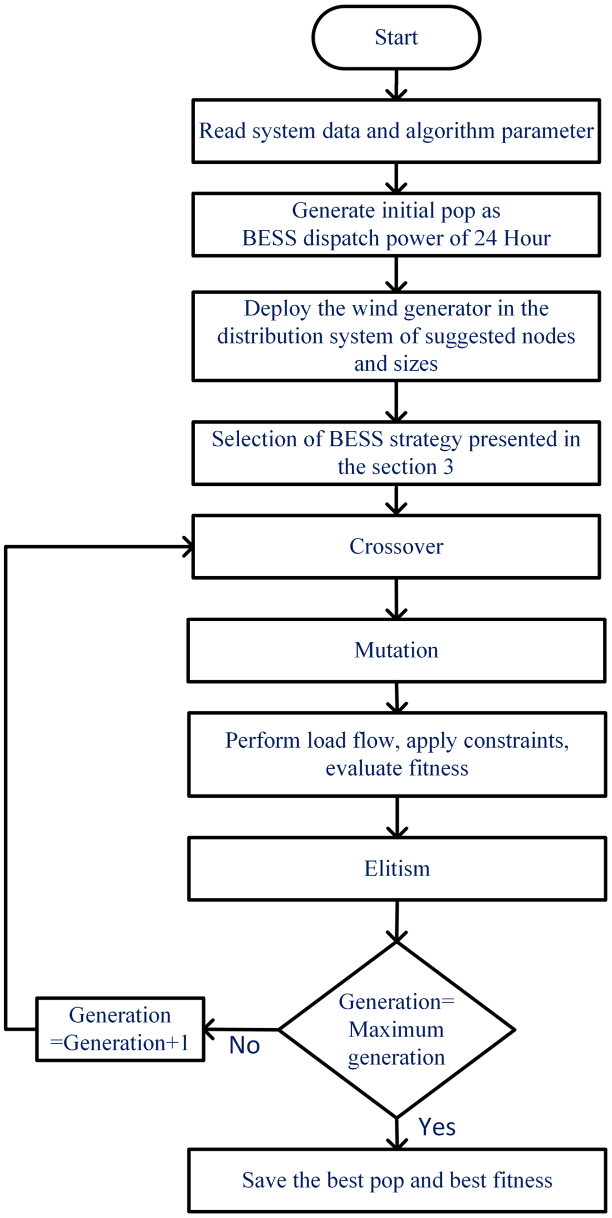

Figure 2. Flow chart of the proposed methodology

4. Simulation Results

In order to validate all three strategies of BESS, it is implemented on IEEE 33-bus radial distribution network. The data of IEEE 33-bus radial distribution system is taken from [27]. It is a distribution network of 12.66 kV with nominal real and reactive demand of 3.715 MW and 2.300 MVar, respectively. In this paper, it is assumed that the demand of the network is increased by 1.6 times of nominal demand. The per unit maximum and minimum node voltage limit is considered to be 0.90 to 1. Maximum charging/discharging dispatch power for BESS is assumed to be 1000 kW to -1000 kW. Initial SOC limit for all the BESS is assumed to be 20% of maximum available energy. Efficiency for the BESS charging/discharging is considered to be 90%. In this study, the following cases are investigated to demonstrate the effectiveness of proposed strategies:

Case 1: Without any integration of BESS and wind generation.

Case 2: In this case, wind generation is integrated in distribution system.

Case 3: In this case, wind is integrated in three different location and BESS is accommodate at two location of wind capacity.

Case 4: In this case, economic validation in terms of operation cost is investigated. For economic validation of considered strategies and cases, operation cost of wind turbine and BESS is presented in Table 2. The location and size of wind and BESS is given in Table 1.

