Locating and Sizing of Storage for Wind Integration

Dinh Duong Le* and Nhi Thi Ai Nguyen

***Abstract*— *In this paper, a two-step approach is presented for placing and sizing storage systems in a grid with high wind integration. The first step in this approach is to select candidate locations for the storage devices based on Lagrangian multipliers. The second step is applying a Genetic Algorithm (GA) – based OPF to find their optimal placement and capacities while optimizing the operation of storage systems in supporting wind generation. This approach is tested on the IEEE 118-bus system. The test system is modified to take into account network congestion with the incorporation of wind and storage systems. The results obtained indicate that the installed storage systems are efficiently employed to accommodate wind farms in supplying loads in a system with transmission congestion. The main contribution of the paper is to present an efficient approach, which combines two steps to reduce the computational burden, for optimal siting and sizing of storage devices in power systems, especially large ones*.

***Keywords*— AC OPF, GA, storage systems, wind, location, capacity.**

1. INTRODUCTION

As a source of clean and renewable energy, wind has been the fastest growing renewable energy integrated into electricity grids. However, the variable nature of this power energy source has made it necessary to employ storage devices. The effect of energy storage on reducing wind curtailment is addressed in [1]. The study shows that energy storage technologies with higher energy capacity, Compressed Air Energy Storage (CAES) system as an example, can result in less wind curtailment. Paper [2] illustrates possible applications of storage systems for wind power operation focusing on its short-duration prospective, i.e., suppressing power fluctuations of wind farms. Storage devices are described in [3] as a solution to reduce wind fluctuations and operating cost, hence enhances grid stability and reliability.

Special attention has been devoted to the combined operation of storages and wind generation. Reference [4] provides an analysis on the combined system of CAES and wind energy to handle wind fluctuations. In [5], an optimal operation policy is proposed for storage systems in grid-connected wind farms, with the purpose of time-shifting wind energy to maximize the expected daily profit. The authors in [6] address both challenges of wind penetration, i.e., wind spillage and wind forecast errors, by presenting an optimal operation algorithm for storage systems based on day-ahead wind forecast data. A technique is proposed in [7] to evaluate energy utilization efficiency and reliability of power system with storage and high wind integration. The paper shows that the use of storage devices can improve wind power capacity credit of a wind farm significantly. Without the use of storage leads to limited system reliability improvement and large amount of energy surplus.

Energy storage sizing in hybrid power systems are studied in [8]–[11]. Paper [12] presents sizing and control methodologies of large scale storage systems for wind applications. A model, which calculates optimal battery size for short-term forecast error compensation is developed in [13]. In paper [14], ESS capacity is determined based on frequency spectrum analysis of wind power output. Optimal ESS siting and sizing approaches for effective spatio-temporal energy arbitrage are proposed in [15]–[16]. Paper [17] proposes an algorithm, using Discrete Fourier analysis, to find an optimal size for a hybrid storage system, accommodating high wind penetration level. A multi-objective approach is proposed in paper [18] to site and size storage units while minimizing system operational cost and voltage profiles. In [19], a planning method is proposed for active distribution network with storage systems and high renewable energy integration. In this paper, an approach is presented for optimal siting and sizing of storage devices in a system with high level of wind penetration. In order to reduce computing time of the planning problem, the best candidate locations of storage systems are first identified by applying the methodology proposed in [20]. Then, a GA-based AC OPF model is applied to optimally place and size the storage while minimizing its capital cost and total system operation cost. By combining the two steps, this approach has an advantage of noticeably reducing computing time. In addition, the applied AC OPF model can describe the system better than DC or relaxed ones. The approach is applied on modified IEEE 118-bus system. The rest of the paper is outlined as follows: Section II introduces the formulation of the problem. In Section III, the methodology of the planning problem is described. Simulations results are presented and discussed in Section IV. A conclusion is drawn in Section V.

