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Optimal Siting and Sizing of Energy Storage System for Power Systems with Large-scale Wind Power Integration

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Abstract—This paper proposes algorithms for optimal siting and sizing of Energy Storage System (ESS) for the operation planning of power systems with large scale wind power integration. The ESS in this study aims to mitigate the wind power fluctuations during the interval between two rolling Economic Dispatches (EDs) in order to maintain generation-load balance. The charging and discharging of ESS is optimized considering operation cost of conventional generators, capital cost of ESS and transmission losses. The statistics from simulated system operations are then coupled to the planning process to determine the optimal siting and sizing of storage units throughout the network. These questions are investigated using an IEEE benchmark system.

Index Terms—Wind power, ESS, optimal siting, optimal sizing.

NOMENCLATURE

A. Parameters

\( N_b \) Number of buses.
\( N_t \) Number of transmission lines.
\( N_g \) Number of conventional generators.
\( N_r \) Number of renewable energy generators.
\( N_s \) Number of ESS units.
\( M \) Number of time steps.
\( \alpha_1, \alpha_2, \alpha_3 \) Weighting factors of cost function.
\( g_{ij} \) Conductance of the transmission line between Bus \( i \) and Bus \( j \).

B. Sets

\( \mathcal{N} \) Set of all buses, \( \mathcal{N} = \{1, \cdots, N_b\} \).
\( \mathcal{L} \) Set of transmission lines, \( \mathcal{L} = \{1, \cdots, N_t\} \).
\( \mathcal{G}_g \) Set of conventional generator buses, \( \mathcal{G}_g = \{1, \cdots, N_g\} \).
\( \mathcal{G}_r \) Set of renewable energy generator buses, \( \mathcal{G}_r = \{1, \cdots, N_r\} \).
\( \mathcal{G} \) Set of all generator buses, \( \mathcal{G} = \mathcal{G}_g \cup \mathcal{G}_r \).
\( \mathcal{S} \) Set of ESS buses, \( \mathcal{S} = \{1, 2, \cdots, N_s\} \).

C. Scalar variables

\( P_{gi}^k(k) \) Power of conventional generator of Bus \( i \) at time step \( k \), \( i \in \mathcal{G}_g \).
\( P_{ri}^k(k) \) Power of renewable energy generator of Bus \( i \) at time step \( k \), \( i \in \mathcal{G}_r \).
\( P_{si}^k(k) \) Power of ESS unit of Bus \( i \) at time step \( k \), \( i \in \mathcal{S} \).
\( P_{di}^k(k) \) Load demand of Bus \( i \) at time step \( k \), \( i \in \mathcal{N} \).
\( \Delta P_{gi}^k(k) \) Ramp rate of \( P_{gi}^k(k) \).
\( \Delta P_{ri}^k(k) \) Ramp rate of \( P_{ri}^k(k) \).
\( \Delta P_{si}^k(k) \) Ramp rate of \( P_{si}^k(k) \).
\( P_{\text{loss}} \) Transmission losses of network.

D. Matrix variables

\( P \) Vector of active power injections for all the buses \( \mathcal{N} \), \( P \in \mathbb{R}^{N_b \times 1} \).
\( B \) Admittance matrix neglecting the resistance, \( B \in \mathbb{R}^{N_b \times N_b} \).
\( F \) Vector of line flows for all the transmission lines \( \mathcal{L} \), \( F \in \mathbb{R}^{N_t \times 1} \).

I. INTRODUCTION

Nowadays, wind energy is considered as one of the fastest growing renewable energy resources in the world. According to the report of European Wind Energy Association (EWEA), the wind energy should meet 15.7% of electricity consumption by 2020 and 28.5% by 2030 [1].

The modern Day Ahead (DA) and Real Time (RT) power market operation with wind power integration is introduced in [2], [3]. In the DA scheduling, the unit commitment problem is assumed to be resolved. In the RT market, short-term wind power production forecasts are submitted to the system operator. The Economic Dispatch (ED) is then executed in order to schedule the dispatchable conventional generators. The interval between two EDs is normally 5 min, according to [3]. During this interval, the wind power fluctuations which are not taken care of by the dispatch signals are handled by the ancillary service—Automatic Generation Control (AGC).

With high wind power penetration level, more operating reserves are required and the ancillary service cost increases. In addition, due to the ramp rate limitation of conventional
sizing algorithms is shown in Fig. 1. The algorithms are interdependent and implemented sequentially.

