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Economic evaluation of batteries planning in energy storage power stations for load shifting

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ABSTRACT

The rapid charging or discharging characteristics of battery energy storage system is an effective method to realize load shifting in distribution network and control the fluctuations of load power substantially. However, the type selection and capacity configuration of the batteries will be directly related to the economy of energy storage system for load shifting in the distribution network. An optimized model of hybrid battery energy storage system based on cooperative game model is proposed in this paper, in which lead-acid battery, lithium ion battery and vanadium redox flow battery are respectively regarded as the participants of the cooperative game model, the cost and benefit models are established in their corresponding game strategy spaces. The Nash equilibrium solutions of each game model obtained by genetic algorithm are applied to the planning and design of battery energy storage station with the most economical types of the batteries and the optimal capacity configuration of energy storage station. The simulation results verify the effectiveness of the proposed method and provide a theoretical basis for the planning and design of battery energy storage station.

1. Introduction

Introducing the energy storage system into the power system can effectively eliminate peak-valley differences, smooth the load and solve problems like the need to increase investment in power transmission and distribution lines under peak load [1]. The energy storage system can improve the utilization ratio of power equipment, lower power supply cost and increase the utilization ratio of new energy power stations. Furthermore, with flexible charging and discharging between voltage differences, it yields economic benefits and features revenues from multiple aspects with input at early periods [2–5].

Energy storage systems can be classified into the systems with mechanic, electrochemical, electromagnetic and phase change energy storage modes based on their storage methods [6–9]. In comparison with other energy storage systems, electrochemical energy storage systems have no rigid demand to locations and can be installed in either the power generation, transmission, distribution or consumption systems. Battery energy storage system, a typical mode of electrochemical energy storage, features short construction period and flexible adjustment of energy saving capacity. Thus, it is practical to apply battery energy storage for the load shifting in power distribution networks. Despite of short cycle life, lead-acid batteries, boasting proven technology, and much lower initial investment comparing with that of sodium–sulfur batteries, can be combined with other batteries in application. Lithium ion batteries, having advantages in initial investment, cycle life and energy conversion efficiency comparing with other batteries, are intolerant to excessive charging and discharging. Vanadium redox flow batteries can stand in-depth charging and discharging and are much longer in cycle life comparing with that of sodium–sulfur batteries [10]. The energy storage system represented by lithium batteries, sodium–sulfur batteries and vanadium redox batteries (VRB) has been widely applied and scaled up. The lithium battery energy storage system is applied to wind power generation, and the fluctuations in active output power of the smooth wind power system can offer certain reactive power support for power grids under failure conditions, which improves the operation performance of the wind power system [11]. With sodium–sulfur batteries as the target, a model for operation of micro-grid systems that include sodium–sulfur battery energy storage is established to analyze the influence of multiple factors

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on the economic operation of systems [12]. Based on different demand for energy storage batteries arising from power grid operation, researches are conducted concerning the features of VRBs to offer data and reference for the theoretical research and engineering demonstration of battery energy storage technologies [13].

However, energy storage technologies vary in response time, power range, storage capacity and cost, and it's difficult for a single energy storage technology to meet the demand for multi-timescale power control by intermittent power sources. Combining several types of energy storage technologies that complement each other can improve the output of energy storage system and extend the service-life of storage batteries and lower maintenance expenses.

Materials show that there are a few researches on energy storage cost, economic efficiency of revenues and selection of battery types. ***Hida Y*** et al. [14] provides an index relationship for the economic efficiency of large-scale energy storage devices based on the features of electrochemical energy storage batteries, and further calculates the economic efficiency of chemical energy storage devices. But the method cannot accurately reflect the economy of large-scale energy storage systems. Energy storage devices are modeled to analyze the values and investment costs involved in load regulation, power balance and load shifting [15]. Despite a range of application models used, the modeling is less precise. Ref. [16] compares the technical and economic features of various kinds of batteries in energy storage, and summarizes the methods to calculate the capacity in smooth wind power fluctuations.