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2. PROBLEM FORMULATION

In this section, the mathematical model of the problem is presented. Objective of the problem is to minimize total operation cost and storage investment cost, as described in (1). The first and second terms in (1) include system total operation cost while the third one is storage capital cost.

$$\begin{aligned} Min \ & \sum_{t=1}^{T}\sum_{i=1}^{Ng}\left[c_{0i}+c_{1i}P_{Gi}(t)+c_{2i}[P_{Gi}(t)]^2\right] \\ & +\sum_{t=1}^{T}\sum_{j=1}^{Ns}\left[c_{dj}P_{dj}(t)-c_{chj}P_{chj}(t)\right] \\ & +C_{cap}(B_{\max,j},R_{\max,j}) \end{aligned} \quad (1)$$

where,

$P_{Gi}(t)$	: Real power generation at bus *i*
$P_{chj}(t)$	: Charging power of storage at bus *j*
$P_{dj}(t)$	: Discharging power of storage at bus *j*
c_{0i}, c_{1i}, c_{2i}	: Cost coefficients of generator at bus *i*
c_{chj}, c_{dj}	: Cost coefficients of storage device at bus *j*
Ng	: Number of generators
Ns	: Number of storage systems to be installed
T	: Time horizon

This objective function is subject to storage constraints and network constraints.

Storage constraints include constraints on its cost, stored energy and charging/discharging power.

Limits on investment budget:

$$\sum_{i=1}^{Ns} R_{\max,i} \le R \quad (2)$$

$$\sum_{i=1}^{Ns} B_{\max,i} \le B \quad (3)$$

where,

$R_{\max,i}$	: Power rating of storage at bus *i*
$B_{\max,i}$	: Energy rating of storage at bus *i*
R, *B*	: Budget limits

Energy balance equation:

$$B_i(t) = B_i(t-1) + [\eta_{ch}P_{chi}(t) - P_{di}(t)/\eta_d]\Delta t \quad (4)$$

where,

$B_i(t)$	: Energy level of storage at bus *i* in hour *t*
$B_i(t-1)$	: Energy level of storage at bus *i* in hour *t*-1
η_{ch}	: Storage charging efficiency
η_d	: Storage discharging efficiency
Δt	: Time interval between two consecutive periods.

Charging/ Discharging power limits:

$$P_{di}^{\min} \le P_{di}(t) \le R_{\max,i} \quad (5)$$

$$P_{chi}^{\min} \le P_{chi}(t) \le R_{\max,i} \quad (6)$$

where, $P_{di}^{\min}/P_{chi}^{\min}$ is minimum discharging/charging power of storage at bus *i*.

Stored energy limits:

$$B_{\min,i} \le B_i(t) \le B_{\max,i} \quad (7)$$

where, $B_{\min,i}$ is minimum energy level of storage at bus *i*.

Network constraints include power balance equations, limits on bus voltage, generating power and branch current.

Power balance equations:

$$\begin{aligned} & P_{Gi}(t)-P_{Li}(t)+P_{di}(t)-P_{chi}(t) \\ & = V_i(t)\sum_{k=1}^{Nb}V_k(t)\left[G_{ik}\cos[\theta_i(t)-\theta_k(t)]+B_{ik}\sin[\theta_i(t)-\theta_k(t)]\right] \end{aligned} \quad (8)$$

$$\begin{aligned} & Q_{Gi}(t)-Q_{Li}(t)+Q_{di}(t)-Q_{chi}(t) \\ & = V_i(t)\sum_{k=1}^{Nb}V_k(t)\left[G_{ik}\sin[\theta_i(t)-\theta_k(t)]+B_{ik}\cos[\theta_i(t)-\theta_k(t)]\right] \end{aligned} \quad (9)$$

where,

$Q_{Gi}(t)$	: Reactive power of generator at bus *i*
$P_{Li}(t)$	: Load real power at bus *i*
$Q_{Li}(t)$	: Load reactive power at bus *i*
$P_{di}(t)$	: Real discharging power of storage at bus *i*
$Q_{di}(t)$	: Reactive discharging power of storage at bus *i*
$P_{chi}(t)$	: Real charging power of storage at bus *i*
$Q_{chi}(t)$	: Reactive charging power of storage at bus *i*
$V_i(t)$	: Magnitude of voltage at bus *i*
$V_k(t)$	: Magnitude of voltage at bus *k*
$\theta_i(t)$	: Phase angle of voltage at bus *i*
$\theta_k(t)$	: Phase angle of voltage at bus *k*
G_{ik}	: Conductance of line *ik*
B_{ik}	: Susceptance of line *ik*
N_b	: Total system buses.

