Guidelines for the Specification of Models to be Used in Design-Oriented Simulations

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Abstract
Simulation-based design requires models at many levels of detail. In the early stages, models must approximate the coarse behavior of the system across many domains – power, efficiency, cost, size, and weight. In later stages, the models must represent the system with increasing accuracy – including dynamic performance, controllability, and other more-subtle manifestations. In this work, we focus on specification of the models for a simulation-based design of ship power systems. We address the issues of levels of detail in models, definition of model ports to support substitution of models at increasing levels of detail, and the application of multiple analyses to one set of simulation models. Eventually, we tackle very detailed issues such as insulation coordination and grounding scheme that are not at all important in the conceptual stages of design.

1. INTRODUCTION
Electric ship power systems have been a major research topic for many years [1-7]. The design of an effective ship power system depends on a suitable selection and arrangement of system components that satisfy all load requirements in the environment and conditions in which they operate. But it is challenging to select and model the components of the ship power systems. At the early stage, the models should relate not only, say, electrical performance, but also mass, size, cost, efficiency, etc. This paper addresses those challenging issues that arise from the use of simulation-based design of electric ship power systems. The work focuses on methods that start with simple models (say, power flow models, weight models, cost models), and then gradually increases the level of details (say, the time response models and dynamic response models). Also, at the early stages, generic models may be used, while in later stages, models of very specific equipment from one or more manufacturers may be needed.

While the basic issues of ship power systems are available in the literature, this article discusses the challenging issues with a view to developing guidelines to model and simulate a ship power system in detail, and thus helps the reader understand the level of information or knowledge required to model and simulate the ship system.

The organization of this paper is as follows. In section 2, the basic configuration of the ship power system is described. In section 3, difficulties associated with modeling of ship power system components are discussed. In section 4, model fidelity and a large scale simulation approach is discussed. In section 5, some examples regarding the challenging issues of ship power system are discussed. In section 6, the importance of including insulation coordination and grounding schemes in shipboard power system modeling and simulation are described. And finally section 7 concludes this work.

2. BASIC CONFIGURATION OF SHIP POWER SYSTEM
Figure 1 shows the one-line diagram of a notional shipboard integrated power system (IPS). At this level, the model represents the following main systems:- the power generation system, the ship propulsion system, and a zonal load distribution system. The main power distribution bus might distribute DC power, AC power (60 Hz), or higher-frequency AC power (e.g. 240 Hz). A medium voltage (MV) bus is supplied by two main generators (main PGM1 and PGM2) and two auxiliary generators (auxiliary PGM1 and PGM2). The bus
supplies two propulsion motors (PM), a high power pulsed load, a special load, and the ship’s service loads which are distributed in zones. The propulsion motors are fed through variable speed drives (VSD). Also, an energy storage device is connected to the MV subsystem.

3. CHALLENGES IN COMPONENTS SELECTION, MODELING, AND SIMULATION OF SHIP POWER SYSTEMS

It is challenging to select and model the components of ship power systems. Before going to the detailed discussion of the challenging issues of ship system modeling, let us consider an abstracted example system shown in Figure 2. The figure depicts the orders of resolutions in terms of space, time, and physical process required for development of any system models. At an early stage, a system might need a very simple model with almost zero resolution (i.e. lying near the origin of time resolution, space resolution, and physics resolution), but with increasing maturity of the system design higher levels of model resolution are needed. And with the increasing and detailed levels of model development, complexity and difficulty would also increase in selecting the system parameters, components, etc.

Similar to the case of the above abstracted example system, there are complexities and challenging issues that might arise from the components selection and their proper modeling during the simulation of ship power systems. And the level of challenges and difficulties increase with the level of detailed model requirements. For example, in order to analyze the cost model, weight model, efficiency model, load flow model, etc., for the ship power system shown in Figure 1, simple models of the system components might be sufficient. However, for higher level of studies, say, transient and dynamic response analyses, some components in the system need to be modeled in more detail, although some of the components might have the same modeling as the case of simple analyses. Again, for other type of higher level studies, some components and control algorithms in the system might need to be modeled in different ways and in much more augmented levels. But the gradually developed higher level system models should be consistent with the original system so that the system connectivity is maintained through the increasing levels of detail. And here are the main challenges and difficulties that arise from modeling, control algorithm development, components selection, etc., depending on the higher level of studies needed for ship power systems.
4. MODEL FIDELITY AND LARGE-SCALE SIMULATION

Shipboard power systems are tightly coupled electrical systems due, in part, to the small impedances of short electrical cables between sub-systems. As a result, capturing the propagation of electrical disturbances throughout an integrated power system (IPS) requires the use of a ship-wide, or large-scale, simulation model. The challenges associated with constructing these “system-level models” are directly related to the outcomes the simulation engineer desires from them. This is where the topic of “model fidelity” comes into the discussion of electric ship modeling and simulation (M&S). If the objective of the simulation is to predict steady-state voltage and current levels at all electrical nodes in a ship power system, a load-flow analysis of a system model comprised of average-value power electronic (PE) converters provides sufficient fidelity.

