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Optimal sizing and control strategy of isolated grid with wind power and energy storage system

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ABSTRACT

Integrating renewable energy and energy storage system provides a prospective way for power supply of remote areas. Focused on the isolated grids comprising renewable energy generation and energy storage, an energy storage sizing method for taking account of the reliability requirement and a bi-level control strategy of the isolated grids are presented in this paper. Based on comparative analysis of current energy storage characteristics and practicability, Sodium–sulfur battery is recommended for power balance control in the isolated grids. The optimal size of the energy storage system is determined by genetic algorithm and sequential simulation. The annualized cost considering the compensation cost of curtailed wind power and load is minimized when the reliability requirement can be satisfied. The sizing method emphasizes the tradeoff between energy storage size and reliability of power supply. The bi-level control strategy is designed as upper level wide area power balance control in dispatch timescale and lower level battery energy storage system V/f control in real-time range for isolated operation. The mixed timescale simulation results of Nan'ao Island grid verify the effectiveness of the proposed sizing method and control strategy.

1. Introduction

The power supply in remote areas where fuel delivery and grid extension are costly due to geographical barriers is an extremely urgent problem. As widely research and utilization of renewable generation especially wind power systems, developing renewable energy as alternative to conventional generation to constitute an isolated grid is an effective solution to satisfy power demands in these areas.

In order to utilize the renewable energy cost effectively for reliable power supply in isolated grid, many relevant research issues such as sizing method of generation and energy storage units [1–4], energy management strategy [5–10], control strategy of power electronic interfaced generation and energy storage units [11–17] have been studied. So far, diesel generators combined with small amount of wind turbines and photovoltaic generation units are the major composition pattern of isolated grid meanwhile increasing the proportion of renewable generation units along with energy storage units. The diesel generator and energy storage devices are absolutely critical to maintain voltage and frequency stability of these isolated grids. However, fuel delivery is quite costly while renewable energy can be exploited to fulfill the local load demand in the remote areas. For example, wind resources in the isolated islands are generally abundant. Wind power can completely satisfy the local load demand with the single problem of power unbalance due to wind power intermittency. Integrating energy storage system and wind power can overcome the drawback of the stochastic nature. It is attractive to develop an isolated grid consisting of wind turbines and energy storage system to supply power in such remote areas. With regard to the control strategy of isolated grid with high penetration of renewable energy, Vrettos and Papathanassiou [5] proposed three operating modes by utilizing renewable generation units with diesel generators and energy storage units. The operation mode is selected based on the forecasts of the expected load and renewable power and the expected renewable energy penetration can be maximized in excess of 60% if sufficient renewable generation units and storage capacities are installed. Sebastian [12] presented multiple flexible operation strategies in isolated grid with high penetration of wind power, diesel generators and energy storage system. Different operation strategies are achieved by regulating diesel generators or energy storage system and load shedding if necessary. Control strategies of energy storage system and load are respectively designed for separate operation strategies. Tucker and Negnevitsky [18] designed a

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hierarchical control strategy for isolated grid constituted of wind turbines, photovoltaic array and storage units. The isolated grid can operate without assistance of diesel generators. In these researches, the wind power penetration can be effectively improved without control of wind turbines, but the stable operation of isolated grid mainly relies on the power regulation of diesel generators and energy storage device. The penetration rate of renewable energy is constrained by capacities of diesel generators and energy storage device. More auxiliary diesel generators or energy storage device need to be installed for improving renewable power penetration. Therefore, the existing control strategy is restricted and not suitable for isolated grid with higher even 100% penetration of renewable energy.

This paper is concentrated on sizing and control methods of isolated grid consisting of wind power and energy storage system. Firstly, the energy storage type is selected by comparative analysis. Then an energy storage sizing methodology taking account of reliability requirement of isolated grid is introduced. The compromise between energy storage size and reliability can be achieved in the sizing model. Moreover, a bi-level control strategy is given for isolated operation with wind power and energy storage system. The validity of the proposed sizing method and the control strategy is examined via case study of Nan'ao Island.

2. Selection and sizing method of energy storage

Due to fluctuation and intermittence of wind power, the stable operation of the isolated grid relies on dispatchable generation units, such as diesel generator, micro turbines, et al. and energy storage units, such as battery, pumped hydro storage (PHS), compressed air energy storage (CAES), flywheel energy storage (FES), superconducting magnetic energy storage (SMES), et al. First of all, energy storage system (ESS) is definitely needed to be designed for storing the surplus energy.

