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Optimal Battery Location for Minimizing the Total Cost of Generation in a Power System

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Abstract— **Wind is one of the major and fast growing source of green energy in the world. However, it's naturally variable and this reduces its percentage penetration in a power system because of costs associated with balancing reserves. One of the solution being proposed in the recent times is the use of battery energy storage systems (BESS). This is coupled by the fact that there has been continuous reduction in the cost of BESS which has been experienced recently. The objective of this research study is to find optimal BESS location for minimum total cost of power generation in a power system with wind power generation and branch flow power limits. The study used the IEEE 30 bus system. Simulations were done using MATPOWER. Particle swam optimization technique was used to determine optimal BESS location. Results show that bus number 24 was BESS optimal location for several wind location buses.**

Keywords—**Battery energy storage system, Generation cost, Optimal location, Wind variability**

I. INTRODUCTION

The installed wind capacity has been on increase [1], however the variability and uncertainty nature of wind power supply imposes severe limits to the integration of wind power generation into power systems. The cost associated with wind power due variability and uncertainty may reach up to 7 $/MWh [2]. In order to mitigate the effects of variability and uncertainty, BESS can provide the required reserves by increasing or decreasing charging and discharging [3]. This effectively reduces the required reserves and leads to increased percentage penetration of the wind power.

The world's cumulative installed BESS capacity is expected to surge from 1.5GW in 2015 to 14GW by 2020 [4]. In addition to this there has been a rise in the capacities of the batteries. In 2017, Tesla completed world largest Li-ion battery of 129MWh in South Australia [5]. There is also ongoing work of constructing 200MW/800MWh vanadium flow battery in Dalian China and is expected to be finished by 2020 [6].

Battery prices have steadily come down for the past 20 years, especially for the Lithium-ion batteries [7]. In 2016, the price of Lithium-ion batteries was $209/KWh and it is projected that prices could fall to $100/KWh by 2025 according to Bloomberg New Energy Finance (BNEF) survey. This trend is illustrated in Figure 1.

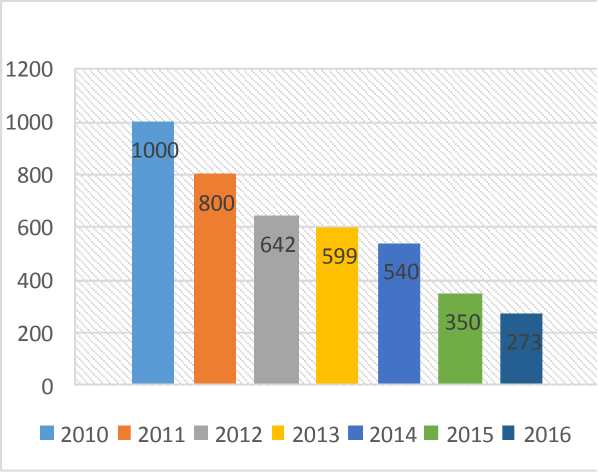

Figure 1. BNEF lithium-ion battery price survey 2010-2016 ($/kWh)

Different methods of optimizing the BESS location in a power system with wind generation have been proposed in the literature. A hybrid multi-objective particle swarm optimization (HMOPSO) is suggested in [8] to minimize the

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power system cost and improve the system voltage profile by probing optimal sizing and sitting of storage units. The study was carried out under consideration of uncertainties in wind power production. Effects of branch flow power limits were not considered.

In [9] a mixed integer linear programming (MILP) approach consisting of loss reduction, voltage improvement and minimization of generation costs is suggested to provide best sites for energy storage systems and wind power. The objective was to optimize distribution system costs taking into account network constraints and the uncertainty associated to the nature of wind, load and price. The branch flow power limits were among the four variables considered.

In [10] an algorithm for optimal siting and sizing of Energy Storage System (ESS) for the operation planning of power systems with large scale wind power integration was proposed. The research was carried out under consideration of wind power fluctuations and lines transmission capacity for ranking buses based on their power exchange percentage. Buses which were ranked high became candidates for siting ESS. In the study, effect of branch flow power limits was considered but further work is needed to reveal effect of different wind locations on the ESS optimal location.

