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Joint sizing and placement of battery energy storage systems and wind turbines considering reactive power support of the system

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ABSTRACT

The probabilistic and intermittent output power of Wind Turbines (WT) is one major inconsistency of these Renewable Energy Sources (RES). Battery Energy Storage Systems (BESS) are a suitable solution to mitigate this intermittency by smoothening WT's output power. Although the main benefit of BESSs mentions as peak shaving and load-shifting, but in this research, it will verify that optimal placement and sizing them jointly with WTs can lead to more benefits like compensating the required system's reactive power support from WTs. The reactive power size of WTs and BESSs will be derived from the result of the joint sizing and placement in this study, as well as their active power output to meet the load demand. This can facilitate WTs and BESSs contribution to cover the system's required reactive power and their participation in the reactive power market and ancillary services. This paper also proposes new cost functions for both WTs and BESSs and minimizes their cost while ensuring minimal total loss (active and reactive) in the power distribution system. This can benefit both WTs' and BESSs' owners as well as system operators. Suitable placement and sizing of the WTs and BESSs can also improve the load bus voltage profiles, which can benefit the end-users, and will verify using the proposed optimization by different case studies on the 33 bus distribution system. The results of case studies ascertain the consistency of the proposed formulation for placement and sizing BESSs and WTs jointly, as well as other benefits to the power system, the power plant owners, and system operators.

1. Introduction

Traditionally Energy Storage Systems (ESS) are used in power systems to stabilize and compensate local power instabilities in the system. According to standards of wind turbines integration to the grid, these Renewable Energy Sources (RESs) should support reactive power at the point of connection, which is necessary for security and operation of the electricity grid. The standards for WT's integration require WTs to provide some percentage of their total capacity in the form of reactive power in addition to active power to prevent the system's security problems and voltage instability. Typically, most WTs are not capable of supporting this reactive power, or it is not profitable for these plants to do that. Thus, ESSs like BESS, when used with WTs, can fill the gap of supporting reactive power and also participate in other ancillary services like frequency regulation. Other benefits of BESS in the presence of WTs are for smoothening the random output of WTs, peak shaving, and load leveling, which are general advantages of any kind of ESSs. Strategically joint sized and located BESSs and WTs can help meet the standard requirements for reactive power while also help in the power quality of the power systems. In addition to the mentioned benefits, the objective of the proposed joint placement and sizing problem for BESS and WTs is defined to minimize the cost of these devices and the total loss in the power distribution system.

Different methods of optimization have been reported in the literature for placement and sizing purposes. In [1] joint placement of photovoltaic (PV) systems and ESSs investigated, where the objectives are minimizing costs in distribution system with high penetration of PVs. They concluded that with more PV penetration, more ESS needs to be install. Authors in [2] study the joint ESSs and WTs, and they have proposed a stochastic cost-benefit analysis model according to wind speed data and use it for the sizing of ESS. Authors in [3] suggested a method to optimally size the ESS so that the wind penetration level can be increased without violating the grid frequency deviation limit. In [4], an algorithm based on long-term wind power time series (WPTS) and the calculation of mean wind power were suggested to evaluate ESS's performance in minimizing the system cost and losses. But none of these studies consider the need for reactive power support from WTs, and the system losses only considered the active loss and the reactive losses are

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ignored.

A methodology to optimally allocate the ESS and DG in a radial distribution system was suggested in [5], where the problem was modeled as a nonlinear optimization problem and resolved by employing a modified PSO. In this work, instead of active power only, ESS and DG's reactive power was taken into consideration, but it didn't consider a joint formulation with other RESs like WTs or PVs. Considering joint ESS and RES placement and sizing is closer to our current grid situation. Many RESs and ESSs are installing currently in the power systems, and solving their placement and sizing problem is a challenging issue in the present and future electricity grids in the presence of large-scale RESs and ESSs. In [6], the objective function is defined to minimize power loss in the distribution system for different seasons, but only active losses were considered. In our research, both active and reactive losses will be minimized as a result of the proposed optimization formulation. In [7], the objective function minimizes the hourly social cost of BESS. Wind generation and load are modeled probabilistically using actual data and a curve-fitting approach. This study lacks the reactive power sizing of BESS, which is also considered in our study.

The average active power stored in the storage unit at each bus and the total budget for BESS are included in the optimization problem formulation in [8]. But the formulation is not joint with any RES. Also, sizing reactive power is neglected. In [9], The formulation of a problem accounts for: (i) the voltage support of storage systems to the grid, (ii) the network losses. In [10], an optimal location for BESS has to be identified in the system such that the distribution system losses are minimized. The power flow constraints are included, but power bounds and BESS budget is not in the formulations. In our research, the power bounds and BESS's limits are considered in constraints of the proposed optimization.

ESS and DGs can have various benefits to the power system to improve the reliability, power quality, and stability of the system. Therefore, the optimal sizing and placement of DGs and ESSs is considered in previous research for different objectives separately [11-14]. Some of these objectives include improving reliability of the system [11,12], improving the voltage stability of the system [13], improving the power quality, loss reduction and demand-side voltage profile [14]. In our study the objectives are defined to minimize the total loss of the susyem and the costs of the BESS and WTs. However, the reactive power support by the WTS and BESS are also facilitated in the research by including the WTs' reactive support requirements in the constraints of the optimization. The BESSs and WTs placement in the system also resulted in the voltage profile improvement in the load busesthat can mention as power quality impromenent.

The sizing and placement of hybrid systems are more complicated to model since the characteristics of each system should be considered separately. The DG and D-STATCOM placement in studied in [14,15]. The placement and sizing of the DGs and capacitor banks is studied in [16]. The hybrid RES and ESS placement and sizing is also studied in the literature, e.g., [1,2,4,6,7,8,10].

As the power system has many uncertainties, many issues can change the charactersitics of the system and affect the results of the sizing and placement of ESS and RES. For e.g. the load profile have variable nature. Therfore some papers studied the time-varrying loads impacts on the placement and sizing of RES and ESS in the system, e.g. [15,17]. However a constant load profile is assumed in our study.

