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Optimal hybridization and amortized cost study of battery/supercapacitors system under pulsed loads

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ABSTRACT

Hybrid electrical energy storage systems (HESS) show promise for solving the problems and exploiting the benefits of heterogeneous electrical storage systems (ESS). This paper compares the performance of a lead-acid battery/supercapacitors hybrid to that of a battery alone under pulsed loads. Two types of aging protocols, using pulsed and smoothed power, were carried out on VRLA batteries at 40 °C. These protocols typically illustrate a single or hybrid battery's use for an Uninterruptible Power Supply. In HESS, the supercapacitors smooth the power demand applied to the battery, and, when idle, the battery charges the supercapacitors. The same amount of energy is extracted from the battery during both protocols. The experiment indicated that the battery alone performs 150 ten-minute-cycles before reaching the end of its life. In the hybridized battery, the power dissipated was reduced to 36% of that used by the battery alone, and the number of cycles increased by 70%. The use of a hybrid also reduced the battery's capacity fade by 60% and its increase of internal resistance by 83%. Finally, the amortized cost of the hybrid system was 17.6% less than that of the battery alone.

1. Introduction

In order to maintain the quality and reliability of electrical grids and to prevent interruptions, outages and sags, extra power plants are built to generate reserve power to satisfy increasing energy demands and rapid changes in power requirements. These plants can incur additional costs and negative environmental and social consequences. Energy storage systems (ESS) can store excess energy and so limit energy waste. ESS systems also enhance grid availability, reduce the need for additional energy generation and balance supply-demand disparity [1–3]. However, since ESS systems consist of a single type of storage device, they are entailed with many limitations. They do not offer features such as high cycle efficiency, high power and energy storage capacity, low cost, high specific power and energy, and a high cycling lifetime [4].

However, hybrid energy storage systems (HESS) are a promising option for enhancing the performance and longevity of energy storage systems. They consist of various heterogeneous ESS systems that use the complementary properties of each unique ESS element to capitalize the advantages of each and minimize their drawbacks [5,6]. HESS systems that combine more than two power sources with different features are popular in EV/HEV applications [7–11], portable electronics [12,13], renewable energy sources [14–17] and UPS systems [17–22].

There are a multitude of HESS technologies, but the combination of battery and supercapacitors has been the topic of several recent studies. Various applications of battery/supercapacitors hybrids have been presented in recent technical literature. The technological advances in battery manufacturing have permitted very high energy densities, but they often have insufficient power densities for applications that use a large amount of pulsed power. For systems that often experience large power surges, the batteries become the weakest part of the UPS and require regular maintenance and replacement [23]. The current variations cause voltage transients that can be interpreted by the low-voltage detection circuit as a discharged battery, leading to a premature shutdown [24,25]. Furthermore, extracting pulsed power instead of average power from a battery significantly reduces its service life [26]. The pulsed currents generate high RMS values, which heat the battery. This reduces battery cell lifetime, as gassing and, hence, electrolyte loss and grid corrosion are all temperature dependent [25]. Various simulations and experimental studies of active hybrid battery/supercapacitors power source have examined peak power enhancement, discharge cycle life, specific power and energy loss

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Nomenclature

SC, SCs	Supercapacitor and supercapacitors, respectively
SoC	State of Charge
SoH	State of Health defined as the actual capacity divided by the nominal capacity
DoD	Depth of Discharge
ESS	Energy Storage Systems
HESS	Hybrid Energy Storage Systems
RMS current	Root Mean Square of the current
CC–CV	Charging at Constant Current and then at Constant Voltage
P_L	Load power
P_{bat}	Battery power
P_{SC}	Supercapacitor power
W_{SC}	Energy delivered by the supercapacitors during the first half period
E_{SC}	Total supercapacitors energy during a charge/discharge cycle
E_{3000F}	Energy stored in one 3000 F supercapacitor element
U_{n_bat}	Battery nominal voltage
v_{sc}	Instantaneous voltage of one supercapacitor
V_{sci}	Initial voltage of one supercapacitor
V_{scf}	Final voltage of one supercapacitor
τ	Filter time constant
C_{disch}	Battery discharge capacity
C_{charge}	Battery charge capacity
R_{int}	Battery internal resistance after 100 ms
P_{ch}	Power extracted from the battery to recharge the SCs
i_{bat}	Battery current
I_{bat_RMS}	RMS value of the battery current
L_0	Battery alone lifespan under pulsed load at 40 °C
€	Euro

with respect to pulse load profiles [27]. Other studies have proposed new DC/DC converter topologies or control methods to maintain a relatively constant demand on the battery, in order to increase its lifetime [28–30].