In [11], a semi definite relaxation of AC optimal power flow was used to study the problem of optimally placing large-scale energy storage in power grids with both conventional and wind generation. The solution technique for this infinite horizon problem assumed cyclic demand and generation profiles. Changes in storage location in the network were studied as a function of total storage budget and transmission line-flow constraints. Some line-flow limits were varied to study the effect on storage location.

From Literature, more research work should be done to determine the optimal location of a BESS in a power system with wind generation and branch flow power limits and determine how it relates to optimal locations of wind generation. This study was carried out to fill this gap.

II. METHODOLOGY

In this research work, particle swam optimization technique (PSO) was used. It mimics how fish and birds exchange information while in search of food. PSO uses particles which exchanges information while exploring an objective space searching for good function values. PSO is very popular for solving one objective and multi objective optimizing problems as shown by the reviewed works [12]-[14]. In [15]-[17], PSO has been used to determine optimal size of battery storage.

PSO algorithm consists of the following steps:

1. Initialize population in hyperspace in both velocity and position
2. Evaluate fitness of individual particle
3. Update individual and global best fitness and position
4. Update velocity and position of each particle.
5. Repeat step 2 until some stopping condition is met.

Velocity and position update are done using the following equations:

$$v_{i(t+1)} = wv_{i(t)} + c_1r_1[p_{best(t)} - x_{i(t)}] + c_2r_2[g_{best(t)} - x_{i(t)}] \quad (1)$$

$$x_{i(t+1)} = x_{i(t)} + v_{i(t+1)} \quad (2)$$

The constants w, c_1 and c_2 are user supplied constants. The inertia component is represented by $wv_{i(t)}$. This is responsible for keeping the particle heading in the same direction it was originally moving. The particle memory is represented by $c_1r_1[p_{best(t)} - x_{i(t)}]$, which is called the cognitive component. It tends to cause the particle to return to the regions of the search space in which it has experienced its personal best fitness. The social component is represented by $c_2r_2[g_{best(t)} - x_{i(t)}]$. It tends to cause the particle to move to the global best region, the swarm has found so far. This is illustrated in the diagram in Figure 2.

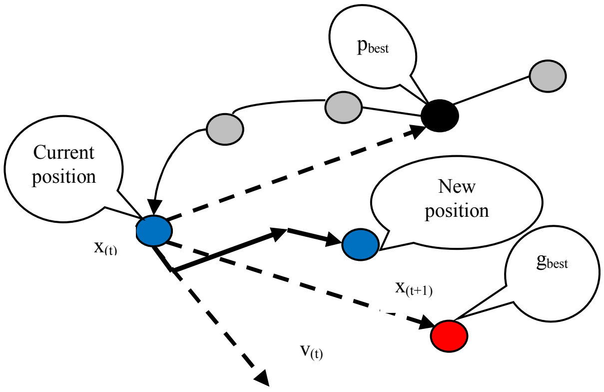

Figure 2. Generation of new position

When determining the optimum location of the BESS, each particle represents the bus number for BESS location. The procedure implemented in this work was:

i. Define the number of particles of the cluster to search for the optimum position and the best objective. The number of particles selected in this work was five, representing five BESS positions in the system under study.
ii. Generate initial random positions for all the particles, specifying the position as bus number. The bus number ranges between 1 and 30 for the IEEE 30 bus system.
iii. Generate random velocities for all particles.
iv. Evaluate the objective function of each particle. This is done by calling MATPOWER program. The best positioned particle which represents the battery storage

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location resulting in minimum total cost of generation for the cluster, is selected as the global best. It is then used to adjust velocity and direction of the other particles, in order to move towards the best solution found.

v. While number of iteration is less than the maximum number:
    a. Generate new position for each particle, hence changing bus location of the BESS by adjusting velocity and position according to (1) and (2).
    b. By calling MATPOWER, evaluate the total cost of generation for each new BESS position.
    c. If the new total cost of generation is better than the local solution, replace the local best.
    d. If the new total cost of generation of any BESS position is better than the global best, replace the global best.

The IEEE 30 bus system shown in Figure 3 was used for this study, and system data taken from [18]. The simulations were done using MATPOWER.