As there might be many different constraints for the power systems in the generation, transmission, and distribution levels, taking into account of grid-related technical constraints and issues is crucial in placement and sizing problems. The possible impact of the reverse power flow (RPF) caused by extended penetration of distributed energy resources is studied in [18]. In our research, as a new methodology, the maximum and minimum constraints of active and reactive power of WTs are taken from a sample real WT's integration standard containing WT's PQ performance chart, as will discuss later.

These requirements are included in the constraints of the proposed joint optimization, which results in facilitating the participation of WTs in the reactive power support, and ancillary services market and can benefit the plants' owners and system operators. Moreover, it results in covering a lack of reactive power in the local and bulk power system by the WTs. The BESSs optimal reactive power in each bus of the system also will be found as a result of proposed optimization. This will facilitate BESSs participation in reactive power marker as ancillary services and help RESs like WTs support less reactive power and generate more active power instead, as will be described later.

The linear programming (LP) model has been proposed in some papers for ESS allocation. Authors in [19] transform the nonlinear AC optimal power flow with a Linear Programming problem, which was then solved using forward-backward sweep optimal power flow. In our study, a complete version of the power flow based on backward, forward load flow (BFLF) is used, which has a less mathematical burden for solving the load flow of power distribution systems, with less computation time. In contrast to the LP method, Mixed-integer linear programming (MILP) was also used in a number of papers for sizing and placement of ESS [20-25]. In [20], the optimal capacity of an ESS in a micro-grid (MG) was computed by minimizing the total MG cost that combined the ESS investment cost and MG operating cost.

Different Artificial intelligent (AI) or heuristic methods can be used to solve placement and sizing problems. Unlike the analytical and numerical approaches for ESS and RES sizing as stated above, the artificial intelligence (AI) approach does not require complex calculations as well as complicated mathematical models and algorithms to obtain the optimal ESS and RES allocation. Instead, the AI approaches search the solution space. The AI approach does not guarantee the optimal solution, but the solution is generally satisfactory, depending on the AI algorithm's solution searching ability. Other methods also are used in previous research for solving similar problems, including Fuzzy and Artificial Neural Networks (ANN) [26], Harmony Search (HS) [27], GA [28-32], and particle swarm optimization (PSO) [33,34].

Comparison between Simulated Annealing (SA) and genetic algorithm in [35] was made by Adewole et al., where they have compared the performance of SA and GA. Their results show that Simulated Annealing runs faster than Genetic Algorithm, however, in terms of solution quality, Genetic Algorithm is better than Simulated Annealing. Bajeh et al. [36] compared the Genetic Algorithm, and Tabu Search approaches to solve scheduling problems. The results show that GA can produce several different near-optimal solutions at the same time because of its holds the whole generation of chromosomes which may not originate from the same parents. In [37], the authors compare the Genetic algorithm (GA), tabu search (TS), and simulated annealing (SA) as Meta-heuristic algorithms. The computational results show that genetic algorithm has a better solution quality than the other Meta-heuristic algorithms and solving complex optimizations problems.

According to the benefits of the Genetic Algorithm (GA), the algorithm is used in our research to solve the proposed joint placement and sizing problem. The main new contributions of the current research are:

- First of all, while most previous papers only consider active power, the joint sizing and placement of BESSs and WTs in this paper will result in finding both optimal active and reactive power by WTs and BESSs. This can determine how much BESSs and WTs can help support the reactive power and participate in the ancillary services market.
- In contrary to most of the previous papers, the objective of minimizing total loss in this study considers minimizing both active and reactive losses of the distribution system.
- To our knowledge, for the first time, a sample of the standards for WT's integration describing their required PQ performance chart is used in this research, and the requirements are included in the constraints of the proposed placement and sizing problem. This will facilitate WT plants' participation in the system's reactive power

support and reactive power market and can ensure the safety and voltage stability of power systems.

- New cost function is defined for BESS. The total cost of the energy storage system is considered as a combination of the cost of the storage system ($cost_{SS}$), plus the cost of the power conversion system ($cost_{PCS}$), and the cost of balance of plant (BoP), resulting in a new formulation of joint WTs and BESSs placement and sizing.
- The cost formulation of WTs is defined to account for the least cost of WTs between different choices of installation, having a total size of WTs. This means, for example, when a total 1MW WT is needed, a possible option can be installing a 1 MW WT, or the 2nd choice can be two 0.5MW WTs, etc. The formulation in this paper finds the best selection of WT types with the least cost.

2. The benefits of the current research to solve existing problems in the electricity grids

Fig. 1 shows the conceptual model of a power system in the presence of RES and ESS.

Generally, ESS and BESS, in particular, can help in peak shaving, stability, and security of power systems. The electricity end users also can benefit from enhanced power quality and voltage profile improvements. Our proposed joint placement and sizing problem solution is helpful to improve the above-mentioned issues in current power systems, which include hybrid systems with RES and ESS. As mentioned in the introduction section, to our knowledge, none of the previous studies consider the strictly required reactive power support from WTs, which are described in WT's integration standards documents. In this paper, these reactive power support requirements are included in the constraints of the proposed optimization formulation for WTs. Fig. 2 shows a typical required PQ performance chart of a WT from one of these standards [38], which is used in this study.

As shown in this figure generating active power should not be the only purpose of employing WTs, but the reactive power generation is also required from WTs due to the large-scale penetration of RES in today's electricity grid. According to Fig. 2, the five boundaries (the green line limits) of the polyhedron are included in the constraints of the optimization problem in this study.

On the other hand, when WTs support reactive power, their generated active power reduces exponentially. Fig. 3 shows a typical result of load flow analysis at the point of common coupling (PCC) for a WT. According to Fig. 3, when WTs provide reactive power at the same time with active power, the drawback is that their generated active power reduces exponentially (more than linear reduction). However, the proposed joint ESS and WTs problem in this study will reduce the need for supporting reactive power by WTs. Instead, the optimal reactive power can be generated from ESS too, and this results in operating WTs near their maximum power limit (P_{max}) and can benefit WT plants operators and owners.

