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Hybrid energy storage management in ship power systems with multiple pulsed loads

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ABSTRACT

As various types of energy storage (ES) types continue to penetrate grid, electric vehicle, and Naval applications, a need arises in extending traditional analysis to cover the revised performance metrics associated with a hybrid energy storage system (HESS). Each ES device has its own respective power density, energy density, response time, and voltage stability under load. In some critical applications, such as ship power systems (SPS), it is recommended to combine two or more ES types to overcome the impediments of the other. In this paper, three different series-configured HESS are mathematically modeled, evaluated, and tested experimentally. Lead acid and lithium ion batteries as well as supercapacitor equivalent circuit models are defined as components for each mixed HESS configuration. The impulse response to a constant and pulsed load was used to evaluate each ES model. The charging of mixed ES technologies was then accomplished using a special controller to handle the unique charging constraints of each ES module. Moreover, this same controller was used to apply a "rolling charging" algorithm to extend the operating time of the HESS. The validity of the derived model and controller were validated experimentally through a hardware setup simulating a multi-pulsed load SPS profile.

1. Introduction

Research into energy storage (ES) systems continues to flourish to support the future microgrid infrastructure. To serve an ever-changing fluctuation in the consumer demand, the grid must rely on the inclusion from a variety of ES sources. The most common solution, an electrochemical battery, can be utilized for a wide range of different tasks including restoring system voltage and frequency following an outage [1–4]. In a utility grid, a wide range of ES can be deployed due to reduced concerns over weight and space. Mobile applications, however, do not have this luxury. The localized microgrid present on a ship, aircraft, or electric vehicle (EV) is susceptible to major operational and logistic challenges. Heavy and frequent pulsed loads, which may present a minimal disturbance to the utility-connected system, can prove to be catastrophic when generation resources are limited. Without the aid of carefully selected ES, the energy must either be available from generators on-demand, or ES units must be prepared and deployed effectively in anticipation of the disturbance.

A Naval ship power system (SPS) is composed of a complex isolated power system, typically consisting of 2 main turbine generators (MTG) and 2 auxiliary turbine generators (ATG) [5]. For example, the upcoming DDG1000 Destroyer all electric ship contains 74.8 MW of onboard total shaft power. Critical loads reserve approximately 15% of the available energy, but the next generation of equipment will introduce loads several magnitudes greater than this figure [6]. Energy and power requirements can vary from 100 kW to 10 GW over microseconds to seconds [7,8]. Without proper selection and control, ES units may experience high depth of discharge (DoD) which would reduce their capability of responding quickly to fluctuating demands while significantly reducing their lifespans, or state of health (SoH) [9].

In smart grid applications, ES deployment and control has recently gained increased attention [10]. These cases have been two-fold; providing a method to reduce the intermittency associated with renewable energy sources while offering ancillary backup services. The grid-connected hybrid system in [11] demonstrated a combination of the zinc bromide flow battery (FB) and electrochemical supercapacitors (SC) to reduce the voltage and frequency instabilities as a result of variable wind generation. Several vignettes were tested varying the size of the parallel SC bank where the SC handled short variations and the FB handled

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longer variations. Just as ES has been utilized to handle some of the intermittencies associated with generation, their inclusion has been equally as useful in supporting pulsed loads. Pulsed loads are commonplace in military applications, but are present in a wide range of other applications and fields [12].

The aforementioned grid-connected systems can reduce the impacts following a major disturbance or a variance in generation but under islanded or stand-alone cases, system stability will rely solely on the support of ES when MTGs and ATGs reach their generation capacities. In [13], a battery management system scheme is demonstrated to control the power flow in a lithium ion based battery array. The system is tested under both grid-connected and islanded modes of operation. In islanded mode, a battery with an inverter acts as a synchronous generator providing voltage and frequency support. A number of other control strategies have been demonstrated, but have only focused on one type of ES [14–17].

A SPS presents unique challenges in terms of ES deployment, since they are inherently islanded systems. Pulsed load management and mitigation is an emerging topic in the future all-electric SPS. In [18], a 0.25 Hz 36 MW pulsed load is tested on a notional SPS model where case studies were conducted over the use of a dynamic reactive compensator to maintain bus voltages. However, power demands of multiple pulsed loads present a major challenge in terms of design and implementation. The electromagnetic (EM) railgun and EM catapult were investigated in [19] where short-term pulsed loads were tested, both significantly exceeding the available energy from the MTGs when tested independently. ES was proposed as a solution to support both, but was not demonstrated. An extensive review into the impact of multiple pulsed loads on the electric SPS was performed in [20]. EM railgun and free electron laser firing profiles were tested as connected pulsed loads without electrochemical ES, but employ the railgun launcher rotor as flywheel ES. The system proved the current infrastructure could support at least one important pulsed load, but not both.

