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Optimum battery energy storage system using PSO considering dynamic demand response for microgrids

Thongchart Kerdphol *, Yaser Qudaih, Yasunori Mitani

Department of Electrical and Electronics Engineering, Kyushu Institute of Technology, 1-1 Sensui-cho, Tobata-ku, Kitakyushu-shi, Fukuoka 804-8550, Japan

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ABSTRACT

This article proposes a novel optimum sizing of battery energy storage system (BESS) using particle swarm optimization (PSO) incorporating dynamic demand response (DR) to improve a fast, smooth and secure system stability and performance, avoiding a microgrid from instability and system collapse during an emergency situation. An optimum size of BESS integrating DR can play an important role in frequency control of the microgrid in order to rapidly improve the system stability, restore the power equilibrium and prevent system collapse in the microgrid. The optimum size of BESS is evaluated by PSO incorporating DR based on frequency control of the microgrid. The results show that the optimum size of BESS-based PSO with DR can improve a fast, smooth and safe system performance and dynamic stability compared with the optimum size of BESS-based simulated annealing (SA) with DR and the conventional size. Nevertheless, the proposed sizing methods also determined the impact of BESS specified costs between modern and conventional BESS technologies. The capital cost, operating and maintenance cost of BESS were then investigated and compared in terms of economical performance for microgrid operations.

Introduction

Today, energy and environmental crisis are critical concerning such as depletion of fossil fuel resources, growth of electricity demand and greenhouse gas emission (GHG). To solve such a crisis, a microgrid concept, which composed of small-scale distributed energy resources (e.g., photovoltaic microsource, wind turbine microsource, fuel cells and energy storage systems), is being considered as one of the solutions [1]. A microgrid is an integration system for supply resources (i.e., microsources), battery energy storage systems (BESS) and demand resources (i.e., controllable loads) located in a local distributed network. A microgrid should be capable of handling both normal operation (i.e., grid-connected mode) and emergency operation (i.e., islanding mode). As the output characteristics of distributed resources and renewable energy resources in microgrids are quite different from the conventional energy sources, the microgrids should be capable of handling unexpected fluctuation and maintaining system stability and flexibility. Therefore, BESS units serve as a significant component in microgrid operations [2,3].

Modern developments and advances in BESS are enhancing the applications of energy storage technologies, allowing the system to be operated in a more flexible and controller manner. The benefits of BESS include an enhancement of the system stability particularly when BESS is applied for system frequency control. For small disturbances, BESS can inject/discharge the power to a system when the system frequency is lower than the nominal frequency (i.e., 50 or 60 Hz). Otherwise, BESS can absorb/charge the power from a system when the system frequency is higher than the nominal frequency. For large disturbances, BESS can improve the performance of the system frequency control by combining BESS with an under-frequency load shedding/demand response, an under/over frequency generation trip. Therefore, it is summarized that BESS is a fast, flexible and effective device for power systems [4–6]. Proceeding [7] derived a dynamic model of BESS implemented to power system; [8] studied the effect of a large BESS capacity (i.e., 30 MW) on frequency regulation in power system stability; [9] performed a value analysis of different BESS applications; [6] combined an incremental model of BESS into load frequency control of an isolated power system and observed the system performance; [3] implemented BESS to a microgrid system and investigated an operation and control strategy; [5] studied the optimization and dimensioning of BESS based on the state of charge (SOC) which applied to primary frequency control in interconnected networks.

Considering a modern power system such as microgrids, the main challenge in integrating BESS into a microgrid is to determine

* Corresponding author.
E-mail address: n589504k@mail.kyutech.jp (T. Kerdphol).

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Nomenclature

E_t	AC voltage between a line and neutral
α_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 converter
E_{b1}	battery overvoltage
E_{bt}	terminal voltage of the battery side
E_{boc}	battery open circuit voltage
I_{BESS}	DC current though the battery
P_{BESS}	active power of BESS
Q_{BESS}	reactive power of BESS
r_{bt}	connecting resistance
r_{bs}	battery internal resistance
r_{bp}	self discharge resistance
r_{b1}	overvoltage resistance
c_{b1}	overvoltage capacitance
c_{bp}	battery capacitance
X_{co}	commuting reactance
ith	iteration number
jth	particle number
v_i	velocity of a particle at iteration ith
x_i	position of a particle at iteration ith
P_{best}	best solution at iteration ith
G_{best}	best global solution at iteration ith
r_1	random number one between 0 and 1
r_2	random number two between 0 and 1
c_1, c_2	learning factors
T_k	temperature at k
T_{k+1}	temperature at $k+1$
a	constant between 0 and 1
δ	distance constant between 0.1 and 1
σ_{Tk}	standard deviation of the values generated at kth of Markov chain

