Network allocation of BESS for improving rotor angle stability

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Abstract. This paper presents a novel methodology for an efficient allocation of Battery Energy Storage Systems (BESS) in order to improve rotor angle stability of power systems. The proposal uses a genetic algorithm (GA) specifically designed to solve the allocation problem. The use of GA enables us to evaluate each candidate using time-domain simulations in a set of critical operating conditions and contingencies. This in turn allows us to obtain an accurate estimation of the impact that different BESS allocations may have in the stability of the system. Results from a network based on the IEEE 39-bus New England System demonstrate the benefits of our proposed methodology in terms of improvements in the rotor angle stability that can be achieved and its practical implementation in real-world power systems.

1. Introduction

The deployment of converter-based variable generation technologies (VGTs) in power systems, such as wind and photovoltaic generation, has been remarkable during the last years. The worldwide installed capacity of VGTs, considering wind and photovoltaic generation, exceeded 790 GW by the end of 2016 with a yearly growth rate of 129 GW [1]. This growing trend of VGTs reveals that these power plants will play a key role in power systems of the future. However, the sustained development of VGTs leads to different challenges in power systems operation and control, especially from a system stability perspective [2], [3]. Stability issues arise due to the fundamental differences between conventional synchronous generators (SGs) and converter-based VGTs, such as lack of inertial response and limited short circuit currents during contingencies [4]. Moreover, as the integration of VGTs increases, the dynamic response of the system starts to be progressively more dependent on fast-response power electronic devices, thus significantly affecting power system dynamic performance [5].

To prevent future instability problems in systems with high shares of VGTs, recent works have focused on exploring new control strategies and technologies for improving the system dynamic performance during contingencies, thereby making it less prone to face stability problems. In this regard, Battery Energy Storage Systems (BESS) emerge as a potential solution to support power system stability. BESS are key fast-response devices that not only add more flexibility for frequency and voltage regulation, but also provide a wide range of technical benefits from a stability point of view [6], [7], [8]. Although the benefits that BESS can bring to system stability have been widely reported, the BESS allocation problem has been mainly addressed from economic and/or steady state perspectives, such as costs reduction, power losses minimization, and voltage regulation (see for
example [9] and [10]). In this regard, BESS allocation for improving system stability, and specifically rotor angle stability, is still a pendent issue. The main reasons for this are the modeling complexity and the computational burden involved in the optimization processes for BESS allocation when considering the dynamic behavior of the system.

In the aforementioned context, this paper presents a novel methodology for an efficient allocation of BESS in order to improve power system’s rotor angle stability. To solve the allocation problem, we developed a methodology based on genetic algorithms (GA). The impact of different BESS allocations in the rotor angle stability is evaluated through time-domain simulations using a complete dynamic model of the system (multi-machine system). We then use these results to calculate the system stability margin by means of the SIME method [11]. Using time-domain simulations within the optimization enables us to obtain an accurate assessment of the system stability for each BESS allocation candidate. This in turn allows us to obtain an efficient BESS allocation for improving the rotor angle stability of power systems. It is worth mentioning that, although in this article we focus on rotor angle stability, other kinds of stabilities can be addressed with our proposed methodology as well. In addition, our methodology is not restricted to the use of GAs. Other meta-heuristic algorithms can be used as well.

The remainder of this paper is organized as follows. Section II presents the mathematical formulation of the allocation problem. Section III presents the proposed BESS allocation methodology. Section IV presents the case study and the results. In Section V, we conclude.

2. Mathematical formulation of the problem

A. Theoretical background

To introduce the basic concepts used in our proposal, consider the one machine infinite bus (OMIB) system in Figure 1.

![Figure 1. OMIB system.](image)

By neglecting the stator and rotor transients, the behavior of the system during a short-circuit in one of the transmission lines with impedance $X_L$ is described by the following equations:

$$M \frac{d^2 \delta}{dt^2} = P_m - P_e - D \frac{d \delta}{dt}$$

(1)

$$\frac{d \delta}{dt} = \Delta \omega$$

(2)

$$P_e = \frac{EV}{X_{eq}} \sin(\delta)$$

(3)

where $\delta$ is the rotor angle, $P_m$ and $P_e$ are the mechanic and electric power, respectively, $M$ is the inertia constant and $D$ is the frequency damping coefficient.

