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An economic analysis model for the energy storage system applied to a distribution substation

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A R T I C L E I N F O

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A B S T R A C T

Recent developments and advances in energy storage technologies are making the application of energy storage technologies a viable solution to power applications. The energy storage system can store energy previously, and then release it in the proper time. Due to their flexibility, it is suitable to apply this technology to deregulated power markets. Therefore, this paper will build the economic analysis model for the energy storage system to apply to a distribution substation in a deregulated power market. The costs including installing energy storage system and operation and maintenance expense, and the revenues containing energy price arbitrage, reducing transmission access cost, and deferring facility investment are considered in this model. All these factors are evaluated by present worth value. Due to complexity of this problem, this paper proposes a method combining the genetic algorithm with linear program (GALP) to determine the optimal capacity and operations of the energy storage system.

1. Introduction

With the progress of the storing technology, applications of the energy storage system to the power systems become feasible. Many practical examples described in [1–3] are shown below. A large 20 MW/15 min storage facility in Puerto Rico kept the entire island grid stable for several years. An even bigger 27 MW/15 min facility was commissioned in Fairbanks, Alaska, in 2003. A 250 kW/8 h Vanadium Redox Batteries (VRBs) facility was put into service on a long distribution line in Utah. In Wisconsin, a system of six 1 MW/1 s Superconducting Magnetic Energy Storage (SMES) devices was effectively used to inject power into a collapse-prone transmission loop. A number of demonstrations in the 100 kW to 1 MW range have been field-tested with the US Department of Energy's support and in cooperation with major utilities.

Large scale energy storage systems are gradually popular around the world. These technologies are categorized into three kinds-bulk energy storage, distributed generation, and power quality-with significant variations in discharge time and storage capacity. The SANDIA National Laboratories have launched a series of researches [4–8] about their applications to the power systems. In [4], the energy storage technology and life-cycle costs analyses have been performed to give a more complete representation of the comparison between technologies. In [5], it characterizes electric energy storage applications and related benefits. It also describes criteria and a framework for estimating market potential and provides maximum market potential estimations. In [6,7], these reports outline a wide range of innovative ways in which storage could be advantageously used in all aspects of the electric supply system of the future. It discusses ways to expand the envelope of possible storage applications and suggests creative uses for storage. In [8], the handbook makes the business case for energy storage on the national and corporate levels and also provides a guide for T&D utilities looking at particular energy storage systems for representative applications in grid stabilization, grid operation support, and load shifting.

In addition to SANDIA, many authors also present applications of the energy storage system. In [9], automatic generation control with interconnected two-area multi-unit all-hydro power system and two more test systems as all-thermal and thermal-hydro mixed have been investigated. To stabilize the system for load disturbance, comparative transient performance of two cases as (a) Thyristor Controlled Phase Shifter installed in series with the tie-line in coordination with Superconducting Magnetic Energy Storage (SMES) and (b) SMES located at each terminal of both areas are analyzed. It is observed that the case (b) suppresses the frequency oscillations more effectively.

In [10], design of control strategy for hybrid fuel cell/energy storage distribution power generation system during voltage sag has been presented. The proposed control strategy allows hybrid distributed generation system works properly when a voltage disturbance occurs in distribution system.

In [11], the authors present the applications of the energy storage system to advanced power applications. In [12], the authors

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present a methodology to evaluate energy storage installations in distribution substations. This work is based on multiple objective optimization. In [13], this paper investigates the robustness of damping control implemented by the energy storage system to the variations of power system operating conditions. A load-leveling application is proposed in [14], and an application of deferring upgrades on distribution is proposed in [15]. In [16,17], the authors present the application of the energy storage system to industrial customers.

In [18], the concept of combining photovoltaic power stations and energy storage systems comprises a promising solution for small scaled autonomous electrical networks, increasing the reliability of the local network as well. According to the calculation results obtained, one may clearly state that an optimum sizing combination of a PV generator along with an appropriate energy storage system may significantly contribute on reducing the electricity generation cost.

Due to the flexibility and progress of the energy storage system, it will play an important role on the operations of power systems. Therefore, this paper will build the economic analysis model for the energy storage system to determine its maximum power level (kW), its energy storage capacity (kWh), and its operation to obtain the maximal benefit.