Voltage constraint:

$$V_{\min,i} \le V_i(t) \le V_{\max,i} \quad (10)$$

where, $V_{\min,i}$, $V_{\max,i}$ are voltage limits at bus *i*.

Limits on real and reactive generation power:

$$P_{G\min,i} \le P_{Gi}(t) \le P_{G\max,i} \quad (11)$$

$$Q_{G\min,i} \le Q_{Gi}(t) \le Q_{G\max,i} \quad (12)$$

where,

$P_{G\min,i}$, $P_{G\max,i}$: Real power limits of generator at bus *i*

$Q_{G\min,i}$, $Q_{G\max,i}$: Reactive power limits of generator at bus *i*

Line current limits:

$$I_{ij}(t) \le I_{\max,ij} \quad (13)$$

where,

$I_{ij}(t)$: Current flowing on line *ij*

$I_{\max,ij}$: Limit of current flowing on line *ij*

3. METHODOLOGY

The overall approach is described as in Fig. 1. In this approach, location and size of storage devices are determined through two steps. In the first step, the most suitable area to install storage devices is determined by solving the AC OPF problem without storage connected (base case OPF). The resulting Lagrangian multiplier $\lambda_i(t)$ is then determined for each bus *i* in each time *t*.

The sum of $\lambda_i(t)$ in all time periods is calculated for each bus *i* [20]:

$$\lambda_i = \sum_{t=1}^{T} \left|\lambda_i(t)\right| \quad (14)$$

The parameter λ_i in (14) is ranked and buses with the highest values of λ_i are selected as candidates for installing storage systems.

At this point, a set of candidate locations for storage are obtained. In the second step, the GA-based OPF is applied to find optimal sites and sizes for the storage. With its robustness and efficiency, GA has been a powerful optimization method in solving many power system problems [21]–[25]. GA is a population-based heuristic search method which contains random variation and selection. It includes iterative procedures that try to optimize a fitness function while maintaining the population of candidate solutions [26].