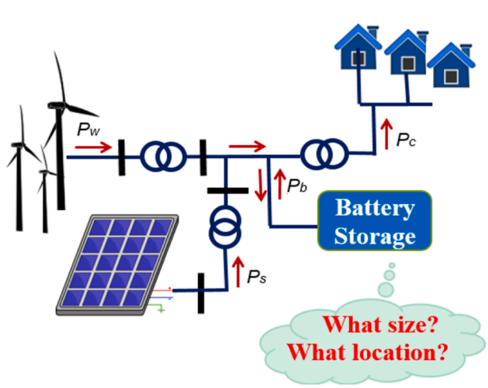

Fig. 1. The conceptual model of RES and ESS in current power systems and their placement and sizing problem.

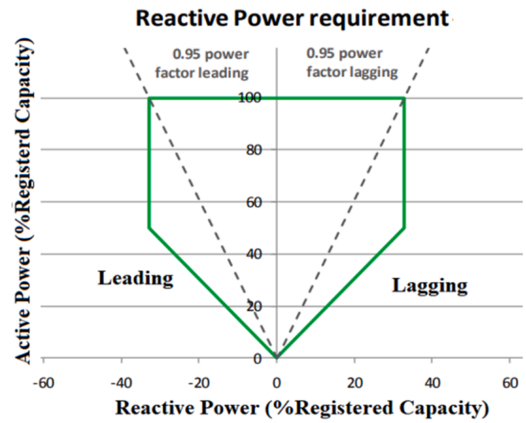

Fig. 2. Typical PQ. (performance) chart [38]

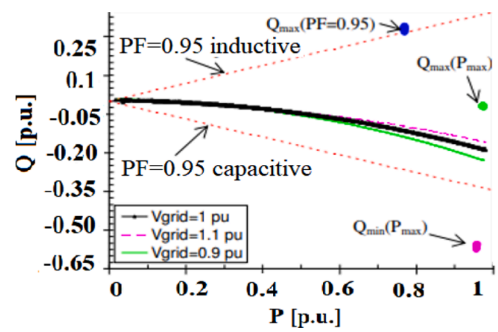

Fig. 3. load flow of typical wind farm at PCC.

The evaluation of the impacts of ESS while using in hybrid systems like with WTs is out of the scope of this paper. But no need to mention that in addition to reactive power support mentioned, generally, ESS can help in peak shaving, load-shifting, load leveling, smoothening the output power of RES, enhancing power quality, and stabilizing the power system for e.g., serving for the grid frequency regulation as well.

The joint placement of ESSs and WTs not only helps for optimal allocation of active power and supporting reactive power in the electricity grid, but also satisfies the end-users as it can improve the voltage profile in the demand side, as will be shown in the results section. Further, the main objective of the optimization is defined to benefit both ESS's and WT's owners by decreasing the cost of WTs and ESS while reducing the distribution system's loss that can benefit system operators and all grid participants in general.

3. Optimization problem formulation

In the last section, the need for WT's participation in reactive power support and the reason why ESSs can help with this issue described. Reactive power sizing is not considered in many previous papers for e.g. [5-10]. As a result of the proposed sizing problem, the active and reactive power of both BESSs and WTs (P_{BESS}, Q_{BESS}, P_{WT}, and P_{WT}) will be identified. The result of optimization will verify that the reactive power compensation from BESS can help WTs to work near their maximum active power limits, which is especially necessary for peak hours of a day that WT's full contribution to generating maximum active power is needed.

In finding the optimal solution of the joint placement and sizing of BESSs and WTs, with objectives of loss and cost minimization, both active and reactive losses are modeled and minimizing. The solver iterates the load flow program several times, and the total loss calculates in each iteration to be minimized. The power flow in each iteration is based on the backward forward load flow (BFLF) method in this study, which has less computation burden and computation time at the same time for distribution systems applications. The complete BFLF method is formulated base on currents of branches and bus voltages, as described in [39].

In the distribution network, the complex load at the bus (*i*), is modeled as:

$$S_i = (P_i + jQ_i)\ i = 1, \ldots, N \tag{1}$$

For *k*th iteration, it can be written as:

$$I_i^k = I_i^r\left(V_i^k\right) + jI_i^i\left(V_i^k\right) = \left(\frac{P_i + jQ_i}{V_i^k}\right)^* \tag{2}$$

Base on the bus's load and the differences between the bus's voltage, BIBC, and BCBV matrixes can be created as:

$$\begin{aligned} [\mathrm{B}] &= [\mathrm{BIBC}][\mathrm{I}] \\ [\Delta V] &= [\mathrm{BCBV}][\mathrm{B}] \end{aligned} \tag{3}$$

Where BIBC is the bus-injection to branch-current (BIBC) matrix, and BCBV is the branch-current to the bus-voltage (BCBV) matrix. The solution for this distribution load flow method obtains by solving the following equation iteratively:

$$I_i^k = I_i^r\left(V_i^k\right) + jI_i^i\left(V_i^k\right) = \left(\frac{P_i + jQ_i}{V_i^k}\right)^* \tag{4}$$

$$\left[\Delta V^{(k+1)}\right] = [BCBV][BIBC]\left[I^k\right] \tag{5}$$

$$\left[V^{(k+1)}\right] = \left[V^0\right] + \left[V^{(k+1)}\right] \tag{6}$$

$$\mathrm{V} = V_m(\cos\delta + j\sin\delta) \tag{7}$$

$$\delta = tg^{-1}\left(\frac{imag(V)}{real(V)}\right) \tag{8}$$

where V_i^k, I_i^k are the bus voltage and equivalent current injection of the *i*th bus at the kth iteration. As mentioned, the active and reactive losses are both considered and will be minimized by the optimization problem. Thus, these losses are derived using the lines' resistances and impedance as follows:

$$P_L = \mathrm{R}I_L^2 \tag{9}$$

$$Q_L = XI_L^2 \tag{10}$$

$$P_{TL} = \sum P_L \tag{11}$$

$$Q_{TL} = \sum Q_L \tag{12}$$

$$S_{TL} = P_{TL} + jQ_{TL} \tag{13}$$

Where P_L, Q_L, S_L are active, reactive, and complex losses associate with each distribution line, respectively. The solver minimizes the total loss in the system (S_{TL}):