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Figure 2 shows the power-angle characteristic of the system before, during and after clearing the contingency.
The system stability depends on the relationship between the accelerating (red) and decelerating (blue) areas in Figure 2 [12]. The system will be stable only if the decelerating area is bigger than the accelerating one. This relationship enables us to define the following transient stability index:

$$\eta = A_{\text{dec}} - A_{\text{acc}}$$

where \( A_{\text{dec}} \) and \( A_{\text{acc}} \) are the decelerating and accelerating areas, respectively. The stability index \( \eta \) enables us to evaluate preventing actions to ensure system stability. For example, a reduction in the load of the machine before the contingency results in a shift of the \( P_m \) line in Figure 2 down the y-axis. This in turn results in a reduction of the accelerating area \( A_{\text{acc}} \) and in an increment of the decelerating one \( A_{\text{dec}} \). This preventive action increases the stability margin index \( \eta \) and thus improves rotor angle stability.

For its application in real-world power systems, the concepts of accelerating and decelerating areas can be extended to a multi-machine system using the single machine equivalent (SIME) method [11]. With this method, the state variables of the machines in the system are combined into the state variables of one single equivalent machine. The system stability margin can be then evaluated using the \( P-\delta \) curve of this equivalent machine.

**B. Transient stability support provided by BESS**

To assess the stability improvement that a BESS can provide to rotor angle stability, consider again an OMIB system, but now including a BESS module as shown in Figure 3. The BESS is modeled as a current source.

Assuming the occurrence of a short circuit in the transmission line, it can be demonstrated that the effect of the BESS in the active power output of the machine is:

$$P_e = a \frac{EV}{X_{eq}} \sin(\delta) + \frac{aX_L}{2X_{eq}} EI_{\text{BESS}} \cos(\delta - \phi)$$

where \( X_{eq} \) is the system equivalent reactance, \( \phi \) is the BESS current angle, \( P_e \) is the machine’s active power, and \( a \) indicates the position of the short circuit (in percentage) in relation to the length of the line, starting at busbar 2.

**Figure 3. OMIB system with a BESS at busbar 2.**
Equation (5) shows that the influence of the BESS in the electric power output of the generator depends on its $PQ$ control scheme ($I_{\text{BESS}}$ and $\phi$). In this context, to reduce the acceleration of the rotor during the contingency, one possible supportive strategy is to operate the BESS in order to increase $P_e$. This strategy would lead to an increase in the accelerating area and to a reduction of the decelerating one, thus increasing the value of the stability index $\eta$. By this way, the dynamic performance of the system, in terms of rotor angle stability, can be improved. This is illustrated in Figure 4, which shows the accelerating power of the system of Figure 3 during a short circuit, with and without the BESS. When the contingency occurs, the voltage at the connection point of the BESS drops and the machine speeds up according to the law of motion of a rotating body. The electrical frequency of the system will increase accordingly. In response to the voltage drop, the $QV$ control of the BESS will inject a reactive power in order to increase the voltage at its connection point. At the same time, in response to the frequency increase, the frequency droop control will absorb active power to reduce the system frequency, trying to restore it to its nominal value. Both control actions support the rotor angle stability by increasing the power injection of the generator and thus reducing the rotor acceleration. This idea is exploited in our proposed methodology for BESS allocation.

![OMIB accelerating power vs rotor angle with and w/o BESS.](image)

**Figure 4.** OMIB accelerating power vs rotor angle with and w/o BESS.

**C. Optimization problem**

The main objective of this work is to allocate BESS in order to improve power system’s rotor angle stability. To this end, our proposed algorithm aims at maximizing the value of the stability index $\eta$ for a given set of operating conditions and contingencies. Compared to a case without BESS, the increase in $\eta$ can be achieved by exploiting the control flexibility of BESS to reduce the rotor acceleration of synchronous machines during a contingency. The mathematical formulation of the optimization problem when $m$ operating conditions and $n$ contingencies are considered is as follows:

$$\max_{\{n_k\}} \frac{1}{n + m} \sum_{i=1}^{n} \sum_{j=1}^{m} \eta_{ij} - \frac{1}{n + m - 1} \sum_{i=1}^{n} \sum_{j=1}^{m-1} \left( \bar{\eta} - \eta_{ij} \right)^2$$

$$\sum_{k=1}^{N_K} n_k = N_{\text{BESS}}$$

where $\eta_{ij}$ represents the value of the stability index in operating condition $i$ and contingency $j$, $\bar{\eta}$ represents the mean value obtained for all operating conditions and contingencies and the $n_k$ are the allocation decision variables. The objective function (6) aims at maximizing the mean value of the stability indices and reducing the standard deviation. While the mean value is used to represent the overall increase of the transient stability, the standard deviation allows paying special attention to those operating points and contingencies with the poorest transient stability performance. In (7), $N_K$ and $N_{\text{BESS}}$ represent the number of allocation busbars and the number of BESS modules to be installed in the network, respectively. Therefore, (7) forces the deployment of all available BESS modules.
The allocation problem (6)–(7) is a mixed-integer, non-linear, non-convex and large-scale optimization problem. In particular, evaluating the stability indices requires solving a set of high-dimensional non-linear differential algebraic equations [13]. Consequently, solving the proposed allocation problem using traditional mathematical optimization methods without performing major simplifications is extremely challenging. To overcome this issue, we developed a meta-heuristic algorithm based on GA, which is presented in the next section.