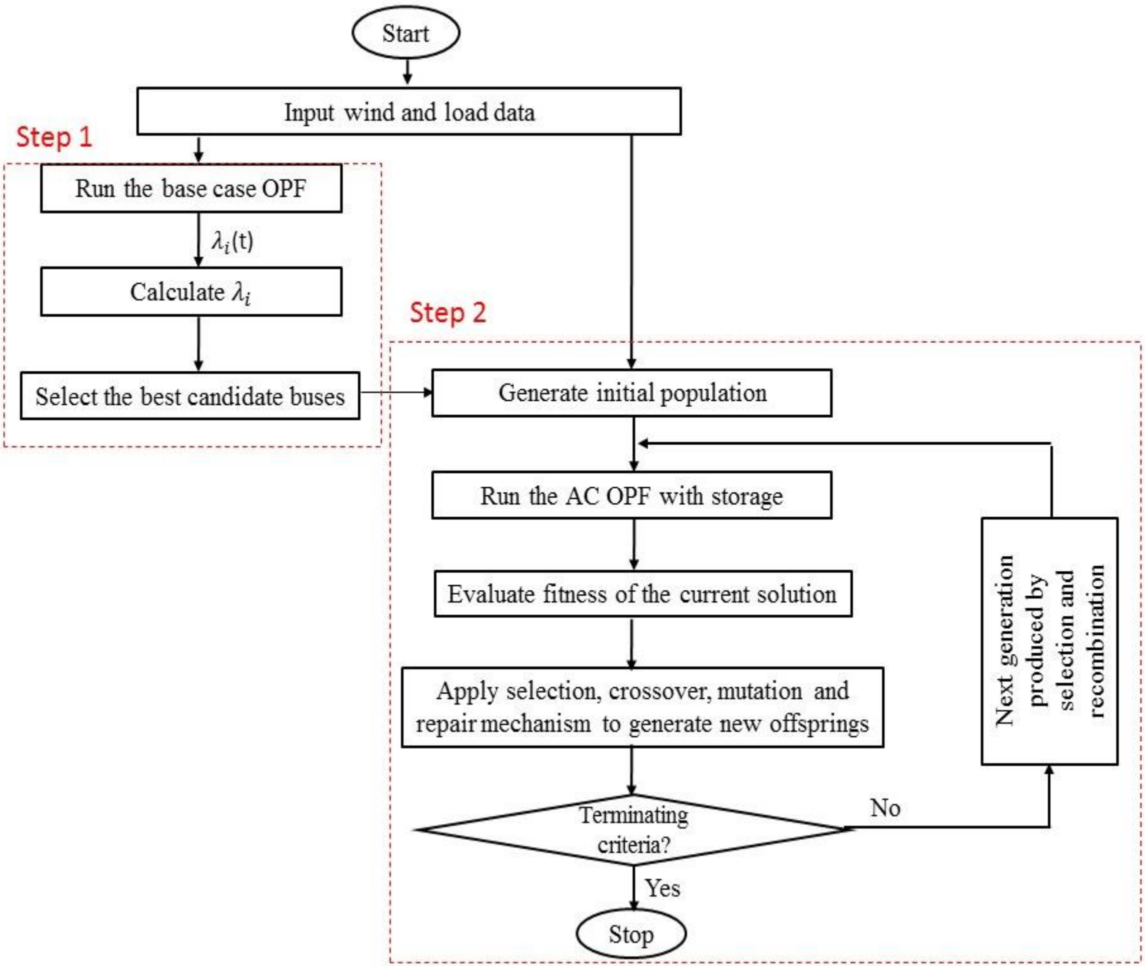

Fig.1. Flowchart of the methodology.

