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End-to-end system level modeling and simulation for medium-voltage DC electric ship power systems

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Abstract

Dynamic simulation is critical for electrical ship studies as it obtains the necessary information to capture and characterize system performance over the range of system operations and dynamic events such as disturbances or contingencies. However, modeling and simulation of the interactive electrical and mechanical dynamics involves setting up and solving system equations in time-domain that is typically time consuming and computationally expensive. Accurate assessment of system dynamic behaviors of interest without excessive computational overhead has become a serious concern and challenge for practical application of electrical ship design, analysis, optimization and control. This paper aims to develop a systematic approach to classify the sophisticated dynamic phenomenon encountered in electrical ship modeling and simulation practices based on the design intention and the time scale of interest. Then a novel, comprehensive, coherent, and end-to-end mathematical modeling and simulation approach has been developed for the latest Medium Voltage Direct Current (MVDC) Shipboard Power System (SPS) with the objective to effectively and efficiently capture the system behavior for ship-wide system-level studies. The accuracy and computation efficiency of the proposed approach has been evaluated and validated within the time frame of interest in the cast studies. The significance and the potential application of the proposed modeling and simulation approach are also discussed.

Keywords: Naval electric systems; Medium-voltage DC; Modeling and simulation; Shipboard power systems; Integrated power systems

1. Introduction

The onboard power system has become the most critical infrastructure for the next-generation naval warships which are envisioned to be fully electricity driven and have a power demand of up to 100 MW (Ericsen et al., 2006). In order to meet such critical power requirements, the Integrated Power System (IPS) that directly supplies power to propulsion and other onboard service loads is proposed as a promising solution to create a new paradigm for shipboard electrical power generation, conversion and distribution (Amy, 2002; Doerry, 2009). Among different distribution strategies that are currently available for IPS, power-electronic based DC distribution is considered the most practical means for advantages such as weight and size reduction, better power density, and improved reliability (Ali et al., 2011).

Time-domain simulation has been used extensively for the planning, design, operation and control of DC shipboard power system (IEEE Std 1709-2010, 2010; Langston et al., 2012; Zhang et al., 2015). It aims to capture all relevant system conditions and determine the time-domain trajectory when the system is subject to disturbances of various types such as device outages, equipment damages and failures, and faults. A set of first-order Differential-Algebraic Equations (DAE) needs to be solved to approximate the ship-wide interactions of on-board dynamic components and the distribution network.

Like its terrestrial counterpart, electric ship power system generally contains different classes of phenomenon with

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different physical origins and occurs within different time scales. Especially with the heavy employment of power electronic converters, the coexistence of closely coupled electrical and mechanical equipment on the ship, and the widely varying characteristics of onboard loads from continuous duty loads such as propellers to intermittent loads such as pulsed laser weapons, it is a well accepted fact that dynamic phenomenon encountered in electric ship power system studies can range over various time scales. Therefore there does not exist an universal model for different types of dynamic studies. The level of fidelity and the choice of solution method directly depend on the nature of the phenomena and the design purpose for the application.

To set the stage of the rest of the paper, the specific types of the studies that we consider in this paper and their time frames of interest need to be specified. It is commonly suggest that time-domain simulations of SPS can be categorized using three system layers based on the response time for the intended studies: Ericsen et al. (2006); Qi (2006).

- *Operational level*: The response time is on the order of minutes. Studies on this level mainly involves long-term stability studies involving slower acting equipment, and ship operational and mission studies where only steady-state operating conditions are of interest.
- *System level*: The response time is on the order of 10 ms. It covers the essential electromechanical dynamics of the system with a time step in the range of 0.1 ms or less. System-level analysis is directed towards: 1) analysis of the interactive system-wide electro-mechanical dynamics and post-disturbance analysis; 2) the early-stage design and exploration iterations where the fully detailed system specifications are not yet specified; and 3) the optimization design process where system behaviors need to be repeatedly evaluated under a variety of conditions, such as ship-wide power management system design.
- *Waveform level*: The response time is in the range of microseconds and milliseconds, depending on converter frequency. Analyses on this level require computational of the detailed electromagnetic transients with a time step of microseconds or less. Such practices include the design of power electronic apparatus, fault protections, insulation coordination and gating signal generation.

Waveform-level models have been traditionally used in previous literature to approximate the system behaviors when time-domain simulation is required (Andrus, 2010; Bash et al., 2009; Lahiri, 2011). The major limitations of waveform-level models are: waveform-level MVDC SPS models are built to maintain extremely high fidelity to represent the physical system behavior. However, due to the large number of fast switching power electronic apparatus within the DC system, the waveform-level models suffers from slow simulation speed which makes it inapplicable and computationally expensive to be used for system-level analysis. Meanwhile the detailed switching actions make the system discontinuous which adds significant complexity to convert the system to linearized form which is common for linear-form based system-level analysis such as small-signal stability analysis (Chiniforoosh et al., 2010).

In the case of model formulation for system-level analysis, currently very limited amount of work have been reported. In Schmitt (2010), the author develops the system-level modeling strategy focusing on the evaluation of propeller and maneuvering dynamics while low order models are utilized for the electrical components. In Doktorcik (2011), the reduced-order model was developed around the specific requirements of power management, thus a lot of domain specific assumptions are made and the method itself doesn't provide a generic solution to other types of system analysis. In Zahedi and Norum (2013), the author develops the model focusing on the modeling and simulation of power electronic devices. Reduced-order modeling for AC shipboard power system has been conducted in Abdelwahed et al. (2013), however, the modeling approach for the latest DC distribution system, which is fundamentally different than the conventional AC-based distribution structure, has not been discussed. Other disadvantages of the existing literature include: 1) Empirical approaches have been commonly adopted to simplify the model development, however, due to the conservative nature of data-fitting based methods, the applicability and adaptivity of empirical approaches are in question. 2) The trade-offs between computational performance and model fidelity have not been systematically studied and reported. 3) Little effort has been made towards adjusting the modeling formulation to accommodate the specific needs for system-level studies.

This paper attempts to address the limitations summarized above. The main objective of this paper is to set forth a mathematical modeling and simulation approach to specifically address the requirements of system-level studies for the MVDC SPS. The proposed model is highly representative and includes all the essential electromechanical dynamics associated with synchronous generator-rectifier system, governors and voltage regulators, gas turbine and propeller, induction motor drive, storage and filter elements, service loads, ship hydrodynamics and their closely-coupled interactions. At the same time, the computational efficiency for the simulation has been significantly improved to enable the ability to design and analyze SPS and other similar islanded electrical power systems with close electrical proximity and intensive dynamic behaviors.

Comparing with the existing SPS modeling and simulation approaches, the novelty and intellectual merits of this paper can be summarized as:

1. This paper presents a MVDC SPS model that offers true end-to-end functionality. As a model-based approach, it provides a high degree of similarities in topologies, specifications and functionalities to the waveform-level model and physical testbed. Thus it is realistic and comprehensive for existing and future time-domain response based electric ship related studies.
2. This paper offers a novel modeling approach as well as a simulation program that has been tailored specifically for