$$Minimize\ S_{TL} \tag{14}$$

Subject to

$$[\Delta V] = [BCBV][BIBC][I] \tag{15}$$

$$I_i^k = I_i^r\left(V_i^k\right) + \mathrm{j}I_i^i\left(V_i^k\right) = \left(\frac{P_i + jQ_i}{V_i^k}\right)^* \tag{16}$$

$$\left[\Delta V^{(k+1)}\right] = [BCBV][BIBC]\left[I^k\right] \tag{17}$$

$$\sum_{i=1}^{n} P_{wt,i} + \sum_{i=1}^{n} P_{BESS,i} = h \tag{18}$$

$$P_{BESS,min} \le P_{BESS} \le P_{BESS,max} \tag{19}$$

$$Q_{BESS,min} \le Q_{BESS} \le Q_{BESS,max} \tag{20}$$

$$V_{min} \le V_i \le V_{max} \tag{21}$$

$$0 \le P_{wi} \le P_{WT,max} \tag{22}$$

$$-0.32\ p.u. \le Q_{wi} \le 0.32\ p.u. \tag{23}$$

$$Q_{wi} - 0.64P_{wi} \le 0 \tag{24}$$

$$-Q_{wi} - 0.64P_{wi} \le 0 \tag{25}$$

Where Eqs. (15-17) ensures execution of the BFLF load flow in each iteration. Eq. (18) ensures the sum of BESSs' and WTs' power is equal to the needed power generation by them, which imposes from the total available budget, or the amount which the load is lower than supply in a period (like an hour). Eqs. (19) and (20) accounts the minimum and maximum limits of BESS's active and reactive power (P_{BESS}, Q_{BESS}). Eq. (21) ensures the buses' voltages are within required limits, which further helps the voltage profile improvements in all buses of the system, including the load buses. The Eqs. (22-25) are taken from the WT's standard describing the required performance (PQ) chart (illustrated in Fig. 2) for a sample WT [38].

Solving the optimization problem, the unknown active and reactive power of BESSs and WTs ($P_{BESS}, Q_{BESS}, P_{WT}$, and P_{WT}) can be derived; however, one can calculate the capacity of BESSs and WTs as a result of the four optimal variables mentioned above as follows:

$$S_{BESSi} = \sqrt{P_{BESSi}^2 + Q_{BESSi}^2} \tag{26}$$

Where S_{BESSi} is BESS's complex apparent power (also known as its capacity).

$$S_{WTi} = \sqrt{P_{WTi}^2 + Q_{WTi}^2} \tag{27}$$

Where S_{WTi} is WT's complex apparent power (also known as its capacity). It should be noted that Eq. (26) denotes the AC capacity of BESS; thus, the DC capacity of BESSs can be determined considering the inverter efficiency as:

$$S_{BESS,i}^{DC} = S_{BESS}^{AC} \Big/ \eta_i \tag{28}$$

Where η_i is the inverter efficiency.

The loss minimization is formulated by Eqs. (9-14), but as mentioned, this paper also considers the total cost of BESSs and WTs. Different kinds of BESS use in power systems applications, and depending on these applications (like bulk power system, distributed generation, or as power quality enhancement), the cost of the energy storage systems are different. In this paper, the cost per installable power ($/kW) and per energy ($/kWh) is taken from [40]. The total cost to be minimized in optimization formulation is defined as:

$$cost = \sum_{i=1}^{n} cost_{WT,i} + \sum_{i=1}^{n} cost_{BESS,i} \tag{29}$$

A new formulation for BESS costs is considered in this study as follows. The total cost of the energy storage system is the cost of the storage system ($cost_{SS}$), plus the cost of the power conversion system ($cost_{PCS}$), and the cost of balance of plant (BoP) as follows:

$$\begin{aligned} cost_{BESS,i} &= cost_{SS} + cost_{PCS} + cost_{BoP} \\ &= c_e\frac{1}{\eta}E + c_pP + cost_{BoP} \end{aligned} \tag{30}$$

Table 1 shows the related cost coefficients for Li-ion, and Lead-acid batteries, which are the majority of battery types use as BESS in power systems. The total cost of BESS in our study is calculated based on

Table 1
The costs of different types of BESS

Battery type	Energy coef. (c_e) [$/kWh]	Power coef. (c_p) [$/kW]	BoP cost [$]	Storage efficiency
Li-ion	500	175	0	85%
Lead-acid	200	175	50	75%

the data of Table 1.

The average cost of WTs with different sizes (kW) are estimated using the data from wind turbine producers and are shown in Table 2. The average maintenance cost of WTs is considered 48($/kW), which is based on real data. The maintenance is higher when the WT size is bigger, as shown in Table 2.

Here the objective is defined to produce the highest amount of wind energy at the minimum cost. This will ensure the maximum production of clean energy from WTs and, at the same time, minimize their costs. Therefore, the cost optimization of WTs and BESSs considering maximum production of wind energy is defined as Eqs. (31-33).

$$Minimize\ \frac{\sum_{i=1}^{n} cost_{WT,i}}{\sum_{i=1}^{n} P_{WT,i}} + \sum_{i=1}^{n} cost_{BESS,i} \tag{31}$$