Investigations have been performed into deploying electrochemical ES as well [21]. In [22], a SC was tested independently with an EM railgun to fill an 800 kA firing pulse. The topology was capable of supplying the pulse but required an enormous 500 F SC. Combinations of ES have offered more realistic solutions [23–26]. In [26], lead acid and sodium sulfide battery banks are simulated in parallel on a SPS to fill a single pulsed load. Each ES bank was installed on a different zonal bus where it was noted that the ES units were able to respond quicker than the MTG to deliver energy. However, hybrid energy storage system (HESS) support has not yet been evaluated on the same bus or in a series configuration. A control topology for a SPS is proposed in [27] where a parallel-configured battery-SC HESS was simulated with respect to a constant and pulsed load. Four operation modes were tested to meet critical and pulsed load demands, but only the voltage recovery period following the pulse was discussed and no investigation was provided into the SC or battery performance. Furthermore, the battery type was not identified.

Typical battery and SC HESS have utilized parallel topologies, however, control of these systems is challenging as a result of the wide voltage operating range of the SC. Without a specialized interfacing converter, the SC terminal voltage would follow that of the battery leaving a significant amount of unutilized energy due to a narrowed operating range [28]. Moreover, a mismatch in the equivalent series resistance of each ES would result in unequal, uncontrolled charging or induce internally circulating currents, a phenomenon which parallel-configured lead acid and lithium ion batteries would also be prone to. In [29], a supervisory energy management controller was developed to effectively split EV load demand between a lithium ion battery and SC in a parallel-configured HESS. A multiobjective optimization procedure accounting for both the battery and SC equivalent models and converter topology was solved using dynamic programming. Using these results, a neural network was trained and deployed on the controller with objectives to preserve the battery SoH and enhance total HESS efficiency.

Although literature has demonstrated the impacts of pulsed loads on SPS, it has been limited to testing of each pulsed load independently. In practicality, a robust system should have the capability to handle multiple pulsed loads under the same period. Multiple pulsed loads can be seen under a multitude of applications from manufacturing facilities to EVs, but for this focus, this will be realized under a SPS. To the best of the authors' knowledge, serving multiple pulsed loads on the SPS has not yet been tested and analyzed.

In order to overcome this challenge, two novel concepts have been established in this paper. First, several series-configured HESS combinations are proposed and tested through utilizing lead acid and lithium ion batteries as well as a SC bank. The performance of each combination is analyzed. Second, following the selection of each series-connected ES, a specialized dispatch control scheme is demonstrated in an effort to replenish some or all of the energy required to serve one of the pulsed loads considering the SoH trade-offs. Coined as "rolling charging," a coordination scheme between the load and charging is applied to the heaviest pulsed load in an effort to recover a portion of the discharged energy. The dynamics of each ES is optimized with respect to their operational constraints as well as best practices to preserve their SoH.

The remainder of this paper is organized as follows: Section II discusses the concept of multi-chemistry ES and discusses the mathematical models for each type used in this study. Section III discusses the equivalent model and theory of integrating HESS. Section IV describes the proposed coordinated control and rolling charging algorithm in detail. The hardware implementation and experimental results are presented in Section V and Section VI concludes this work.

2. Modeling of multiple energy storage types

The following sections describe the model of each electrochemical ES type in-detail. The operational characteristics of each ES play a pivotal role in improving the base case: a traditional series-connected lead acid battery system. In order to demonstrate the limitations of each ES, the performance and operational constraints of each are briefly discussed.

2.1. Lead acid batteries

The lead acid battery can provide seamless, inexpensive energy to serve a load but suffer from a number of drawbacks. First, their lifespan is heavily dependent on the operational current. Numerous experimental charts have been produced recommending the level of discharge current versus that of the nameplate battery capacity to remain close to the 20-h discharge rate (or C/20), but this can be unfeasible when designated as a primary battery. Second, their lifespan is governed by the operational DoD. Consistent deep discharging of the lead acid battery will exponentially reduce its SoH. Third, their response time to an energy demand is slow as a result of a large double layer capacitance, making it inefficient in high frequency pulsed load applications [30].

The lead acid battery can be represented through a model consisting of two parts. The first part models the energy storage portion through the application of a very large capacitor in