3. Proposed algorithm for BESS allocation

To solve the allocation problem presented in (6)–(7), we developed a meta-heuristic algorithm based on GA. GAs appear as a sound alternative since integer variables can be easily codified as chromosomes. Moreover, the use of GA allows us to evaluate allocation candidates using time-domain simulations and, consequently, without performing major simplifications that may affect the quality of the results. It is worth mentioning that the proposed methodology is not restricted to the use of GA. Other meta-heuristic algorithms and software to compute time-domain simulations can be used as well. Next, we present main features of the proposed GA.

A. Individual codification

GAs evaluate the performance of a set of candidates, called population, for searching the optimum. A population consists of a number of individuals, where each individual is a vector of eligible busbars for allocating BESS modules. The value of each individual’s component corresponds to the number of BESS modules located in the corresponding network busbar.

B. Fitness function and its evaluation

The purpose of the fitness function is to evaluate the stability index \( \eta \) of the power system for a given BESS allocation. Consequently, the value of the fitness function \( f \) for candidate \( q \) considers the stability index \( \eta \) for each operating condition and contingency as follows:

\[
 f(q) = \frac{1}{n+m} \sum_{i=1}^{n} \sum_{j=1}^{m} \eta_{ij} - \frac{1}{n+m-1} \sum_{i=1}^{n} \sum_{j=1}^{m} (\eta_{ij} - \eta) \]

(8)

where \( \eta_{ij} \) is the stability index of operating condition \( i \) and contingency \( j \). Figure 5 shows the methodology for evaluating the fitness function of each BESS allocation candidate.

![Figure 5. Methodology for evaluating BESS candidates.](image)

As seen from Figure 5, to evaluate each candidate we first run time-domain simulations in each operating condition and contingency using a complete dynamic model of the system. Once we obtain the rotor angle trajectory of each machine, we determine the \( P-\delta \) curve of the equivalent machine using the SIME method and calculate the stability index according to (4). Finally, we derive the value of the fitness function using (8).

C. Operators of the Genetic Algorithm
Selection operator: To build a new population we use tournament selection. Within this approach, $q$ individuals are randomly chosen from the previous population. Among them, the one with the highest the fitness value is selected. This process is performed until all needed parents are obtained. This selection mechanism gives individuals with low initial fitness values the chance of passing through their characteristics to future populations, reducing the risk of premature convergence. To explore new allocation alternatives, we use an extinctive GA, where a new population is built from new individuals only.

Cross-over operator: After parents are selected, new individuals are created by randomly selecting two parents and exchanging their components. The cross-over operator is modeled with multiple points of cross-over, where components to be exchanged between the two parents are randomly selected. Note that the total sum of all components must be equal to the number of BESS to be allocated $N_{BESS}$. To avoid building unfeasible solutions, we run the cross-over operator exchange as long as all solutions obtained are feasible.

Mutation operator: The mutation operator is applied to randomly select individuals. For each one of them, the operator performs slight changes in some of the components as follows. First, $n$ BESS modules are randomly chosen and subtracted from the individual’s components. Then, all subtracted modules are added again to randomly chosen components. This procedure allows us to avoid building unfeasible solutions.

4. Case study

The proposed methodology was implemented in the IEEE 39-bus New England System shown in Figure 6. This model consists of 39 buses, 46 transmission lines, 19 demands and 10 generators. To consider a case of large-scale VGTs penetration, we added 5 double feed induction generators wind turbines, as shown in orange in Figure 6. The case study consisted of allocating 10 BESS modules with 60 MVA capacity each, in each of the 28 busbars with 345 kV, representing 25% of renewable capacity. For illustrative purposes, we considered one worst-case operating condition and three critical contingencies, showed in red in Fig. 6. Critical generators in each contingency are shown in red.