Subjected to

$$cost_{WT,i} = \sum_{k=1}^{n} n_k \widetilde{P}_k cost_k \tag{32}$$

$$P_{WT,i} = \sum_{k=1}^{n} n_k \widetilde{P}_k \tag{33}$$

Where n_k is integer number of WTs of type k, and i is the number of buses, and $\widetilde{P}$ is the nominal output power of each type of WTs (k1…k9), which is shown in column 1 of Table 2. The output power of WTs in each bus is considered in the denominator of the cost objective function (31) to ensure the maximum level of clean energy production by WTs. Also, the constraints of the above cost optimization determine the cost of WTs in each bus depending on the size and type of WTs that is used in the buses and its associated cost, according to Table 2. Therefore, the cost formulation of WTs is defined to account for the least cost of WTs between different choices of installing the total sized capacity. This means, for example, when a total 1MW WT is needed, a possible choice can be installing a 1 MW WT, or another choice can be two 0.5MW WTs, and etc. This newly proposed formulation in Eqs. (32) and (33) ensures finding the choice of WTs that has the least cost. This consideration can benefit the operators and owners of WT plants, as mentioned before. Ultimately, the overall objective function, which is considered in this study minimizes both the total distribution system loss and the cost of WTs and BESS as follows:

$$Minimize\ w_1\left[\frac{\sum_{i=1}^{n} cost_{WT,i}}{\sum_{i=1}^{n} P_{WT,i}}\right] + w_2\left[\sum_{i=1}^{n} cost_{BESS,i}\right] + w_3[S_{TL}] \tag{34}$$

Subject to all constraints and bounds defined in Eqs. (14-25). The Genetic Algorithm (GA) is used as the solver of the above optimization problem to find the location and sizes of WTs and BESSs on each of the system's buses. The flowchart of the optimization by GA is shown in Fig. 4. In each iteration load flow program runs to find the current and voltages in each bus, and then the power losses of each branch calculate. The best (optimal) location and size of WTs and BESSs determine according to equation (35) and the constraints defined in Eqs. (14-25). The GA algorithm shows a suitable performance for solving this problem, as will discuss in the results sections.

Table 2
wind turbine average cost per watt.

K	WT size ($\widetilde{P}_k$)	Cost [$] ($cost_k$)	Maintenance cost [$] per year
1	1 kW	2130	48
2	1.5 kW	9000	72
3	2.5 kW	17000	120
4	5.0 kW	32000	240
5	10 kW	64000	480
6	15 kW	100000	720
7	800 kW	1813000	38400
8	1.5 MW	3200000	72000
9	2.5 MW	4014700	120000

4. Results of solving the proposed optimization

In this section, the results of applying the defined optimization by the objective function of equation (35) and the constraints of Eqs. (14-25) are tested on 33 bus distribution system [41] by defining several case

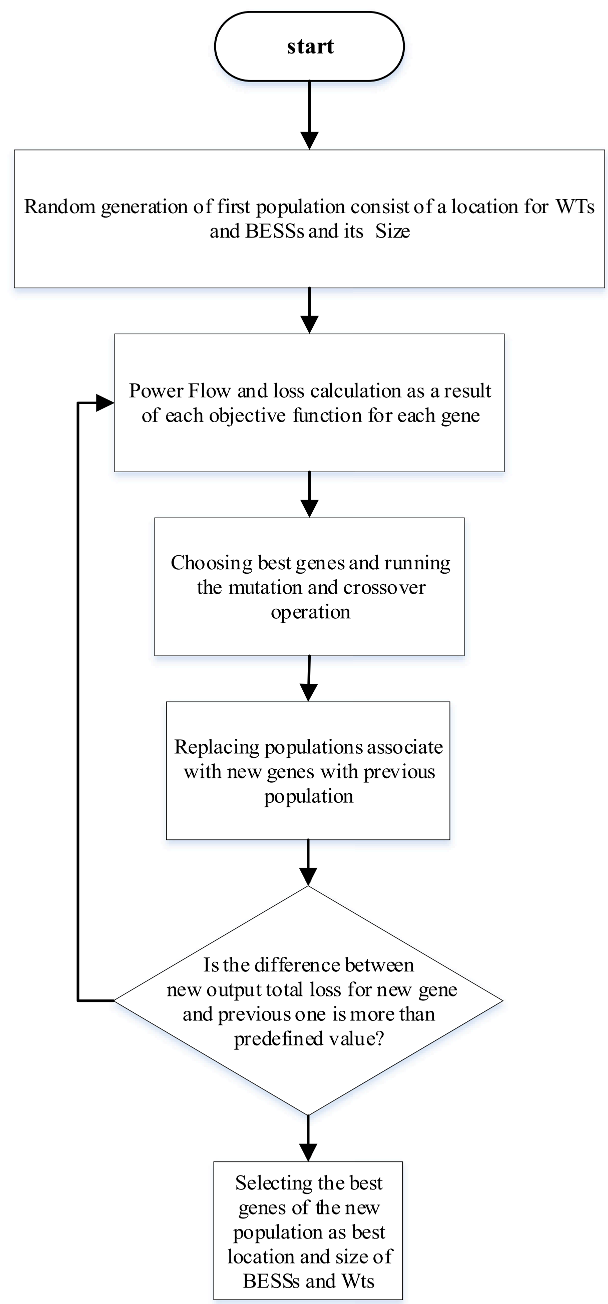

Fig. 4. Placement and Sizing procedure flowchart.

studies to test the consistency of optimization formulation.

Subsection 4.1 only considers BESS's placement and sizing. In subsection 4.2, it is assumed that only WTs are going to place and size in the system, and the optimal results are provided using GA solver. In subsection 4.3, the joint WTs and BESSs sizing and placement are studied only when the objective is the distribution system's loss minimization. Finally, in subsection 4.4, which shows the contribution of this research better, the proposed joint cost and loss minimization for WTs and BESSs is studied, and the results of the optimization is provided.

4.1. Placement and sizing of BESSs

In this subsection, six cases are compared based on a different number of BESSs to be installed in the system. It is assumed from minimum zero to a maximum of six BESSs are going to install considering a total of 1000 MW of BESS in the system based on available budgets or the required load demand. The optimal location and sizes of BESS on each bus of the system are determined using the GA algorithm procedure. Table 3 shows the optimal location and sizes of these BESSs, and Fig. 5 shows how much each of the six case studies improves the voltage profile of each bus in the system. Column 4 of TABLE III shows the sizes of BESS in complex format, in which the real part is the optimal result of active power from the BESSs, and the imaginary part shows the optimal reactive power of the BESSs.