Table 1. Data for the considered cases

S.No.	**Integrated Sources**	**Location**	**Sizes**
1	Wind Turbine	14, 24,30	1048,1005,1128 (in kW)
2	BESS	14,24	5000,5000 (in kWh)

Table 2. Data for the considered DERs

S.No.	**Integrated Sources**	**Operation cost ($/kW)**	**Fixed operation cost ($/kW)**	**Variable operation cost ($/kWh)**
1	Wind Turbine	0.090	-	-
2	BESS	-	0.010	0.002

The results for all four cases are discussed below:

Case 1:

In this case, BESS and wind is not integrated in the distribution network. Therefore, network loss and minimum mean voltage obtained in this case is used for reference purpose only. The electricity consumption cost of grid is also maximum in this case because all the load is supplied by the grid. Table 3 shows that maximum network loss is obtained in this case.

Table 3. Results for base case

Case	Network loss (MWh)	Min mean voltage (p.u.)
Case 1	3.7097	0.9391

Case 2:

In this case, only wind is integrated at the three different optimal locations in distribution system. The network losses due to wind integration is 2.113 MWh with 43.04 % reduction as compared to base case. The minimum mean voltage is also improved from 0.9391 to 0.9745 p.u.

Case 3:

In this case, two BESS is coordinated with the wind generation to minimize the network losses. It is found that network loss for all the three BESS strategies reduces sharply as compared to Case 2. The minimum mean voltage for all strategies are larger than lower limit constraints of node voltage. Table 4 shows the comparison of all three strategies for the 20% of initial SOC. It is found from the table that for strategy 3 achieve network loss reduction of 57.20 %. However, percentage network loss reduction in strategy 1 and 2 is 56.43% and 56.90% respectively. It is shown in the figure 3 and 4 (strategy 1) that the BESS at both location is charged during first 7 hours. This periods is low demand period. Therefore, the BESS charging increases the system demand during low demand periods. The discharging of BESS is limited to peak demand periods and therefore reduces the peak demand of the network. Whereas, in strategy 2 (figure 5 and 6) charging period increases from first seven hours to first 11 hours and 8 hours at BESS location 14 and 24 respectively. It is clear that in strategy 2 the BESSs are charged during high availability period of renewable energy. The discharging of BESS is again during peak hours. The charging and discharging of BESS for strategy 3 are shown in Figure 7 and 8. In strategy 3, the charging and discharging of BESS are governed by its objective function and constraints. From the figures and tables it is clear that the strategy 3 provides the best results compared other two strategies. The initial and final SOC are maintained constant for all the three strategy.

Table 4: Comparison of BESS strategies

strategy	Initial SOC (%)	Network loss (MWh)	Min mean voltage (p.u.)
1	20	1.6163	0.9744
2		1.5987	0.9742
3		1.5875	0.9739