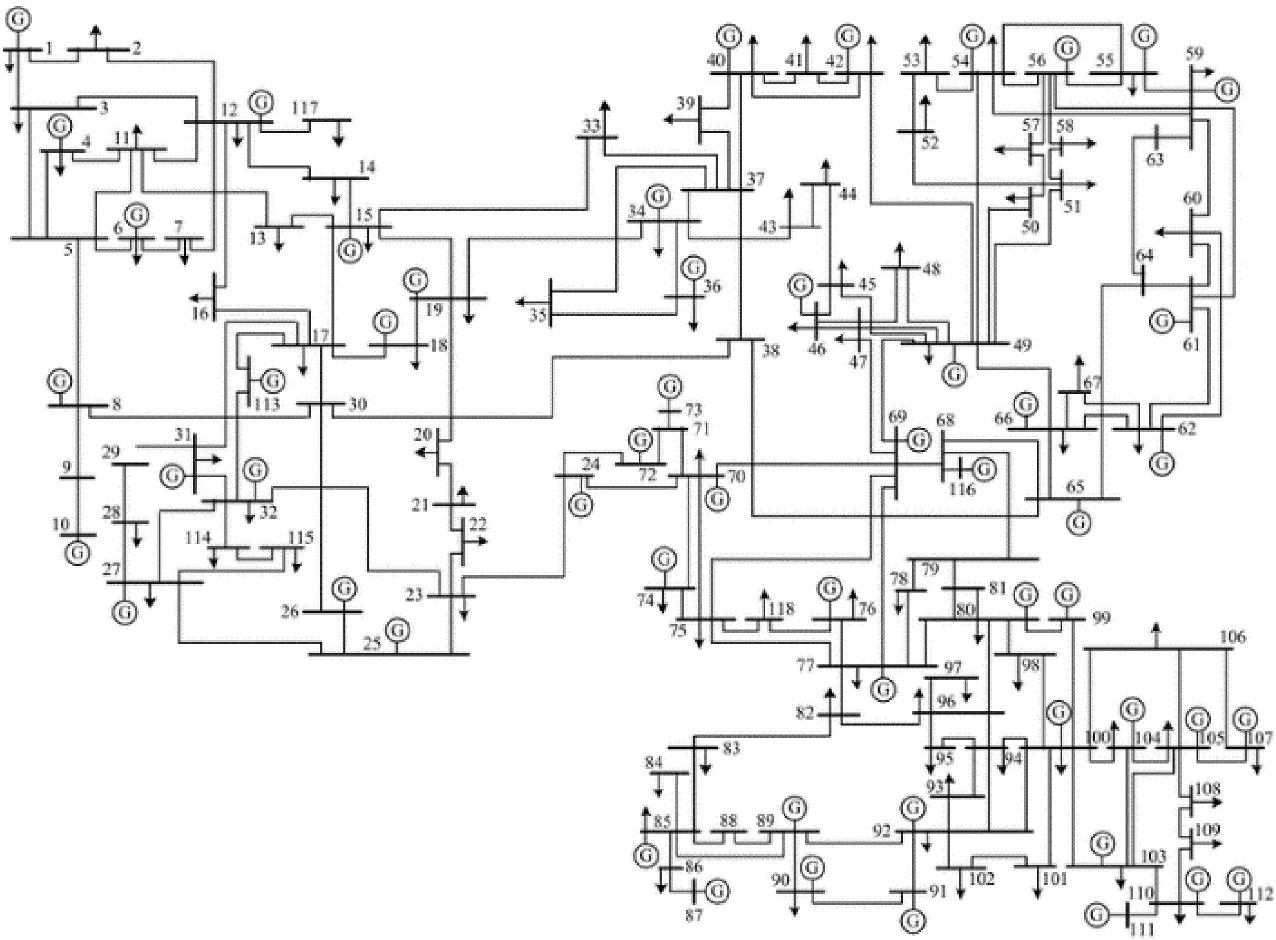

Fig.2. The IEEE 118-bus system.

The fitness function of the problem is as described in (15), which optimizes the operation of storage devices and wind. To locate storage systems, an initial population is randomly produced. The OPF is run with this placement to minimize the objective function (1). The fitness function (15) of each individual is then evaluated. This fitness is ranked and individuals are selected to produce offspring. New offspring is then generated by applying selection, crossover, mutation and repair mechanism. This routine is repeated until the convergence is reached. Optimal locations and sizes of storage devices are obtained.

$$Fitness = -\frac{\sum_{t=1}^{T}\sum_{k=1}^{Nb} P_{Lk}^{t} - [\sum_{t=1}^{T}\sum_{j=1}^{Nw} P_{Gj}(t) - \sum_{t=1}^{T}\sum_{j=1}^{Ns} P_{dj}(t)]}{\sum_{t=1}^{T}\sum_{j=1}^{Nw} P_{wj}(t)} \quad (15)$$

where,

$P_{Gj}(t)$: Wind generation at bus *j*

$P_{Wj}(t)$: Available wind power at bus *j*

4. SIMULATION RESULTS AND DISCUSSIONS

The applicability of the presented approach is illustrated with a test on modified IEEE 118 - bus system (Fig. 2). The system is supplied from 2300 MW of conventional generation and 700 MW of wind generation. System load has peak value of 2200 MW. Wind farms are connected to bus 8 and bus 10. In this test, branch limits are imposed on lines 8-5 and 8-30 to create congestion in the system.

The first step is performed by running the OPF problem without storage connected. In this way, candidate locations for installing storage devices are selected as described in the methodology. These buses are listed in Table 1.

Next, the GA-based OPF is run to optimally locate storage systems. The storage devices are assumed to have an efficiency of 85% ($\eta_{ch} = \eta_d = \eta = 0.85$). The obtained optimal location and size of storage devices are presented in Table 2. Accordingly, two storage systems are connected to buses 16 and 117, which are load centers. A big storage system is connected to bus 16 (with energy rating of 531.7 MWh and power rating of 182.7 MW) and a smaller one to bus 117 (with energy rating of 170 MWh and power rating of 74.3 MW).