2. Introduction to the energy storage system

The use of stored energy is fundamental to the generation of electric power, whether in fuel stockpiles for fossil or nuclear power plants, or the seasonal runoff and dammed waterways for hydroelectric power plants. The use of stored energy for the real time and short notice support and optimization of the transmission and distribution system has been limited to date, primarily due to a lack of cost-effective options. Recent developments in advanced energy storage technology are providing new opportunities to use energy storage in grid stabilization, grid operation support, distribution power quality, and load shifting applications. These applications can be found in [4–10], and the introductions of these papers are mentioned in the previous section.

In this paper, the energy storage system is used to charge at the lower electricity prices, and discharge at the higher prices to gain the profits. According to [8], it is suitable to adopt the Vanadium Redox Batteries (VRB). In order to build the economic analysis model, some parameters about the VRB energy storage system is described below.

2.1. Capacity

The capacity of a battery energy storage system is measured in both maximum power level (kW) and energy storage capacity (kWh). In the case of the VRB, these two system ratings are independent of each other. Most VRB systems are capable of discharging at maximum design power for a period of 4 to 10 h.

2.2. Maintenance requirements

There are only two moving parts in a typical system – pumps on the positive and negative sides. Thus maintenance costs are relatively low.

2.3. Efficiency

In the VRB energy storage system, several losses including transformer losses, power conversion system losses, battery DC losses, and pumping losses must be accounted for in characterizing the VRB performance. Considering these factors, the VRB efficiency is about 75%, and the operating modes for the charging and discharging periods are shown in the following equation

$$\text{Charging periods}: E_{t+1} = E_t + P_t * \text{Eff} \quad (1)$$

$$\text{Discharging periods}: E_{t+1} = E_t - P_t \quad (2)$$

where E_t (kWh) is the energy stored in the storage device at the time t, P_t (kW) is the power charging or discharging at the time t, the time interval of t is 1 h, and Eff is the efficiency of the energy storage system.

3. The economic analysis model for the energy storage system

In the deregulated power market, the distribution company is responsible for buying electricity to serve its customers. Due to price differences between different periods, the distribution company could purchase the inexpensive electricity during periods when demand for electricity is low to charge the storage system, so that the low priced energy can be used or sold at a later time when the price for electricity is high. In addition, the energy storage system could also reduce the transmission access charges and defer distribution upgrade. This model will consider these benefits and costs for the energy storage system to build a mathematic model to determine its maximum power level (kW), its energy storage capacity (kWh), and its operation.

In this model, the operating powers (P_i) of the energy storage system for 24 h are selected as the state variables. The following paragraphs will use these state variables to represent the benefits and costs involved in this model and build the economic analysis model for the energy storage system.

3.1. Benefit 1: Energy price arbitrage

Fig. 1 shows the average energy price for each hour of a power market. These values are modified from the New York Independent System Operator (ISO) market. The peak demand periods occur between the 10 a.m. and 10 p.m. The state variables are represented by (3). During the charging periods, $P_i = -P_i^-$, and $P_i = P_i^+$ when the energy storage system discharges power. Therefore, the benefit of energy arbitrage can be represented by (4).

$$P_i = P_i^+ - P_i^- \quad i = 1\text{–}24 \quad (3)$$

$$\text{PrBen} = \sum_i (P_i^+ - P_i^-) * \text{Pr}_i \quad (4)$$

where Pr_i is the energy price of the ith hour, and PrBen is the benefit of energy price arbitrage.

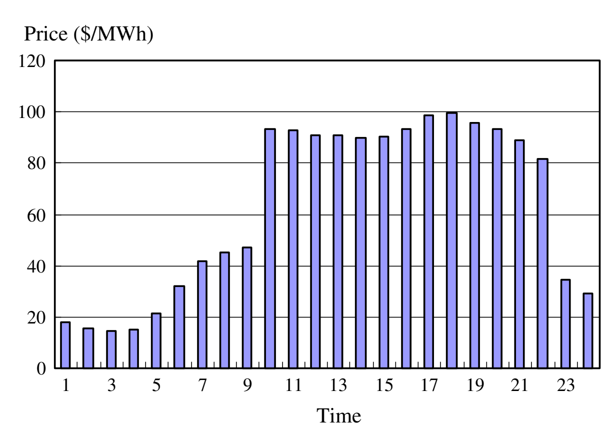

Fig. 1. Energy price for each hour.