4.2. Placement and sizing of WTs

In this subsection, six cases are compared based on the Number of WTs to be installed in the system. It is assumed from minimum zero to a maximum of six BESSs are going to be installed considering a total of 1000 MW of WTs in the system based on available budgets or the required load demand. The optimal location and sizes of WTs on each bus of the system are determined using the GA algorithm procedure. Table 4 shows the optimal location and sizes of these WTs in the 36 bus distribution system, and Fig. 6 shows how much each of six case studies improve the voltage profile of each bus in the system. Column 4 of Table 4 shows the sizes of WTs in complex format, in which the real part is optimal active power needed from the WTs and the imaginary part shows the optimal reactive power needed from the WTs to minimize the total active and reactive losses in the distribution system.

The required reactive power support is imposed on the constraints of the formulation by the sample PQ chart of a typical WT in the standard [27]. Although, as mentioned in the introduction and section 2, the WTs may not be able to provide these amounts of reactive power mentioned in WT's integration standards; therefore, ESSs can help WTs to provide the needed reactive power as will be discussed in subsection 4.3.

4.3. Joint BESS and WT placement and sizing for loss minimization

In this subsection, nine cases were considered to study different number of WTs and BESS in the 33 bus distribution system. Then, the best locations and sizes for them are determined based on the total loss minimization of the system and are shown in Table 5. It is assumed that a total of 1000 MW of BESSs and WTs needed to be installed in the system based on available budgets. The voltage profile improvement of buses, while both BESS and WTs are employed in the 36 bus distribution system, is shown in Fig. 7.

The results show which combination of BESSs and WTs can better decrease the total active and reactive losses of the system. Also, the results show that BESSs considerably contribute to both active and reactive power generation to the system in the joint BESS and WT optimization, and verifies that BESSs not only provide necessary active power for peak shaving and load-shifting, but they can also compensate for the reactive power needed from WTs by the required PQ performance charts in the WTs' standards.

According to the results of this subsection and Table 5, this compensation of reactive power by BESS, facilitates the operation of WTs near their maximum active power limits instead of generating reactive power. WTs' active power generation capability decreases exponentially when they support reactive power generation, as described in section 2. The results of Table 5 verifies that comparing to the last case study, which employed only WTs in the system, in the case study 4.3, where joint BESS and WTs used, the WTs need to generate less reactive power with the help of BESSs. As a result, WTs can work near their maximum active power limit.

4.4. Joint BESS and WT placement and sizing by minimizing both their costs and total system loss

In this subsection, minimizing the costs of WTs and BESSs (lithium-ion batteries according to parameters and coefficients mentioned in tables 1 and 2) is considered in addition to minimizing system total loss.

Table 3
BESS sizing and placement (6 test cases).

Case Studies	No. of BESSs	Best BESS Locations (Bus No.)	Size of BESSs (MVA) $\left(\begin{array}{c}P_{BESS}\\+jQ_{BESS}\end{array}\right)$	Total loss (kVA) $\left(\begin{array}{c}P_{Loss}\\+jQ_{Loss}\end{array}\right)$	Power loss minimization (%)
Initial	0	—	—	244	%0
Case 1	1	29	1000+j1000	91.652	%62.28
Case 2	2	13, 30	493.22+j546.34 506.78+j635.72	69.035	%71.59
Case 3	3	29, 13, 30	314.94+j506.38 353.89+j493.29 331.17+j489.33	63.766	%75.575
Case 4	4	13, 29, 24, 30	280.50+j484.83 250.72+j507.61 221.74+j497.81 247.03+j477.11	66.225	%72.74
Case 5	5	28,29,13,24,31	200.46+j488.48 249.88+j491.75 238.71+j498.02 148.70+j496.83 162.25+j175.79	66.243	%72.73
Case 6	6	30,25,24,25,29,31	172.24+j483.48 162.55+j467.20 156.77+j500.36 161.71+j454.12 167.75+j478.55 178.98+j0.2933	82.798	%65.92

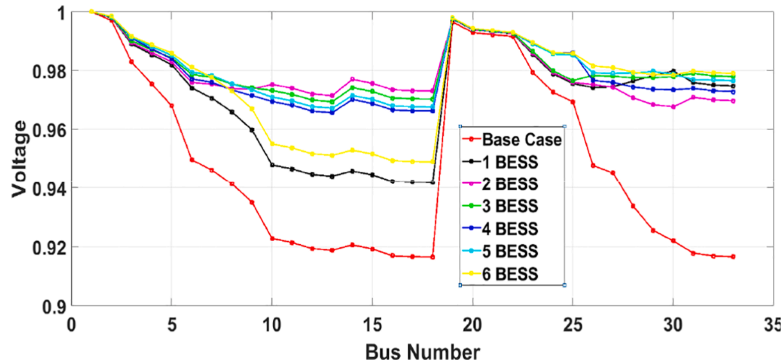

Fig. 5. The voltage profile improvement in load buses by installing different BESSs

Table 4
WT sizing and placement (6 test cases)

Case Studies	No. of WTs	Best WTs Locations (Bus No.)	Size of WTs (MVA) $\left(\begin{array}{c} P_{WT} \\ +jQ_{WT} \end{array}\right)$	Total Loss (kVA)	Power loss minimization (%)
Main Case	0	—	—	244	%0
Case 1	1	29	1000+j640	103.83	%57.44
Case 2	2	31, 13	198.74+j351.22 801.26+j288.76	92.12	%62.24
Case 3	3	14, 31, 9	38.358+j254.69 80.771+j279.72 880.87+j105.53	99.294	%59.30
Case 4	4	11, 13, 15, 29	18.909+j114.24 12.009+j119.85 12.219+j128.72 956.86+j276.88	103.64	%57.52
Case 5	5	7, 5, 15, 7, 9	1.2699+j68.284 4.2502+j207.78 0.13718+j106.25 2.1906+j44.644 992.15+j213.04	116.18	%52.38
Case 6	6	31, 29, 29, 31, 30, 9	7.0981+j61.64 2.3244+j291.91 3.4859+j102.56 3.8872+j68.98 2.176+j65.317 981.03+j49.578	98.916	%59.46

