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# Optimization of a battery energy storage system using particle swarm optimization for stand-alone microgrids

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ABSTRACT

The main challenge in integrating a Battery Energy Storage System (BESS) into a microgrid is to evaluate an optimum size of BESS to prevent the microgrid from instability and system collapse. The installation of BESS at a random size or non-optimum size can increase in cost, system losses and larger BESS capacity. Thus, this paper proposes the new method to evaluate an optimum size of BESS at minimal total BESS cost by using particle swarm optimization (PSO)-based frequency control of the stand-alone microgrid. The research target is to propose an optimum size of BESS by using the PSO method-based frequency control in order to prevent the microgrid from instability and system collapse after the loss of the utility grid (e.g., blackout or disasters) and minimize the total cost of BESS for 15 years installation in the microgrid. Then, the economical performance of BESS with modern different storage technologies is investigated and compared in the typical microgrid. Results show that the optimum size of BESS-based PSO method can achieve higher dynamic performance of the system than the optimum size of BESS-based analytic method and the conventional size of BESS. In terms of BESS economical performance with modern storage technologies, the installation of the polysulfide–bromine BESS is likely to be more cost-effective than the installation of the vanadium redox BESS for 15 years installation in the typical microgrid. It is concluded that the proposed PSO method-based frequency control can improve significantly power system stability, grid security, and planning flexibility for the microgrid system. At the same time, it can fulfill the frequency control requirements with a high economic profitability.

## Introduction

Nowadays, a microgrid system is being considered as one of the solutions to the energy concern around the world and it is gaining more attention recently [1]. It can be viewed as a group of distributed generation sources (DGs) connected to the loads in which the DGs can be fed to loads alone or be fed to a utility grid [2,3]. In recent years, a Battery Energy Storage System (BESS) can be used in various aspects of the power systems. As the output characteristics of these DGs are quite different from the conventional energy sources, the system should be able to handle unexpected fluctuations and maintain system reliability. When an islanding operation occurs in a microgrid where a DG or a group of DGs continue to supply the microgrid system which is separated from the utility grid, the system needs to have the master generator which can provide voltage and frequency support. Generally, a synchronous generator can fulfill this demand. When there is no synchronous generator, converters interfaced batteries can act as the master control. Therefore, battery storage devices serve as an important aspect in microgrid operations [4].

BESS is implemented in various aspects of power systems as one key factor for sustainable energy in many countries particularly in Europe, America and Japan. Advantages of BESS include an improvement of system frequency, especially when BESS is used for system frequency control. For small disturbances, BESS is discharging when the system frequency is lower than 50 or 60 Hz. On the other hand, BESS is charging when the system frequency is higher than 50 or 60 Hz. For large disturbances, BESS can enhance the performance of the system frequency control by integrating BESS with an under frequency load shedding scheme, an under or over frequency generation trip. With these different functions, BESS can offer a good solution. Thus, it is concluded that BESS is a rapid and flexible element for power systems [5–8].

Previous optimization procedure [4] was implemented for a large interconnected power system case using a small BESS rated power (i.e., 2 MW) compared to the total volume of the spinning reserve provided by the conventional generations (i.e., 3000 MW). Therefore, the impact of BESS on system frequency behavior was widely negligible. Considering now the case of a

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## Nomenclature

| | |
|---|---|
| $\alpha_i$ | firing delay angle of converter *i* |
| $K_b$ | control loop gain |
| $T_b$ | measurement device time constant |
| $E_{d0}$ | maximum DC voltage of the batteries |
| $E_{b1}$ | battery resistance |
| $E_{bt}$ | phase voltage of the battery side |
| $E_{boc}$ | battery open circuit voltage |
| $E_t$ | AC voltage between a line and neutral |
| $I_{BESS}$ | DC current through the battery |
| $P_{BESS}$ | active power provided by the batteries |
| $Q_{BESS}$ | reactive power provided by the batteries |
| $r_c$ | battery overvoltage |
| $r_{bt}$ | terminal voltage of the battery |
| $r_{bs}$ | battery internal resistance |
| $r_{bp}$ | self discharge resistance |
| $r_{b1}$ | overvoltage resistance |
| $\Delta f$ | frequency deviation |
| *i*th | iteration number |
| *j*th | particle number |
| $v_i$ | velocity of a particle at iteration *i*th |
| $x_i$ | position of a particle at iteration *i*th |
| $P_{best}$ | best solution at iteration *i*th |
| $G_{best}$ | best global solution at iteration *i*th |
| $r_1$ | random number one between 0 and 1 |
| $r_2$ | random number two between 0 and 1 |