an optimum size of BESS to avoid the microgrid from instability and system collapse due to load/generation changes or outage of a generation/utility grid. The installation of BESS at a random or non-optimum size can increase in cost, system losses, stability issues and larger BESS capacity. Thus, an optimum size of BESS is a significant issue for microgrid operations. An optimization technique for evaluating an optimum BESS size can be achieved by means of linear programming method, enumerative method, iterative algorithm, simulated annealing (SA), genetic algorithm (GA) and particle swarm optimization (PSO) [10–15]. The advantages of PSO include simplicity, ease of use, high convergence rate and minimal storage requirement. Nevertheless, PSO has less dependent on the set of the initial points compared to other approaches which implies that convergence of PSO is robust [12–15]. With these reasons, this study proposes the PSO as an effective method to evaluate an optimal size of BESS.

Together with one of the key technologies in smart grid applications, dynamic demand response (DR) can assist operators or users to optimize power usage and participate in reducing peak demand of microgrids. DR is defined as the time domain (i.e., 1 s to several seconds) real and reactive power response to a frequency disturbance [16]. Due to high costs of a large capacity of BESS and the limited availability of a microgrid during an emergency condition, DR can be considered as real-time intelligent responsive load participation. It is well known that DR can increase system stability, reliability and flexibility to manage the variability and uncertainty of distributed resources and renewable energy resources in microgrids [17]. Control of load shedding is an effective way to reduce the loads for DR. In modern power systems, load is controlled only during severe stability conditions using load shedding or DR to restore the system frequency [18]. The study of DR for providing ancillary services was proposed in [19]. Later, the idea of dynamic demand response for load frequency control was proposed in [20]. By combining the performance of BESS and DR for improving system stability and performance, thus, this research proposes a novel sizing method of BESS using PSO-based dynamic demand response in order to improve and restore a fast, smooth and secure system stability, avoiding a microgrid from instability and system collapse during an emergency situation such as a loss of distributed generation/utility grid. DR is considered as frequency load shedding for rapidly restore the system frequency. The proposed methodology is using PSO incorporating DR with multi-objective functions for determining an optimum size, capital cost and operating and maintenance cost of BESS. Afterwards, the proposed methods also evaluated the impact of BESS specified costs with modern BESS (i.e., redox-flow BESS) and conventional BESS (i.e., lead-acid BESS) technologies for microgrids. The capital, operating and maintenance costs of BESS were demonstrated and compared in terms of economical performance for microgrids. The rest of the paper is organized as follows: Section 'System configuration and design' presents a brief description of the typical microgrid, PV modeling and BESS modeling; Section 'Dynamic demand response' describes a brief description of dynamic demand response incorporating BESS; Section 'Modern and conventional BESS cost considerations' illustrates the cost considerations of BESS; Section 'the proposed optimum sizing of BESS with dynamic demand response' proposes the optimum sizing of BESS using PSO with DR and the optimum sizing of BESS using SA with DR; Section 'Results and discussion' reveals and discusses the simulation results; Section 'Conclusion' concludes the work.

System configuration and design

Microgrid system and design

A microgrid is a group of distributed generations, renewable energy generations and domestic loads. The typical microgrid consists of the mini-hydro microsource with a peak power of 1.2 MW, the hydro microsource with a peak power of 2 MW, the photovoltaic microsource with a peak power of 3 MW as shown in Fig. 1. Each generation has its own local microsource controller to handle the relevant electrical variables. This microgrid consists of group of feeders which could be parts of the distribution design. Each unit's feeder has a circuit breaker for disconnecting the corresponding feeder in order to avoid the impacts of severe disturbances. The domestic load can be separated to sensitive and non-sensitive loads via separated feeders. The loads 1 and 4 are the sensitive loads with a peak power of 1.85 MW and 1.9 MW, respectively. The loads 2, 3 and 5 are the non-sensitive loads with a peak power of 1.7 MW, 1.75 MW and 2.4 MW, respectively. Finally, the microgrid is connected to the distribution system by a point of common coupling (PCC). The PCC is able to island the microgrid for maintenance purposes or when a fault or contingency occurs. This microgrid is typical to the real microgrid at Mae Hong Son province, Thailand which has initiated and funded by United Nations Development Programme (UNDP) [21–24].