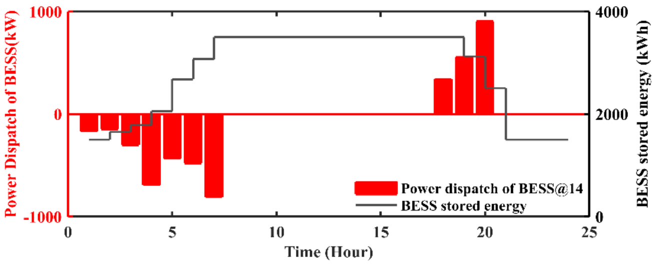

Figure 3. Battery status of case 3 (Strategy 1) BESS@14

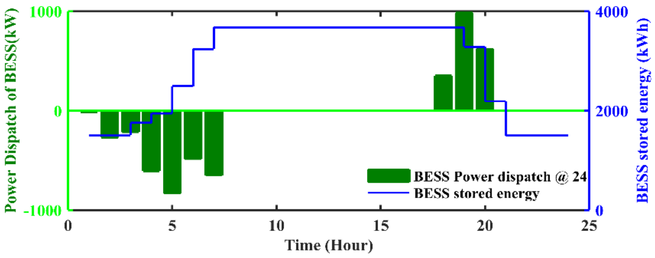

Figure 4. Battery status of case 3 (Strategy 1) BESS@24

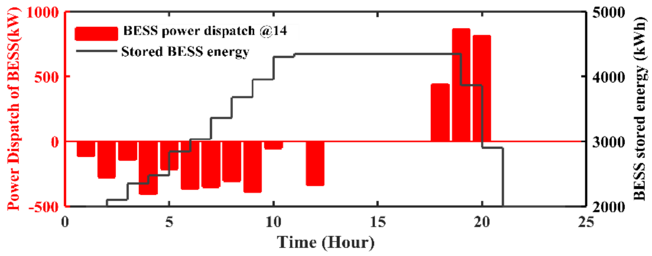

Figure 5. Battery status of case 3 (Strategy 2) BESS@14

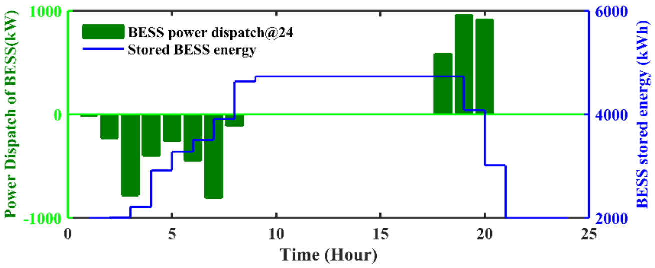

Figure 6. Battery status of case 3 (Strategy 2) BESS@24

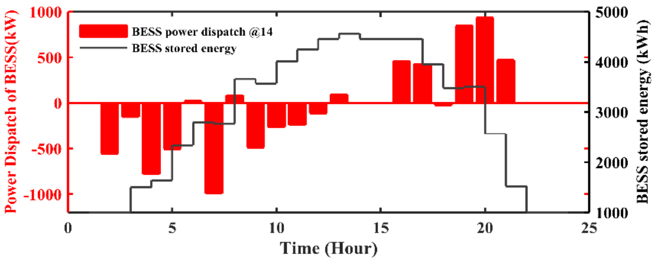

Figure 7. Battery status of case 3 (Strategy 3) BESS@14

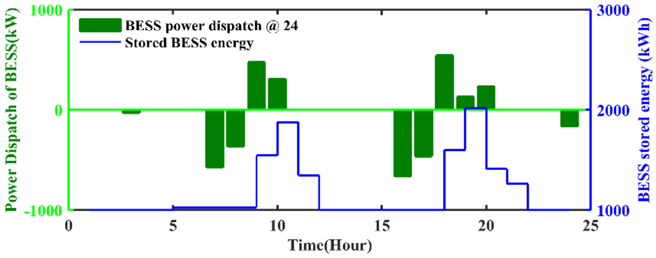

Figure 8. Battery status of case 3 (Strategy 3) BESS@24

Case 4:

In this case, the operation cost, electricity consumption cost and respective benefits by adopting all the three operation strategies of BESS in presence of wind generation is investigated. The benefits of distribution system with the integration of wind generators alone is 44.54 % as compared to Case 1. It is also shown in Table 5 that BESS integration particularly for Strategy 3 is giving best revenue benefits to distribution system. It is also shown that 69.82 % of consumption cost is reduced with the Strategy 3.

Table 5: Comparison of Economic benefits with different cases

Cases	Strategies	Initial SOC (%)	Consumption cost ($)	Operation Cost ($)	Benefits ($)
C 1	-	-	5386	-	-
C 2	-	-	2113	286	2987
C 3	S 1	20	2009	308	3069
	S 2		1701	317	3369
	S 3		1625	316	**3444**

5. Conclusion

In this paper, three different operational strategies of BESS in presence of wind generation is proposed and compared. GA is used to solve the problem of network loss reduction of distribution system. The Strategy 3 model offers greater flexibility in terms of charging and discharging of BESS in active distribution system. It is concluded from the results that Strategy 3 gives the maximum network loss reduction as compared to other two operational strategies. Technical and economical investigations also highlights the applicability of the proposed organized dispatch of BESS. The simulation results shows that the optimum scheduling of BESS with a large wind power have positive impact on distribution system. Also, the results shows that the proposed strategy of BESS keeps the node voltage magnitude of all buses within the permitted range and absorbs the wind energy variations.

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