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Pole-mounted battery energy storage for reliability enhancement of local distribution companies

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ABSTRACT

Power systems currently experience paradigm changes due to the integration of renewable sources, penetration of electric vehicles, and advancements in smart grid technology. Energy storage elements are accordingly sought to rectify some drawbacks of the new system components. Energy storage technologies and their power grid applications are, therefore, developing in fast pace.

This paper presents the design, development, and testing of a pole-mounted energy storage system (PMESS) based on lithium-ion batteries. The PMESS aims at enhancing the reliability of a local distribution company (LDC) at the residential level. The system provides load curve smoothing and peak shaving services to a pole-top distribution transformer feeding residential customers. An intelligent control algorithm is developed for optimal scheduling of the battery pack. The algorithm employs communication, load forecasting, and optimization software modules. A prototype unit of the PMESS is installed and tested on a Canadian LDC where the results show positive impact on the performance of the distribution transformer. Findings of this research are anticipated to attract the attention of those interested in distribution system operation, planning, and asset management.

1. Introduction

The integration of battery energy storage systems (BESS) into modern power networks has been lately on the rise. Recent dramatic changes in power generation, rising peak load, and smart grid infrastructure mandate the rapid deployment of energy storage elements in power networks. Energy storage can be employed in a huge spectrum of power grid applications, including but not limited to, load curve smoothing, peak shaving, frequency support, power quality improvement, and asset upgrade deferral. One vital motivation for energy storage usage is the swift penetration of distributed intermittent and fluctuating renewable energy sources. Energy storage can always bridge the gap between the variable generation profile and load demand, no matter which one exceeds the other.

Once the addition of BESS to an existing power network has been decided, the first challenge facing system designers and planners is the sizing and location of the new asset. The size of a BESS in a university campus equipped with photovoltaic (PV) panel generators is estimated in [1]. When distributed BESS are meant for voltage regulation and peak load shaving, the BESS size is optimized, and the cost-benefit analysis is derived [2]. In [3], the formulation of an optimization problem which benefits from multi-period power flow analysis is given. The objective is to co-optimize battery size, location, and operation profile for a pre-specified number of BESS units to be installed in a given distribution network. Asset upgrade deferral is expressed in terms of load growth rate, renewable generation penetration, and peak shaving fraction [3]. Once size and locations of BESS are determined, the next challenge is to develop the operation schedule. Dynamic programming is used to schedule the charge and discharge operation of BESS to minimize the energy bill [4].

Peak shaving is one of the first and most fundamental applications of BESS in power grids, particularly in the presence of PV panels [5]. Yau et al. [6] present an early study on the effects of BESS on power dispatch in terms of regulation and peak shaving either independent or combined. In [7], an active power management scheme of BESS is presented for PV capacity firming and energy time shift. Distribution system support is always possible using not only autonomous BESS, but also battery capacities in plug-in electric vehicles [8].

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Wind energy generators can also benefit from the services of BESS. An artificial neural network (ANN) is developed in [9] to control the power flow in a BESS-supported wind power system. In [10], coordinated control is exploited such that BESS can provide frequency regulation support to wind energy conversion systems. BESS are also used to enhance wind farm integration to power systems by smoothing the power generation curve and providing a variable level of reserve [11]. Frequency regulation and peak shaving are realized via proportional integral differential (PID) control for BESS acting of a Diesel/wind power system [12].

The role of energy storage devices in smart grids is highlighted in [13]. A distinction is made between energy storage, where consumption time shifting is concerned, and power storage, where speed response in frequency regulation and spinning reserve applications is more honored. Bulk energy storage facilities have a main objective of providing off-peak base-loading for large coal and nuclear plants [13]. However, with the increasing integration of renewables, the need for distributed storage units is becoming more essential. Hussein et al. [14] present a scheme for design and operation of distributed micro-storage battery systems with respect to system architecture, sizing, power stage design, and economic aspects. A distributed cooperative control strategy is proposed to maintain the balance between supply and demand at minimum power loss in a microgrid incorporating distributed BESS [15].

