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On battery state estimation algorithms for electric ship applications

George S. Misyris [a,b], Antonios Marinopoulos [a,*,1], Dimitrios I. Doukas [b], Tomas Tengnér [a], Dimitris P. Labridis [b]

[a] ABB Corporate Research, 72178 Västerås, Sweden
[b] School of Electrical and Computer Engineering, Aristotle University of Thessaloniki, P.O. Box 486, 54124, Greece

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ABSTRACT

In the last decade increasing concerns about the environment, financial reasons based on fuel prices and application-specific operational challenges have been driving the development of electric propulsion and hybrid or full-electric ships. The use of battery energy storage systems (BESS), which are suitable for a broad range of ship applications with different requirements, can reduce the use of fossil fuels. In this paper the benefits of an onboard DC grid, as applied by ABB, are briefly presented. The integration of BESS and the challenges for ship applications are also discussed. The focus of this paper is on a parameter identification method for an electric model of a battery and the evaluation and validation of a battery state estimation method, in respect to the accuracy requirements for ship applications.

1. Introduction

Environmental, financial and operational reasons have been driving the development of electric propulsion and hybrid electric ships. Recently, the concept of all electric ships (AES) has been also introduced, due to many benefits, such as flexibility in space and weight allocation, more degrees of freedom in the power system layout, enhanced operating life, increased survivability and maintainability and overall efficiency, etc.[1]. Main drivers behind this are the naval applications [2], which involve special loads, e.g., the pulsed load of electromagnetic aircraft launchers, however other type of vessels also start to become interesting applications for electric ships with energy storage, like ferries [3,4].

The use of battery energy storage systems (BESS), which among others could be also charged by renewable energy sources mostly onshore, may reduce the use of fossil fuels for some ship applications. A broad range of specific applications, like peak shaving, capacity firming, spinning reserve, backup power and pure electric operation etc. are suitable for BESS, however they usually have quite different requirements. Vessel types specifically benefiting from such applications are offshore support vessels, drill rigs, ice breakers, tug boats and shuttle ferries.

For such hybrid or full electric ships, the optimization of the power system's operation relies heavily on the management of the energy storage. This has been already identified as a key issue for the control of the power system in AES [5], and it is for this reason that an accurate state estimation of the BESS is also so important. In specific, fast acting energy storage can compensate the lag of diesel generators and reduce their negative effects on power quality, while for longer time scales, an appropriate BESS could satisfy temporary increases in power demand, avoiding the need to start an additional generator, which would have to operate in partial load with low efficiency. The modular nature of BESS can also be seen as ideal for distributed energy storage, which can increase the reliability and flexibility of the complete power system, comparing to centralized storage, and is also easier to adjust to different types of load variation by reprogramming the inverters' control algorithms [5].

The technology of choice today is the Li-ion battery, which keeps improving continuously [6], while its cost is coming down quickly. The cost per kWh for electric vehicles (EV) batteries dropped by 35% during 2015 alone, according to Bloomberg New Energy Finance [7]. Much of this is driven by the economy of scale when battery manufacturers are ramping up production to meet increased demand from electric vehicles and stationary energy storage, but improvements in energy density is also an important factor. This increased interest in batteries for EVs in combination with environmental and energy issues is reflected to the recent work of a number of researchers [8–11].

* Corresponding author.
E-mail address: antonis.marinopoulos@ieee.org (A. Marinopoulos).
[1] A. Marinopoulos is now employed by the Joint Research Centre of the European Commission, Directorate C – Energy, Transport and Climate, Petten, The Netherlands.

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Depending on the system requirements for a BESS in a marine application stated by power profile, design lifetime, footprint and safety, etc., Li-ion batteries based on lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA) or Li-phosphate (LFP) cathodes and carbon or Li-titanate (LTO) anodes may be chosen. Different battery systems have their respective strengths and weaknesses in terms of cost, charge and discharge rate capabilities, calendric and cyclic lifetimes and safety. That said, most BESS have to be designed with a sufficient initial over-sizing in order to cope with the fade in energy capacity and/or power capability over its lifetime. A marine BESS is typically comprised by one or more parallel strings with a nominal voltage in the range of 700 and 1000 V. Strings are paralleled to meet energy capacity and power capability requirements.

In this paper, an overview of an onboard DC system, as applied by ABB, is briefly presented and its benefits versus AC are shortly discussed. The integration of BESS along with some technical requirements and challenges for marine applications are also mentioned. The focus is on a parameter identification method for a typical battery model, and on a capacity and state-of-charge estimation using a combination of algorithms. The estimation method is validated with experimental results from lab measurements and shown to provide good accuracy. A discussion on the method's challenges to make it robust for demanding ship applications is also done.