microgrid system (e.g., a small power system), the BESS rated power cannot be negligible anymore, and thus the grid frequency is now sensitive to BESS output power variations. So, the installation of large/inappropriate size or random size of BESS can cause frequency problems, increase system losses and add an extra cost to the microgrid system. For these reasons, an optimal sizing of BESS is an essential method for a microgrid [5]. However, the optimization method can be achieved by many ways such as balanced generation and load demand method, linear programming method, enumerative method, iterative algorithm, genetic algorithm, particle swarm optimization. According to [9–12], the advantages of particle swarm optimization (PSO) include simplicity, ease of use, high convergence rate and minimal storage requirement. Especially, it is less dependent on the set of the initial points compared to other methods which implies that convergence algorithm is robust. In [13], an optimal sizing of BESS by using PSO-based reliability is already proposed for an islanded microgrid. However, two basic problems need to be addressed in a microgrid operation: voltage control and frequency control. When in islanding mode, frequency control becomes the main concern for a microgrid operation [14]. Thus, this paper selected and proposed the optimal sizing of BESS by using PSO method-based frequency control of the microgrid to prevent the microgrid from instability and system collapse after the loss of the utility grid (e.g., blackout or disasters).

Modern BESS technologies, which are analyzed and compared the performance and total cost in this study, are the polysulfide–bromine BESS and the vanadium redox BESS (i.e., redox-flow batteries). It is a relatively new commercially available battery and differs from conventional BESS in such a way that the amount of energy it can store is independent on its power rating [15]. Moreover, redox-flow batteries can be designed for both high power and large energy storage. Due to its new commercialization, recent studies on redox-flow BESS in a microgrid are limited [16,17]. In this study, the specified costs of two BESS technologies are separated and analyzed in order to compare performances of different technologies for 15 years installation in the typical microgrid.

The main purpose of this paper is to determine an optimal size of BESS at minimal total BESS cost by using the proposed PSO-based frequency control of the microgrid to prevent the microgrid from instability and system collapse after the loss of the utility grid. The proposed optimal size of BESS based-PSO is compared with the optimal size of BESS based analytic method (i.e., balanced generation and load demand) and the conventional size of BESS. It is clearly shown that the proposed optimal size of BESS based-PSO method gives the best performance in achieving the optimum size of BESS at minimum total cost of BESS for the microgrid. Then, the impacts of BESS specified costs with different storage technologies are investigated and compared for 15 years installation in the typical microgrid. The rest of this paper is organized as follows; Section 'Introduction' describes the background of the research and previous work; Section 'System configuration' gives a brief description of the study microgrid; Section 'Cost consideration of modern BESS technologies' demonstrates the proposed optimal sizing of BESS by using the PSO method and the analytic method based on frequency control of the microgrid; Section 'The proposed optimal sizing of BESS based frequency control' shows the results and analysis; Section 'Results and discussion' concludes what has been done in this work.

## System configuration

### *Microgrid system*

The typical microgrid can be operated either in a grid-connected mode or stand-alone mode. Under a normal operation, the microgrid is connected to the utility grid. Fig. 1 shows the microgrid system, which contains a 1.2 MW mini-hydro generator, 2 MW hydro generator and 3 MW photovoltaic sources and BESS, is connected to the microgrid system at bus 1. The system contains the group of feeders which could be a part of the distribution system. The critical loads 1 and 4 require a local generation and the non-critical loads 2, 3 and 5 are not connected to any local generation. This system is typical to a real system available at the promoting renewable energy in Mae Hong Son project (i.e., pilot project) which initiated and funded by United Nations Development Programme (UNDP) and Global Environment Facility (GEF). This project operates initially in Mae Hong Son province, which the ministry of energy has identified as the target to be the first energy self-sufficient province in Thailand [18–21].

### *Photovoltaic power generation system*

The output power of solar photovoltaic (PV) is uncertain as it is mostly affected by the environmental factors, particularly the environmental random changes will inevitably lead to constantly changing of output power of PV [22,23]. In order to illustrate PV characteristics in the operating condition, the influence of solar radiation and atmosphere temperature are designed. The temperature effect is denoted by a temperature coefficient of $T_{co}$ (1/°C). The efficiency of the inverter is multiplied by the DC output converting DC to AC output as in (1).

$$P_{PV} = n_{PV} P_{rate\ PV} (G/G_0)(1 - T_{co}(T_A - 25^{\circ}))\eta_{inv}\eta_{rel} \tag{1}$$

where $n_{PV}$ is PV module number, $P_{rate\ PV}$ is PV array rated power (W), $G$ is the global insolation on PV array (W/m$^2$), $G_0$ is the standard amount of insolation rating capacity of PV modules (W/m$^2$), $T_A$ is