2.1. Energy storage type selection

Survey and investigation of current energy storage technologies has been performed for appropriate type selection as briefly stated below. Both of pumped hydro storage (PHS) and compressed air energy storage (CAES) are considered long-term time scale storage technologies with similar characteristics. However, installation of PHS or CAES should be permitted by the topographical conditions of local region. Besides, the response time of PHS or CAES is not fast enough to smooth or balance fluctuation of wind power. Long cycle life, low self-discharge, low capital cost and large power and energy volumes are advantages of hydrogen-based energy storage system, but its major drawback is low energy efficiency (about 42%). Even though flywheel energy storage system (FES), superconducting magnetic energy storage (SMES) and supercapacitor energy storage system present some good features regarding high energy efficiency, long cycle life and high power density, all of them are candidates for short time scale applications in power system but not logical options for remote areas where long-term energy storage is needed in the isolated grid application [19–22]. Battery energy storage system (BESS) is the most widely used storage technology available for power system application. Enormous power and energy capacities of the battery can be obtained by electrically connecting the cells in series and parallel. Different types of batteries have been developed and many are mature technologies available on the market. Among all of these batteries, the lead-acid battery is the oldest and most mature technology. The cycle life of lead-acid battery is 1000–2000 cycles at 70% depth of discharge, with round trip efficiency of 72–80%. The lifetime of lead-acid battery is relatively short because of poor performance at low and high ambient temperatures and short cycle life. The other major drawbacks of lead-acid battery are frequent water maintenance (flooded type) and heavy. Nickel–cadmium (NiCd) battery is a type of alkaline rechargeable battery, which is a well-established technology in the market. Compared to lead-acid battery, NiCd battery has a longer cycle life (3000 cycles at 100% depth of discharge) and less maintenance but costs much more. Meanwhile, both of lead-acid and NiCd batteries contain toxic heavy metals and suffer from severe self-discharge. Lithium-ion (Li-ion), Sodium–sulfur (NaS), and redox flow batteries are the promising technologies for applications in power system. Li-ion battery offers superior energy efficiency, high power density, fast charge and discharge capability, low weight, and long cycle life (3000 cycles at 80% depth of discharge). However, high self-discharge rate (1–5%/day) and high cost due to special packaging and internal over charge protection circuits are the major obstacles for wider and larger applications. Vanadium Redox battery (VRB) and Zinc Bromine battery (ZBB) are widely considered redox flow batteries in the market. The principal characteristics of redox flow batteries are decoupled power and energy capacity, fast response, low self-discharge and long lifetime. Redox flow battery is one of the appropriate options for long duration energy storages. The major weakness of redox flow battery is the increased capital and running costs associated with pump and flow control systems. NaS battery is also one of the leading technologies with high energy efficiency (75–89%), no self-discharge, long cycle life (2500 cycles at 100% depth of discharge), pulse power capability and lower capital cost than other batteries except lead-acid battery. The defect of NaS battery is high temperature operation (around 350 °C) [23–25].

From the above analysis, there exist a large variety of storage technologies with different attributes and intended for different applications. The ideal choice of storage technology for a specified application depends on a number of factors including the amount of energy or power to be stored, the time scale of stored or released energy to be required, spacing and environmental constraints, investment cost, the exact location in the network, and the functionality of storage to be required [19]. Here, the principal functionality of energy storage system is long-term power balance of isolated grid. Therefore, the energy storage technologies with high energy density are suitable to satisfy isolated grid requirement, such as PHS, CAES and battery technology. Since the typical power applications for PHS and CAES are in the order of 100 MW and depend on suitable geographical environment, the PHS and CAES are not ideal storage solution for small isolated grid. Among the various battery technologies, lead-acid battery and NiCd battery are unlikely to be used in isolated grid due to limited cycle life and pollution concerns [26]. Li-ion battery has better performance but is still far too expensive. Finally, NaS battery and redox flow battery are recommended as best cost-performance compromise for long-term application in isolated grid. NaS battery technology is comparatively more mature than redox flow battery technology in commercial market and has several practical applications [27–29], so NaS battery is selected as the energy storage technology in this paper based on above comparative analysis.

2.2. Energy storage sizing

2.2.1. Objective function

The capital cost of ESS is generally the major factor of energy storage sizing. ESS is sized in terms of power and energy capacity. Thus, the capital cost of energy storage capacity consists of power and energy capacity components. The energy capacity component represents the cost of energy storage medium and the power component represents the cost of power electronics converter. Energy capacity determines the energy that can be stored or drawn in the ESS, and the power rating determines the average power that can