2. BESS integration into an onboard DC system

There are many ways to integrate a BESS into the electric power system of a ship, in terms of circuit configuration, hardware interface and control. For example, even though the BESS is usually interfaced to the power distribution grid with its own power converter, it can also be connected directly to the DC-link of the electric propulsion system, eliminating the need for a DC/DC converter, but increasing the size of the frequency converter and the propulsion inverter that have to control the voltage of the DC-link to control the state-of-charge (SOC) of the BESS [12].

In the last years, the onboard DC grid is being adopted for various applications. For example, its advantages versus traditional AC systems regarding dynamic positioning operation of offshore support vessels (OSV) include improved efficiency, optimization of operation and fast ramping connected with the integration of energy storage [13]. In Fig. 1, an onboard DC distribution system including the BESS, as applied by ABB [14], can be seen in high-level detail. The main benefits from including a battery system are the reduction of fuel consumption and emissions, but also the improvement of the dynamic response of the system, compared to a diesel-electric generator, and the increased availability due to the instantaneous availability of energy back-up source.

The onboard DC grid in general provides a highly efficient power distribution system that allows a wide range of sea-faring vessels to cut their fuel consumption, as well as incorporate DC energy sources, such as solar PV panels and fuel cells, and of course BESS. Based on a recent analysis from ABB [14], the implementation of DC grid may reduce the electrical equipment footprint and weight of up to 30% and the fuel consumption and emissions by 20%. In fact, tests made in Dina Star, an offshore platform supply vessel outfitted with ABB's onboard DC grid, in 2014, identified a reduction of specific fuel oil consumption of up to 27% [15]. It has to be noted, that these improvements were the result of the onboard DC grid only, not taking into consideration any extra benefit from BESS integration.

BESS enabled vessels may be highly dependent on their energy storage systems to meet backup power requirements, dynamic performance and overall power system stability. Consequently, it is of key importance to ensure that the BESS at every moment have the capability to meet even the worst case scenarios. This is achieved by state estimation, i.e., SOC and state-of-health (SOH) estimation. Accurate battery state estimation is important since not only does it reflect the battery performance but it also enables appropriate, application-driven control actions. Moreover, information from the state estimation, both SOC and SOH, can be integrated into the onboard diagnostics and maintenance system of the ship. State estimation techniques can be broadly categorized in: direct measurement methods, book-keeping estimation, adaptive systems and hybrid methods.

3. Battery cell modeling

In this section, the battery cell modeling and the main phenomena that need to be taken into account for an accurate model, i.e., the relationship between the open circuit voltage (OCV) and the SOC, the hysteresis effect, the temperature and the charge/discharge current rate, and the capacity degradation, are described. In general and in its simplest form, a battery model can be expressed as a capacitor, whose capacity is equal to the real capacity of the battery. Considering the internal resistance of the battery, a resistor is added in series with the capacitor to simulate the instant drop of the battery voltage, after a current pulse. The capacitor and the resistance simulate the steady state of the battery. In order to describe the dynamic response of the battery (relaxation effect) after a current pulse, series connected RC branch(es) is/are used. A higher number of RC branches can give higher accuracy to the battery model, but also increases the complexity of the battery model. The efficient number of the RC branches, considering the complexity and the accuracy is regarded to be two [16], but in this work to make the model simpler only one RC branch, which gives also adequate results [17], is used. The choice of the number of RC branches is a trade-off between accuracy and complexity. Complexity refers to the computational effort that the algorithms add to the system operation, especially for an online application, which is also translated into increased computational burden as well as cost. Moreover, the proposed ECM is mostly dependent on the OCV–SOV curve and especially within the area of operation (0.1–0.9 SOC), a fact that makes it rather generic and universal and not only for Li-ion batteries. Consequently, considering the additional complexity, especially for online applications, to use a second (or more) RC branch for achieving a rather small accuracy improvement, the modeling with only 1 RC branch for this kind of batteries and applications is justified as more appropriate.

3.1. OCV–SOC relationship

The OCV has a non-linear relationship with the SOC and this non-linearity makes the battery parameter identification and the state of charge estimation rather challenging in terms of the stability and performance of the battery model. Therefore, although for modeling purposes the relationship between the OCV and the SOC could be considered as static, independent of the battery aging and the current rate, it can be shown that in reality it changes for different temperatures, especially below 0 °C. In order to deal with this non-linearity, the average OCV–SOC curve is divided into linear segments. In an approach similar to [18], to find the appropriate number of linear segments the first and second derivative of the OCV versus SOC have been used. The analysis resulted in 18 linear segments i.e., 10 linear segments from 0 to 0.2 of SOC and eight segments from 0.2 to 1.0 of SOC. This non-uniform distribution of linear segments across the OCV–SOC curve has been performed in order to deal with the high non-linearity of the OCV–SOC relationship observed for SOC levels below 0.2. Based on the fact that for normal C-rates the operation point moves "slowly" along the