This paper offers a study on the design of energy storage stations used for load shifting. Based on analyzing the economic features of different types of battery energy storage systems, three types of batteries, namely lead-acid batteries, lithium-ion batteries and VRBs, are selected as the game players. The static cooperative game model for complete information among two or three batteries is set up, taking into account the economic revenues and costs of the energy storage system used for load shifting and with the capacity of each battery as the strategy. The genetic algorithm is used to identify the energy storage battery type with the best economic revenues and the optimal capacity configuration, so as to lay the theoretical basis for the design of energy storage stations.

2. Establishment of cooperative game model for energy storage batteries

2.1. Analysis of game elements

The game theory is about researches on the ways to optimize respective decisions by two or more competitive individuals under interactions [17–20]. As an advanced math tool, the game theory has been widely applied in economy, politics and engineering management. In power system field, some researches are concentrated on power market directly related to economic benefits.

Game players: Lead-acid batteries, lithium-ion batteries and VRBs are players of the game for load shifting and respectively represented byB_a,B_{li} andB_v.

Player strategies: In the game amongB_a,B_{li} and B_v, the strategies are the capacities respectively used for load shifting and represented by E_a,E_{li} and E_v. Affected by actual application environment and policies, the values of decision variables are continuously defined within a permissible range and constitute continuous strategy spaces for players, i.e.P_{B_a}, I andP_{B_v}. Detailed descriptions are as follows:

$$E_{\mathrm{a}} \in \left\{ P_{B_a} = \left[E_a^{\min}, E_a^{\max} \right] \right\}$$
$$E_{\mathrm{li}} \in \left\{ P_{B_{li}} = \left[E_{li}^{\min}, E_v^{\max} \right] \right\}$$
$$E_{\mathrm{v}} \in \left\{ P_{B_v} = \left[E_v^{\min}, E_v^{\max} \right] \right\}$$

where$E_i^{\min}, E_i^{\max}(i = a, li, v)$ respectively represent the upper and lower limits of the capacities of the three batteries, with the capacity range as 0–100 MW in this paper.

2.1.1. Modeling player revenues

Revenues of the battery energy storage systems are defined as the revenues gained by energy storage systems in participating in load shifting of power distribution networks, mainly including direct revenues, revenues on delaying equipment investment, environmental benefits, government subsidies and revenues on reducing line loss.

2.1.1.1. Direct revenues. Under peak and valley power tariffs, energy storage devices are charged when load and tariffs are low, while discharged when load and tariffs are high. Revenues gained on such a basis are called direct revenues, with the math model as follows:

$$S_{income\_i} = \mathrm{n} \cdot (R_{out} - R_{in}) \times Q\_i (i = a, li, v) \tag{1}$$

whereR_{out} suggests the peak tariff in a certain area; n suggests the year of operation of energy storage stations;R_{in} suggests the valley tariff; Q_i suggests the annual on-grid energy of battery I, with the details as follows:

$$Q\_i = E_i \cdot \eta_i \cdot num_i (i = a, li, v) \tag{2}$$

whereη_i suggests the charging and discharging efficiency of battery I; num_i suggests the annual charging and discharging times of battery I; In this paper, the strategy of constant power charging & discharging is adopted for batteries, and one charge and two discharges are kept each day to make the quantity of power charged equal to that of power discharged. So, charging and discharging times number 365 annually.

2.1.1.2. Revenues on delaying equipment investment. If battery energy storage systems are used for load shifting in power distribution networks, the energy storage devices will be responsible for clipping the peak in peak hours, which can delay equipment investment and bring indirect revenues. The math model is:

$$S_{delay\_i} = R_{p\_vest} \cdot E_i / t_i (i = a, li, v) \tag{3}$$

where R_{p_vest} suggests the investment per unit of power of conventional power distribution equipment; t_i suggests the time that the energy storage system participates in load shifting.

2.1.1.3. Environmental benefits. Most peak load regulation in power grid at home is presently assumed by conventional power plants, and an overwhelming majority of peak regulation is assumed by coal-fired power plants, which results in increased coal consumption. Load shifting with energy storage systems can optimize operation of thermal power units and reduce frequent starts/stops, thus lowering coal consumption and helping environmental protection. The math model is as follows:

$$S_{environment\_i} = \mathrm{n} \cdot R_{TP} \cdot Q_i (i = a, li, v) \tag{4}$$

whereR_{TP} suggests the power supply cost of per unit of conventional thermal power sets and the combined environmental