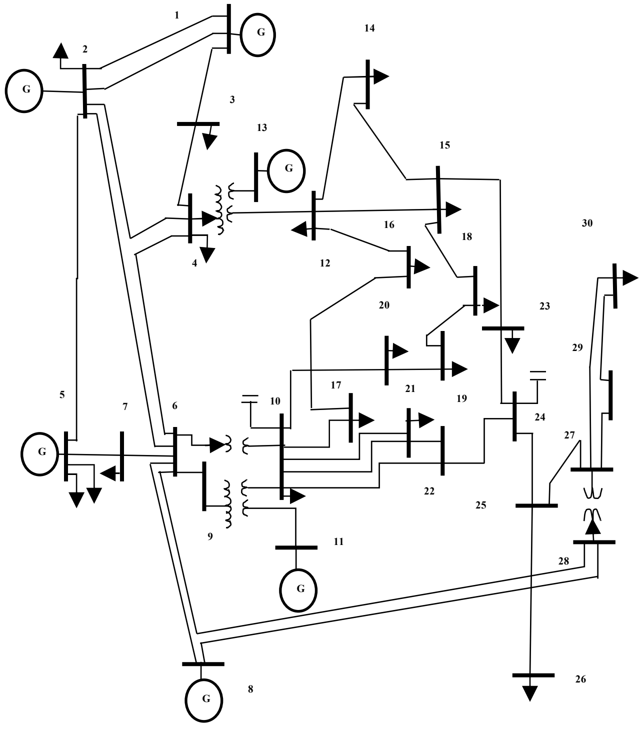

Figure 3. The IEEE 30 bus system

III. OBJECTIVE FUNCTION

For fossil fuel power plants, the variable cost mainly depends on the cost of fossil fuels and is considered a quadratic function of the energy production [19]. Hence for fossil fuels, $C(P_G)$ is given by:

$$C(P_G) = aP_G^2 + bP_G + c \tag{3}$$

Where a, b and c are parameters of the thermal plant and P_G the power generated.

The factors considered in determining the cost of battery energy storage $C(P_B)$ are charging efficiency, discharging efficiency, loss factor and cost of residual charge.

For the wind generation, there are variable and fixed costs. Variable costs depends on the cost of operation and maintenance and are considered to be linear function of energy production. Fixed cost depends on the investment cost. Therefore wind power plant cost, $C(P_w)$ is given by:

$$C(P_w) = dP_w + e \tag{4}$$

Where d and e are parameters of the wind power plant and P_w is the power generated.

Therefore total generation cost is expressed as:

$$C(P) = \sum_{i=1}^{N_G} (a_i P_{Gi}{}^2 + b_i P_{Gi} + c_i) + C(P_w) + C(P_B) \tag{5}$$

Where N_G is the number of fossil fuel power plants.

The objective function is expressed as:

$$Min C(P) = f(x,u) \tag{6}$$

Subject to nonlinear equality constraints:

$$g(x,u) = 0 \tag{7}$$

And nonlinear inequality constraints:

$$h(x,u) \le 0 \tag{8}$$

$$u^{\min} \le u \le u^{\max} \tag{9}$$

$$x^{\min} \le x \le x^{\max} \tag{10}$$

$g(x,u)$ is a set of nonlinear equality constraints (power flow equations). The load flow equations showing the power in ith bus of an N bus system are:

$$P_i = V_i \sum\nolimits_{j=1}^{N} V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \tag{11}$$

$$Q_i = V_i \sum\nolimits_{j=1}^{N} V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij} \tag{12}$$

$h(x,u)$ is a set of nonlinear inequality constraints of a vector argument x and u. The vector x consists of dependent variables and u consists of control variables.

IV. RESULTS AND DISCUSSIONS

In this research study, the first input to the PSO program is a MATLAB file of BESS data. The PSO updates the bus number of the BESS in the file. The second input is the MATPOWER program which calculates the total cost of generation considering the updated BESS location. The MATPOWER program constitutes the MATLAB files for the IEEE 30 bus system. This includes data files for buses, branches, generators and generators cost function. PSO output is the optimal location of the BESS and the minimum total cost of generation.