As the input of the algorithms, long-term Wind Power Time Series (WPTS) can be either the historical wind data records or synthetic data generated by parameterized time series model. For the latter case, various techniques have been developed, such as Markov Chain and Auto Regressive Moving Average (ARMA) models [10]. Since multiple wind farms are integrated, the spatial dependence among different wind sites should also be taken into consideration. In [11], a Copula-ARMA model for wind generation is proposed. In this model, the spatial dependence is modeled by Copula method while the temporal dependence is modeled by ARMA.

A. Optimal Siting Algorithm

The optimal siting algorithm is firstly implemented. The derived WPTS is divided into $N$ cycles according to the ED frequency. In this way, various portfolios of wind fluctuations and penetration levels are included. In this study, the length of a single cycle is 5 minutes which corresponds to the charging-discharging cycle of the ESS as well as the interval between two EDs.

For each cycle, the mean wind power forecast is assumed to be perfect. The dispatch of conventional generators can be decided by solving an ED problem. The classical ED problem doesn’t consider the network constraints. Instead, the Network-Constrained ED is applied in this study, which could be considered as a special case of the OPF problem. In order to reduce the computation complexity, DC-OPF is used. From the system operator point of view, the participation of the ESS in AGC service can reduce the service cost and improve the regulation capability for the fast variation.

In this algorithm, all the buses are assumed with unlimited amounts of power and energy of ESS units. The charge-discharge control of ESS units can be decided by solving an optimal problem, labeled as Problem I. Accordingly, an absolute ESS power at each bus can be calculated, which is used to evaluate the activity of power exchange for this cycle.

After $N$ cycles, the statistics on the ESS activities at all buses can be summarized. These buses can be ranked according to the power exchanges. A bus with larger power
The transmission losses of the whole network in DC load flow $P_{\text{loss}}$ can be calculated approximately by,

$$P_{\text{loss}} = (B^{-1}P)'G(B^{-1}P).$$  \hfill (2)
For the dispatchable generator buses \( G_g \),
\[
P_i(k) = P_i^g + P_i^s - P_i^l, \quad i \in G_g.
\]
(8)

For the renewable energy buses \( G_r \),
\[
P_i(k) = P_i^r + P_i^s - P_i^l, \quad i \in G_r.
\]
(9)

For other buses (load with ESS),
\[
P_i(k) = P_i^s - P_i^l, \quad i \in L.
\]
(10)

Secondly, DC power flow equations can be expressed in the following matrix form,
\[
F = (bA)B^{-1}P,
\]
(11)
where \( b \in \mathbb{R}^{N_b \times N_b} \) is the matrix whose diagonal elements \( b_{kk} \) equal to the susceptance of the \( k \)th line and the non-diagonal elements are zero. \( A \in \mathbb{R}^{N_b \times N_b} \) is the bus-line incidence matrix, whose element \( a_{ij} = 1 \), if the line exists from Bus \( i \) to Bus \( j \). For the starting and ending buses, the elements are 1 and -1, respectively, otherwise \( a_{ij} = 0 \).

Based on (8)–(11), the power flow constraint can be expressed in the matrix form,
\[
F \leq (bA)B^{-1}P \leq F^T,
\]
(12)
where \( F \in \mathbb{R}^{N_b \times 1} \) and \( F^T \in \mathbb{R}^{N_b \times 1} \) are the vector of upper and lower limits of line flows for all the lines \( L \), respectively.

C. Formulation of Problem II

1) Cost function: The cost function of Problem II is identical with that of Problem I.

2) Constraints: The constraints of dispatchable generators, transmission capacity of Problem II are same as these of Problem I. For the ESS constraints, the ESS units are installed at selected buses in Problem II. Therefore, the power and power ramp rate of ESS units at selected buses are limited. Besides, the total power and energy capacity are limited due to the practical constraints. In the following, the additional constraints are listed.

The power and ramp rate constraints are
\[
\begin{align*}
P_i^s & \leq P_i^s(k) \leq \overline{P}_i^s, \forall i \in S, \\
\Delta P_i^s & \leq \Delta P_i^s(k) \leq \overline{\Delta P}_i^s, \forall i \in S.
\end{align*}
\]
(13)
(14)
where \( P_i^s, \overline{P}_i^s \) denote the lower and upper limitation of \( P_i^s(k) \), respectively; \( \Delta P_i^s, \overline{\Delta P}_i^s \) denote the lower and upper limitation of \( \Delta P_i^s(k) \), respectively.

The total energy capacity constraint is
\[
\sum_{i \in S} \left| \sum_{k=1}^{M} P_i^s(k) \Delta t \right| \leq E, \forall i \in S,
\]
(15)
where \( \Delta t \) indicates the interval between two steps, \( E \) is the total energy capacity limit.