To evaluate the benefits of our methodology, we considered four study cases, presented in Table 1.

| Case          | Description                                                      |
|---------------|------------------------------------------------------------------|
| Base          | Without BESS                                                     |
| GA            | BESS located with our proposed GA                                |
| Inverse to CCT| BESS located in generation busbars that loss stability in inverse proportion of the CCT |
| Inverse to $S_k'$ | BESS located nearby generators that go out-of-step (in inverse proportion with the short-circuit power) |

The case “Inverse to CCT” allocates the BESS modules in the busbars of the generators that loss synchronisms for the faults under consideration. The distribution is performed in inverse proportion of the CCT. The case “Inverse to $S_k'$ allocates the modules in the network busbars with the lowest short circuit levels, i.e., in the weakest areas of the grid, which are the most prone to face stability problems [14].
A. System model and time domain simulations
To evaluate the performance of each BESS allocation candidate within the optimization process, we ran time domain simulations for each fault considered. The simulations were performed in DIgSILENT using a full dynamic model of the system, only neglecting the transients related to the network and the stator of the synchronous machines. The model of the SGs considers a standard automatic voltage regulator (AVR) type DC1A IEEE. The speed regulator for the steam turbines is of type IEEE TGOV1. The model of the WTG includes voltage regulation capacity during normal operation and fault ride through (FRT) capability during short circuits. BESS were modelled with voltage support capability and droop frequency control, which means that they can control active and reactive power during contingencies.

The proposed algorithm (including the computation of time-domain simulations) was implemented in a computer with an Intel core i7-4720HQ processor clocking at 2.6 GHz and 16 GB of RAM.

5. Results
A. BESS allocation
For solving the BESS allocation problem, we used a population of 20 candidates and evolved them up to 500 generations. The computer required 11 hours to converge. The results obtained are presented in Table 2. In this table we also show the BESS modules located using the lowest short-circuit power criteria and those located using the CCT criteria. As it can be seen, the BESS allocation obtained with our proposed GA differs from these other approaches. It locates 8 modules close to contingency 2, and 2 modules nearby contingency 3.

Table 2. BESS allocation for each case study.

| Case                   | BESS location and number of modules                        |
|------------------------|------------------------------------------------------------|
| GA                     | B28 (1 module), B29 (7 modules), B22 (2 modules)           |
| Inverse to CCT         | B01 (3 modules), B09 (3 modules), B28 (4 modules)          |
| Inverse to $S''_k$     | B10 (3 modules), B22 (3 modules), B29 (4 modules)          |

Table 3 presents the CCT from the resulting network of each case. From this table it can be seen that the BESS allocation obtained with our proposal not only enables us to increase the average CCT across all contingencies, but also to increase the overall minimum CCT. This latter characteristic was achieved by incorporating the standard deviation into the fitness function.
Table 3. Critical clearing times of each contingency.

| Case          | C1   | C2   | C3   | Average |
|---------------|------|------|------|---------|
| Without BESS  | 0.184| 0.099| 0.134| 0.139   |
| GA            | 0.181| 0.133| 0.145| 0.153   |
| Inverse to CCT| 0.190| 0.116| 0.151| 0.152   |
| Inverse to $S_k$'' | 0.182| 0.102| 0.130| 0.138   |

B. Dynamic performance

Figure 7 shows the SIME equivalent $P$-$\delta$ curve for contingency 2, without BESS and with BESS located according to our GA. From Figure 7 it can be seen that the BESS contribution increases the decelerating area, thus improving the transient stability margin. However, the BESS have almost no effect in the accelerating area. This is because of the proximity of the BESS to the short circuit location. Because of the voltage drop, the BESS cannot exchange any significant power with the system before the voltage is restored after the fault clearance.

![Figure 7. SIME P-\delta curve for contingency 2 with and without BESS.](image)

Finally, Figure 8 shows the rotor angle $\delta(t)$ for all generators in the system during contingency 2. Generator 9 is highlighted, since it goes out-of-step in the case without BESS, falling into instability. As it can be seen, the incorporation of BESS helps generator 9 to sustain stability.

![Figure 8. Rotor angle vs time for contingency 2 with and without BESS.](image)

Similar results were obtained for the other contingencies considered in the optimization, confirming the good performance of the algorithm.

6. Conclusions

This paper presents a novel methodology for an efficient BESS allocation in order to improve rotor angle stability of power systems. The proposal uses a GA specifically designed to solve the allocation problem. This proposal exploits the flexibility of the control strategy of BESS to reduce the rotor acceleration of the machines during short circuits, which in turn improves rotor angle stability. To quantify the impact of possible BESS allocations in the system stability, our proposed algorithm first determines, for each operating condition and contingency, the rotor angle trajectory of each machine in the system using time-domain simulations in a complete dynamic model of the system. Then, using the SIME method, we determine the $P$-$\delta$ curve of the equivalent machine. Based on this curve, we
calculate the value of the stability index. Using time-domain simulations allows us to obtain an accurate estimation of the impact of different BESS allocations in the rotor angle stability. Results obtained in a modified version of the IEEE 39-bus system showed that the proposed BESS allocation strategy enables us to increase the CCT of the system after the occurrence of contingencies, compared to the case of traditional BESS allocation strategies. This in turn enables us to improve the rotor angle stability of the system.

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