Due to distinct operational characteristics of different energy storage technologies, hybrid systems tend to improve the performance and boost the fitting to multiple applications. A hybrid battery and supercapacitor energy storage system is used for peak load shaving of a data centre to reduce the infrastructure investment and electricity bill [16]. Supercapacitors are usually more powerful than batteries, and have longer lifetime in terms of charging/discharging cycles. However, supercapacitors have higher cost and self-discharge rates. Therefore, a hybrid storage system composed of batteries and supercapacitors provide the best performance for the data centre power shaving and capping [16]. Lahyani et al. [17] present an optimal combination of batteries and supercapacitors in a 500 kVA uninterrupted power supply (UPS) application [17]. Wind generator support is also provided by a similar hybrid storage system [18].

This paper presents a pole-mounted energy storage system (PMESS) based on lithium-ion batteries for reliability improvement of local distribution companies (LDC). Load curve smoothing and peak shaving of a 50 kVA pole-top distribution transformer are the main objectives of the proposed PMESS. The system comprises three 5.5 kW inverters connected in parallel and fed from three parallel-connected battery modules rated at 5.3 kW and 5.3 kWh. A software control algorithm is developed in MATLAB to automatically schedule the battery. The algorithm incorporates three software modules for communication, load forecasting, and optimal scheduling of battery operation. The system is enclosed in a cabinet compartment and installed on top of a utility pole close to the distribution transformer to be served. Testing results show notable effectiveness in smoothing the load curve and shaving the peak load on the distribution transformer. Up to the best of the authors' knowledge, no energy storage system has been developed for pole-top installation so far, and no automatic optimal scheduling algorithm for a BESS has been available either in literature or industry.

2. Problem statement

The daily load curve of residential customers is directly affected by the consumption style which depends on the life routine and season of the year. Therefore, the load curve fluctuates and typically has hills and valleys. In North America, air conditioning is powered by electricity, whereas heating is based on natural gas. Accordingly, the average load in summer is usually higher than that in winter. Distribution utilities design different system components according to the peak load value, while such capacity is not utilized all the time. Smoothing the daily load curve of residential customers of an existing distribution network reduces the peak load value resulting in multiple advantages. Firstly, peak shaving increases the margin for emergency loading of the existing infrastructure leading to improvement of network reliability. Secondly, peak shaving elongates the expected lifetime of distribution system components such as transformers and feeders. Thirdly, the gap between minimum and maximum loads on the network reduces and the equipment temperature rise becomes more uniform leading to longer lifetime expectancy. Fourthly, peak

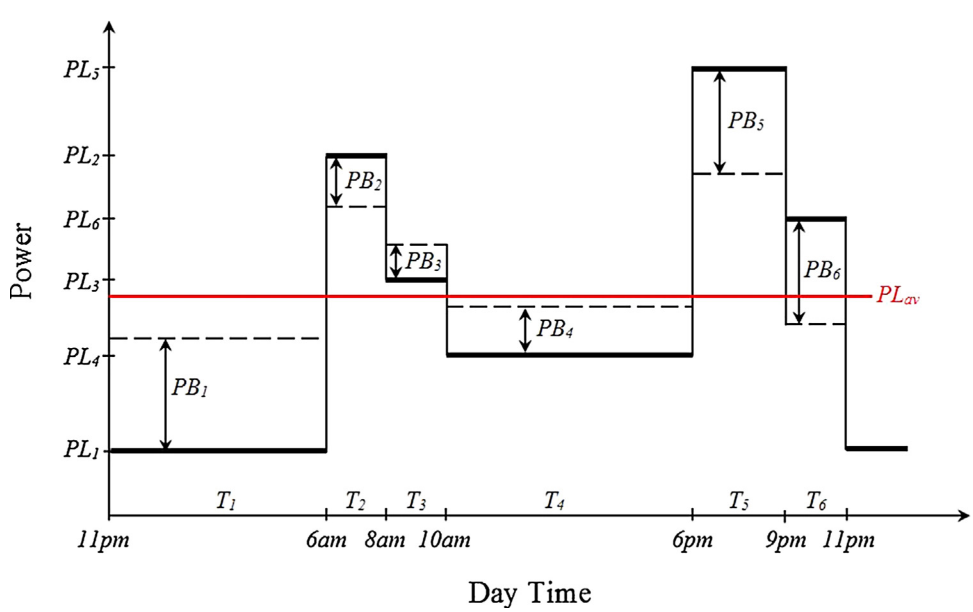

Fig. 1. Daily load profile and battery contribution.