For UPS and backup power systems that include generators set where the high weight of lead is not important, valve regulated lead acid (VRLA) batteries are the conventional energy storage choice [21,31]. These batteries are economically attractive and offer the advantages of low initial cost, a mature and well-established recycling technology and good distribution networks [11,32]. However, VRLA batteries cannot bridge interruptions that last more than a few minutes. They can usually provide 5–15 min of backup power before a generator starts and is ready to accept the full load. Even so, VRLA batteries have a high operating cost because of their short service life. They are unsuitable for long runtimes and very sensitive to temperature and pulse load power [21,33].

The UPS application typically operates VRLA batteries at float charge conditions. This leads to corrosion and drying out which cause premature wear on the battery. Furthermore, applications with high pulsating discharge currents progressively deposit a hard layer of lead sulfate on the surface of the battery plate, dramatically reducing its available capacity and leading to battery failure [34]. In summary, many operating conditions can simultaneously contribute to the battery aging process, including small floating currents, high current cycling, partial state of charge cycling, scarce or partial charging and operation at large temperature ranges. It is then very difficult to dissociate from the interacting aging processes to accurately predict a battery's lifetime [35].

Supercapacitors are very suitable for UPS applications. They have the capability to deliver full backup power within only few seconds (up to 20 s) and are highly efficient when used to supply peak power levels. However, SCs are only a good alternative to batteries for short runtimes because of their high price and low specific energy. In [36], SCs/battery hybrid for UPS was proposed. Such a hybrid combines the high power capacity of SCs (up to 10 kW/kg) and the good energy density of VRLA batteries (up to 50 Wh/kg). A hybrid system combining SCs and batteries guarantees short interruptions and uses the SCs and not the battery to stabilize voltage and frequency variations. This significantly extends battery lifetime and reduces battery stresses by reducing the number of discharge/charge cycles and the cost of maintenance. Furthermore, during autonomous operation of the UPS, the load power is filtered by a low-pass filter and the SCs handle peak power demands, diverting high power demands away from the battery. The battery only supplies the smoothed power, and it can recharge the SCs when power demand is low [23,36].

This study compared the degradation of a single VRLA battery to that of a battery combined with supercapacitors under pulsed load power. A single VRLA battery was subjected to two types of aging cycles at 40 °C. In the first aging protocol, the battery alone supplied the full pulsating load power; in the second protocol, the battery in the hybrid system supplied an exponentially filtered power profile. It also recharged the SCs during idle periods, so the same total amount of energy was extracted from the battery in both protocols.

Online UPS technologies typically operate in this way. Despite the complexity of controlling the fully active hybrid due to the two DC/DC converters employed, this hybrid system offers ultimate UPS performance, with flexible operating voltages and strictly-controlled power sharing between the battery and the SCs [24,37]. In this study, the aging and performance of the batteries in both systems were periodically recorded. Battery capacity fade, the drop of its State of Health (SoH) and the increase of its internal resistance were recorded at 25 °C after each 15 ten-minute-cycles over the battery's entire lifetime.

This study's secondary focus was the determination of the optimal filter constant for battery power filtering. The objective was to track the best amortized lifetime cost of the hybrid system, taking into account power dissipation and the cost of the battery but also the cost of the SCs based on the amount of energy that the SCs must supply to relieve battery stress. Finally, the cost effectiveness of the hybrid was compared to that of the battery alone. The capital expenditure (Capex) was calculated based on the initial purchase cost of batteries and SCs [38]. The operating expenditure (Opex), representing the cost of running and maintaining the storage system, was not included in this study, since our study focused only on the lifetime of the storage system and not on the service lifetime of the electrical equipment that uses the HESS. The number of cycles performed by the battery alone and the hybrid enabled us to determine the amortized cost per 100 cycles and also per year for a 500 kVA UPS.

2. Experimental investigation

2.1. Battery specifications

Two pristine batteries, having the same manufacturer, the same design and the same initial specifications, were subjected to two aging protocols, under pulsed and smoothed load profiles. Each