Equation (35) is used as an objective function and Eqs. 14-25 as constraints. It is assumed that a total of 1000 MW of BESSs and WTs needed to be installed in the system based on available budgets or the required load demand. The same as the last subsection, here also nine case studies are defined with the same Number of WTs and BESSs in each case. The voltage profile improvement is shown in Fig. 8. According to this figure, the analysis of voltage improvement when the cost of BESSs and WTs also is considered is not as easy as previous subsections, and the analysis is more complicated. For e.g., using one BESS and WT has a better voltage profile comparing to have more devices. But the objective of cost minimization suitably finds the minimal costs of WTs and BESS while ensuring minimal total system loss. Table 6 in the appendix verifies another novelty of this research wherein each of the nine case studies in case study 4.4, depend on the Number of WTs employed, the optimal combination of WT with different types of WTs (as defined in Table 2), which has the least cost is resulted from solving the optimization problem. For example, when a total 1MW WT is needed, a possible choice can be installing a 1 MW WT, or another choice can be two 0.5MW WTs, and etc. The formulation finds the least WT's combination cost. Table 7 in the appendix shows the solution of placement and sizing considering minimizing both WTs and BESSs cost and the total system loss. It can be concluded that for choosing the best combination of BESSs and WTs to reduce the costs and loss of the system, the joint optimal placement and sizing of them is necessary, and the best case (like one of these 9 cases here) can be chosen by comparing the costs and losses of each case. It also can be concluded that the same as case study 4.3, when WTs and BESSs optimization is done jointly, the BESSs can help WTs to support required reactive power to the system as well as active power. This issue can pass the requirements from WT's to support reactive power in standards. Further, the cost minimization of the BESSs and WTs is also necessary to benefit their owners and also the system operators while ensuring minimal distribution system loss at the same time.

5. Conclusion

The joint placement and sizing of WTs and BESSs were studied in this research. Different case studies are defined to verify the proposed optimization problem, including using only WTs and BESSs or employing both of them. Several benefits of the proposed optimization formulation were verified in each case study. Improvement of voltage profiles

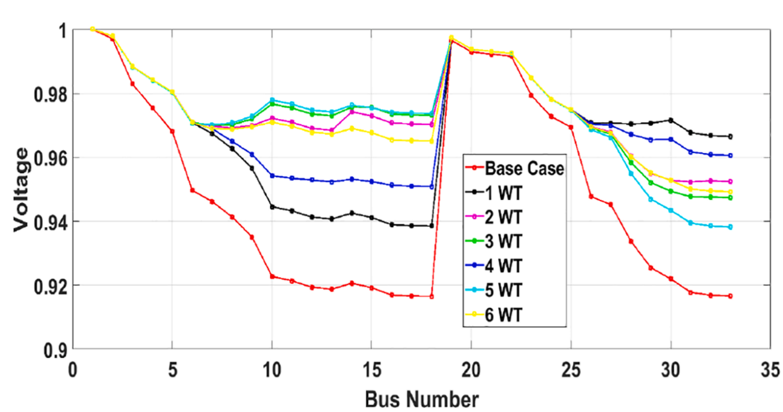

Fig 6. Buses voltage profile improvements with WTs placed.

Table 5
WT and BESS sizing and placement (9 test cases)

Case	No. of WTs	No. of ESS	Best WT place	Best BESS place	Size of WTs (MVA) $\left(\begin{smallmatrix} P_{wt} \\ +jQ_{wt} \end{smallmatrix}\right)$	Size of BESSs (MVA) $\left(\begin{smallmatrix} P_{BESS} \\ +jQ_{BESS} \end{smallmatrix}\right)$	TotalLoss (kVA) $\left(\begin{smallmatrix} P_{Loss} \\ +jQ_{Loss} \end{smallmatrix}\right)$	% lossMin
Main Case	0	0	—	—	—	—	244	%0
Case1	1	1	15	29	224.96+j143.21	775.04+j675.51	81.07	%66
Case2	1	2	17	13, 29	32.835+j20.336	16.262+j320.83 950.90+j524.66	89.91	%63
Case3	1	3	30	29, 25, 31	249.15-j0.217	252.34+j963.17 249.24+j202.89 249.27+j216.1	83.36	%65
Case4	2	1	27, 31	29	642.62+j319.75 184.00+j110.44	173.07+j822.29	86.54	%64
Case5	2	2	15, 11	31, 29	243.19+j71 252.69+j69	250.19+j77.664 253.94+j998.25	64.04	%73
Case6	2	3	27, 31	30, 29, 25	199.27+j46.5 207.18+j47.25	197.30+j36.788 201.74+j999.06 194.52+j232.51	82.83	%66
Case7	3	1	25, 30, 31	29	257.56+j74.5 248.06+j68.75 243.06+j49.632	251.31+j999.87	85.20	%65
Case8	3	2	25, 24, 30	25, 29	46.428+j42.967 14.933+j55.717 812.30+j50.441	125.63+j112.57 0.7132+j1000.0	85.16	%65
Case9	3	3	30, 16, 31	31, 29, 25	153.28+j45.515 189.39+j76.63 166.86+j54.175	151.17+j74.075 183.57+j623.06 155.74+j589.27	65.79	%73

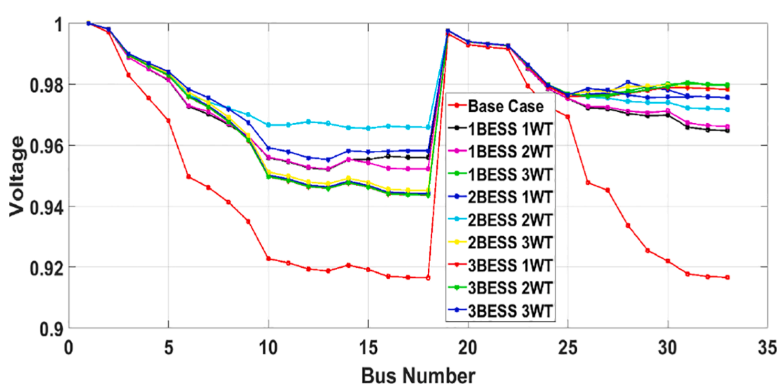

Fig 7. Bus Voltage profiles with WT and BESS placed considering total loss minimization