Fig. 3 shows daily operation of the storage at bus 16. As can be seen from the figure, the storage charges during low load periods, i.e. hours 1 to 5, when there is no transmission congestion. This stored energy is discharged later during hours 10 to 12 and 17 to 20, when congestion occurs. Obviously, the storage device has time-shifted wind energy to release transmission bottlenecks and supply loads.

The simulation results are reasonable since the two storage devices are located at load centers and are efficiently deployed to shift wind from wind side to load side to avoid transmission congestion.

Table 1. Candidate buses for locating storage devices

Bus	λ_i
5	658.28
3	654.75
7	650.06
2	649.77
11	648.80
117	647.73
13	637.95
14	631.46
109	624.09
16	623.80

Table 2. Optimal storage location and size

Bus	B_{max} [MWh]	R_{max} [MW]
16	531.7	182.7
117	170.0	74.3

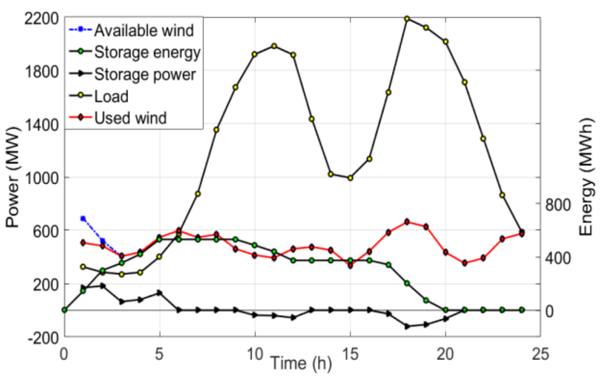

Fig.3. Daily operation of storage system at bus 16.

Tests are also performed with different values of storage efficiency. The resultant storage locations and capacities are obtained as in Table 3. From this table, storage locations are the same in all cases. Their capacities, however, vary with the efficiency. Higher efficiency leads to higher storage capacities. For example, the storage at bus 16 has an energy capacity of 386.6 MWh and power capacity of 174.0 MW when its efficiency is 0.75. When the efficiency is increased to 0.9, the capacities of this device are 684.5 MWh and 189.9 MW. As a result, the amount of wind curtailment is reduced with higher efficiency, i.e., 231.96 MW at the efficiency of 0.75, 228.83 MW at the efficiency of 0.8 and 220.72 at the efficiency of 0.9.

The model is also run with the full set of system buses for storage location instead of the set of candidate buses as above. The computing time is found to be significantly higher in the former case, which is 24950s as compared to 11160s.

Table 3. Optimal storage location and size

η	0.75		0.8		0.9	
Bus	16	117	16	117	16	117
B_{max} [MWh]	386.6	147.8	435.4	153.8	684.5	158.6
R_{max} [MW]	174.0	88.5	174.0	82.0	189.9	67.3

5. CONCLUSIONS

In this paper, an approach for optimal locating and sizing of storage devices in a system with a high level of wind penetration is presented. The approach is incorporated into two steps. Firstly, a set of buses for storage installation is determined based on a parameter, i.e., the Lagrangian multiplier. Secondly, a GA-based OPF is applied for optimal placement and sizing of storage devices while minimizing the capital cost and system total operation cost. The approach is tested on the IEEE 118-bus system. The test system is modified to take into account transmission congestion. Storage locations and sizes, including energy and power ratings, are explicitly determined. Simulation results show that the installed storage systems are efficiently employed to accommodate wind farms in supplying loads in a system with transmission congestion, hence reducing the amount of wind curtailment. Tests are also performed with different values of storage efficiency and the obtained capacities are higher with higher storage efficiencies. The approach is found to remarkably reduce the computation burden in planning problems with storage and renewable integration, which is necessary for problems with large power systems.

ACKNOWLEDGMENT

This work was supported by The University of Danang, University of Science and Technology, code number of Project: T2019-02-10.

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