When wind generation is located at bus 30, the weakest bus from voltage stability point of view [20], the optimal location of BESS for minimum cost of total generation is bus number 28. This means that if the BESS is located at the same bus with the wind generation, the total cost of generation will be higher. The simulation also showed that the worst location for BESS is bus number 6 which would result in maximum cost of total generation.

Table I shows tabulation of total cost of generation considering optimal location, BESS located on the same bus with the wind generation and the worst location.

TABLE I. TOTAL COST WITH WIND LOCATED AT BUS NUMBER 30

Battery Location	Total cost in dollars
Optimal location, bus no. 28	12220
Same bus, Bus no. 30	12352
Worst location, bus no. 6	12668

The result shows that locating BESS and wind generation on the same bus is not always the optimal location. For the case simulated, optimal location is found to be bus number 28 though the wind generation is placed on the weakest bus from voltage stability point of view, bus number 30.

When simulations were done with wind generation located at bus number 6, which had been found to be worst location for the BESS in the previous simulations, the results in Table II were obtained.

TABLE II. TOTAL COST WITH WIND LOCATED AT BUS NUMBER 6

Battery Location	Total cost in dollars
Optimal location, bus no. 6 (and others)	11713
Same bus, bus no. 6	11713
Worst location, bus no. 8	11730

When simulations were done with wind generation located on bus number 28, which had been found to be optimal location for the battery storage in the previous simulations, the results in Table III were obtained.

TABLE III. TOTAL COST WITH WIND LOCATED AT BUS NUMBER 28

Battery Location	Total cost in dollars
Optimal location, bus no. 28 (and others)	13503
Same bus, bus no. 28	13503
Worst location, bus no. 6	13649

From the above simulations, it is evident that different wind generation locations even with optimized storage location results in different total generation costs. Considering optimal total cost when wind generation is placed in bus number 6, 11713 dollars, and optimal total cost when wind generation is placed in bus number 28, 13503 dollars, this is an increase of 15.3%.

The percentage of 15.3% is considerably high. It is therefore necessary, if all other considerations allow, to determine the optimal location of both wind generation and BESS at the same time.

Simulations showed that there are several combinations of wind generation locations and BESS locations that resulted in minimum cost of generation. This is important observation as it clearly shows that depending on other factors there are several possibilities from which a choice can be made. Table IV shows tabulation of the available combinations for optimal cost.

From Table IV it is observed that the bus number 24 is generally the optimal location for BESS. When BESS is located at bus number 24, there are several options for the location of the wind generation which would result into most economical total power generation.

TABLE IV. COMBINATIONS OF BATTERY AND WIND OPTIAL LOCATIONS

Generation Bus	Storage Bus	Total cost in dollars
17	24	11713
16	24	11713
19	24	11713
25	24	11713
3	24	11713

For the purpose of comparison, simulations were also done to determine the combinations of wind generator locations and BESS locations that resulted to maximum cost of generation of total power. From the results, it was also observed that there are several combinations that resulted to maximum cost, as tabulated in Table V.

TABLE V. COMBINATIONS OF BATTERY AND WIND COSTLY LOCATIONS

Generation Bus	Storage Bus	Total cost in dollars
1	8	13787
2	8	13787
3	8	13787
5	8	13787
6	8	13787
7	8	13787

From the Table V it is observed that the bus number 8 is generally the most expensive location for BESS. When BESS is located on bus number 8, there are several options for the location of the wind generation which would result into maximum total cost of power generation. If there is no good reason for locating BESS on bus number 8, then it should be avoided. This results are in agreement with the previous observations.

V. CONCLUSIONS

The study has shown that location of BESS determines the total cost of generation in a power system with wind generation and branch flow power limits. The study revealed that bus number 24 was optimal BESS location for several wind generation location buses. This is an important observation which implies that with BESS optimally located, there are several choices of wind generation location and hence other factors can also be considered. It is also shown that BESS location at bus number 8 resulted into the maximum total cost of generation for several wind generation location buses. Future work in this area includes studying the effects of combined BESS and deferrable loads on percentage wind penetration and reduction of total generation cost.

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