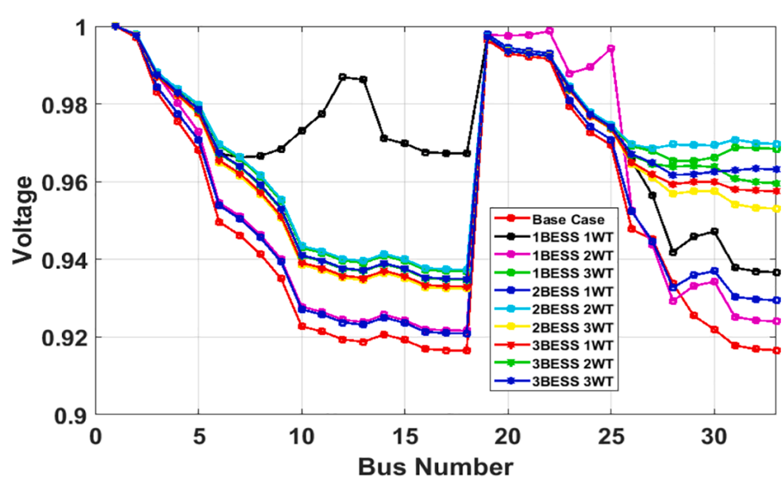

Fig 8. Bus Voltage profiles with WT and BESS placed considering both costs and loss minimization.

Table 6
the optimal number of each type of WTs for the nine case studies of subsection 4.4.

Case studies	Sets	Optimal number of each of 9 types of Wind Turbines according to Table (2)								
Wind Turbine type		1 kW	1.5 kW	2.5 kW	5.0 kW	10 kW	15 kW	800 kW	1.5 MW	2.5 MW
No. of WTs (Case1)	WT1	1	0	1	1	0	1	0	0	0
No. of WTs (Case2)	WT1	99	101	226	124	117	107	365	37	0
No. of WTs (Case3)	WT1	120	170	183	184	176	206	287	33	0
No. of WTs (Case4)	WT1	858	100	105	103	107	101	97	76	68
	WT2	158	207	108	108	101	99	69	39	0
No. of WTs (Case5)	WT1	99	138	111	194	118	114	103	0	29
	WT2	71	61	124	185	106	122	78	0	32
No. of WTs (Case6)	WT1	100	107	109	101	103	103	92	79	65
	WT2	142	158	102	110	104	104	69	38	0
No. of WTs (Case7)	WT1	105	209	103	99	101	101	89	73	73
	WT2	141	164	112	105	109	102	67	41	0
	WT3	98	144	103	106	115	104	65	41	0
No. of WTs (Case8)	WT1	103	183	101	117	126	101	138	200	69
	WT2	128	146	117	104	104	101	68	41	0
	WT3	102	110	103	115	118	133	67	42	3
No. of WTs (Case9)	WT1	104	96	104	99	99	99	87	55	0
	WT2	65	45	113	107	107	104	74	47	17
	WT3	103	106	107	103	103	103	73	47	17

Table 7
Joint placement and sizing results of the case study 4.4 considering choosing the least cost of WT's types.

Case Studies	No. of WTs	No. of BESSs	Best WT locations	Best BESS locations	Size of WTs (MVA)	Size of BESSs (MVA)	WTs Cost ($)	BESSs cost ($)	Loss (kVA)
Main Case	0	0	—	—	—	—	—	—	244
Case 1	1	1	6	11	4.4-j0.3	995.5+j299.4	1.7e3	7.6e5	143.8
Case 2	1	2	21	24	353+j3.28	289.96+j476.41	8.19e8	4.82e5	183
				24		357.01+j542.56			
Case 3	1	3	27	30	290.3+j31.6	208.7+j171.6	6.04e8	5.37e5	110.7
				30		260.3+j148.9			
				31		240.5+j137.4			
Case 4	2	1	18	30	814.13+j6	64.5+j61.65	1.7e9	1.21e4	184.1
			31		121.31+j10.2				
Case 5	2	2	30	30	287.2+j62.4	220.15+j265.1	8.75e8	3.37e5	108.2
			29	29	270.9-j0.19	221.6+j204.08			
Case 6	2	3	29	30	666.1+j1.8	70.6+j10	1.44e9	1.09e5	137.3
			30	27	119+j4.5	72.2+j12.1			
				28		71.1+j10.8			
Case 7	3	1	29	28	684.05-j2.81	72.24+j92.09	1.8e9	5.51e5	133.1
			30		122.18-j7.3				
			31		121.5+j11.1				
Case 8	3	2	29	29	621+j21.8	63.7+j133.4	2.47e9	9.46e4	123.4
			30	29	122+j10.1	60.27+j90.7			
			29		132+j13.7				
Case 9	3	3	31	31	215+j3.4	133+j108	1.39e9	3.2e5	121.5
			31	29	180+j2.81	132+j80			
			30	27	178+j5.08	159+j91			

in load buses in the 36 bus distribution system is verified in each case study. Moreover, this research proposed considering WT's performance PQ charts in the constraints of the optimization to study the contribution of WTs in reactive power support. Further, BESSs contribution to support reactive power, instead of only WTs, can also facilitate by sizing them jointly with WTs in the system. This can also pave the way for their participation in the ancillary services market and also can benefit the system by providing required reactive power. A new cost function defined for both BESSs and WTs, and the related data provided in separate tables, which can be used in future research too. Also, as discussed, different types and sizes of WTs can be installed to meet the total needed capacity with respect to the available budget. But as another new contribution, the best WT sizes with the least cost are found from the result of the proposed optimization formulation in this research. Overall, the optimization formulation has evaluated as a very suitable formulation for joint BESSs and WTs placement and sizing in the power distribution systems

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Appendix

Table 6 shows the result of the case study 4.4 in which the optimal number of each type of wind turbines found based on the capacity of WTs for any of 9 case studies according to Eqs. (32,33). Table 7 shows the placement and sizing results in the case study 4.4 considering minimizing costs of both BESS and WTs and the total system loss.

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