IV. SIMULATION

In this paper, the IEEE 14 bus system was used as the test system to demonstrate the developed algorithms. The algorithms were implemented in YALMIP [12] with the solver SeDuMi [13]. As illustrated in Fig. 2, two wind farms are included in the system, located at Bus 6 and Bus 8 and termed as WF 1 and WF 2, respectively.

A. Optimal Siting

The optimal siting of ESS is dependent on many factors, including the wind power fluctuation, transmission capacity and etc. By taking these factors into account for various realizations of wind power generation, the power exchanges for all the buses can be derived, as illustrated in Fig. 3. Their ranking can be considered as the criterion for the bus selection.

In order to investigate the influence of transmission capacity on the ESS siting, the transmission capacity between Bus 13 and Bus 14 has a tighter limitation (6.5 MW). Obviously, Buses 6, 9 and 13 have the highest power exchanges and they are hereby selected for ESS installation. For Bus 6 and 9, it can be understood that if most wind power fluctuations are compensated on site, the transmission losses will be reduced.
For Bus 13, it can be understood that in order to avoid overloading of the line with limited transmission capacity, the ESS unit is preferred to be installed at the terminal bus of the line.

B. Optimal Sizing

For the power system with multiple wind farm integration, the correlation between wind farms has a significant impact on the ESS sizing. In order to investigate to which extent the correlation of WF 1 and WF 2 affects the power and capacity ratings, two case scenarios are defined in Table I. Pearson’s $r$ is used to represent the linear correlation between WF 1 and WF 2. Smaller value indicates the more obvious smoothing effect of multiple wind farms. In other words, wind power fluctuation is reduced from the system point of view.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Pearson’s $r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>0.22</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>1.00</td>
</tr>
</tbody>
</table>

For the power rating, $F_{\text{pow}}$ is defined as the Empirical CDF (ECDF) of power and $F_{\text{pow}}^{-1}$ is the inverse of $F_{\text{pow}}$. $F_{\text{pow}}^{-1}(0.95)$ represents the guaranteed power rating requirement for 95% of the time. Considering the technical limitation, the upper limits of all ESS units are set as $F_{\text{pow}}^{-1} = 3$ MW in this study. The power ratings of all the selected buses (Buses 6, 9, 13) for both scenarios are almost the upper limits: 3 MW.

For the energy capacity rating, $F_{\text{cap}}$ is defined as the ECDF of capacity and $F_{\text{cap}}^{-1}$ is the inverse of $F_{\text{cap}}$. $F_{\text{cap}}$ of all the selected buses (Buses 6, 9, 13) is illustrated in Fig. 4 and $F_{\text{cap}}^{-1}(0.95)$ are listed in Table II. It can be observed that for the selected buses, larger energy capacities are required to compensate the larger power fluctuations in Scenario 2, compared with these in Scenario 1. The total required energy capacity in Scenario 2 is 1.64 MWh which is 18.0% larger than that of Scenario 1 (1.39 MWh). Thus, the correlation between wind farms has a significant impact on the ESS sizing.

<table>
<thead>
<tr>
<th>Bus index</th>
<th>$F_{\text{cap}}^{-1}(0.95)$ (Scenario 1)</th>
<th>$F_{\text{cap}}^{-1}(0.95)$ (Scenario 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 6</td>
<td>0.52 MWh</td>
<td>0.61 MWh</td>
</tr>
<tr>
<td>Bus 9</td>
<td>0.54 MWh</td>
<td>0.59 MWh</td>
</tr>
<tr>
<td>Bus 13</td>
<td>0.33 MWh</td>
<td>0.44 MWh</td>
</tr>
<tr>
<td>Summary</td>
<td>1.39 MWh</td>
<td>1.64 MWh</td>
</tr>
</tbody>
</table>

V. Conclusion

In this paper, the algorithms for optimal siting and sizing of ESS in the grid with high wind power penetration are presented. For optimal siting algorithm, all the buses are assumed to have ESS installation with unlimited amounts of power and energy. The absolute power exchange of ESS at each bus is used to evaluate its activity. The activity ranking of all the buses can be used as the criterion for the optimal siting. It can be concluded that the placements of ESS include not only the wind farm sites, but also other buses, such as terminal bus of critical transmission line. For optimal sizing algorithm, the additional power and energy constraints are incorporated in the optimization problem. By solving a large number of cyclic optimization problems, the ECDFs of power and energy capacity of ESS for different realizations of wind power fluctuations are obtained. Accordingly, the optimal power and energy rating can be determined by setting the probability level (95% in this study). It shows that the correlation between wind farms has a significant impact on the power and energy rating.

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REFERENCES