If the objective is to predict a generator set’s (genset) electrical and mechanical responses to a sudden loss of loading, then the only detailed “high fidelity” model required in the simulation would be that of the generator-excitation-prime mover under study. The rest of the ship power system could be represented by aggregated loads and average-value PE models. This is because this study is addressing the process by which the electrical disturbance caused by the loss of a pump load in one zone, for example, propagates through the electrical and controls sub-systems of the IPS to the genset under study in another zone.

A simulation requiring higher fidelity sub-system models would involve the study of an IPS protection system’s response to an electrical fault on the main power bus (either AC or DC). The level of model fidelity required in this case includes the following:

1. Switching models for the valve groups of AC/DC converters supplying power to the bus (in the case of a DC power system),
2. Electrical representation of the output filter characteristics of the rectifier referred to above,
3. Protection relay trip response curves, trip times, and coordination logic,
4. Transformers modeled with saturation, and
5. IPS configuration/reconfiguration state maps.

An example of a true “high fidelity” power system simulation is the power quality (PQ) studies of AC power systems that typically include an assessment of the total harmonic distortion (THD) of bus voltage and current due to the harmonics generated by PE converters. Electromagnetic transient (EMT) computer programs, such as EMTP, PSCAD/EMTDC, VTB, Simulink\textsuperscript{\textregistered}, and RSCAD/RTDS are used to capture these high frequency effects. Steurer, et. al. [8] showed the ship-wide PQ impact of pulsed load operation on the IPS of a multi-zonal, notional destroyer. The ship system model they used was run on a Real-time Digital Simulator (RTDS) [9] in non-real-time with a 5 μs time-step. All 18 PE converters of a five-zone notional destroyer IPS were represented with valve switching models. Because the RTDS employs more than four hundred digital signal processors (DSPs) operating in parallel, an accurate high frequency response to the pulsed load’s operation was computed for every zone of the ship, with a typical run execution time of 20 minutes.

These examples demonstrate the importance of carefully defining the objectives of any large-scale ship power system simulation model in the light of achievable model fidelity.

5. EXAMPLE SYSTEMS

In the following sections, examples describing complexity and challenges associated with gas turbine and generator modeling are given.

5.1. Modeling Gas Turbines

Gas turbine engines are complex thermodynamic machines that convert fluid and fuel energy into mechanical energy. They come in various topologies that include single-shaft, twin-shaft, multiple-spools, centrifugal and axial flow compressors, simple and advanced thermodynamic cycles, and different combustion chamber types. A single-shaft, simple-cycle gas turbine schematic, and an advanced-cycle, twin-shaft gas turbine schematic are shown in Figures 3 and 4, respectively.

Because of these various topologies and the thermodynamic processes involved, modeling of the gas turbines proved to be a very challenging problem. To further illustrate this complexity, consider a
simple-cycle, single-shaft gas turbine, as shown in Figure 3. For this turbine, a simplified relationship between the gas turbine shaft speed, $\omega$, and output power, $W_{out}$, was derived through an analysis of various thermodynamic and mechanical processes involved [10]-[11]. This relationship is given by the equation:

$$\omega = \sqrt{\frac{(M^2 \gamma RT - V^2)}{\rho \pi (1 - \zeta^2)}} W_{out}$$

where $w_{max}$ is the maximum specific work, obtained for a given compression ratio $P_{02}/P_{01}$, and $T$, $V$ and $\rho$ are the working fluid (air) temperature, velocity, and density, respectively; and $\zeta$ is the ratio of the compressor blades’ inner and outer radii, $M$ represents the Mach number, and $R$ and $\gamma$ are gas constants.

Figure 3. Simple-cycle, single-shaft gas engine

The important result is that the shaft speed and power relation includes a dependence on thermodynamic quantities (temperature and fluid velocity) as well as gas turbine geometric parameters (blades’ radii). Consequently, for a dynamic analysis that involves a gas turbine where its shaft speed is changing due to external disturbances, one needs to know the turbine’s geometric parameters as well as the values of various thermodynamic quantities involved. In other words, a thermodynamic-based model and gas turbine geometric parameters are needed to properly model a given gas turbine for system stability studies. As a result, a single generic gas turbine model that applies to all gas turbine types and cycles is not realistic.

Another approach to modeling gas turbines is often used but not always justified. It is a simpler approach but has limitations as well. Early in the 1980’s General Electric (GE) provided a simple gas turbine model for use in power system stability studies. This model, described in a published paper [12], is based on transfer functions and applies to some of GE’s simple-cycle, single-shaft gas turbines. The rotor time constant and other time delays associated with combustion reaction time, the compressor discharge volume, and gas transport from the combustor through the turbine were provided for several GE turbines along with other relevant parameters needed in the model. Figure 5 shows the model lay-out [12].

In principle, this type of gas turbine representation for power system stability studies is reasonable and can be applied for single-shaft and twin-shaft gas turbines. However, realistic time constants and other turbine parameters are needed. A major problem with this approach is that manufacturers do not provide these data to their customers. A solution to this problem is to conduct tests on these machines and measure the relevant parameters whenever it is possible to do so. Otherwise, gas turbine parameters can be assumed for modeling purposes, with the assumptions based on limited published data found in papers describing test results for specific machines.

This inherent complexity associated with gas turbine modeling is indeed a major challenge in power system studies. However, research to develop simpler but relevant thermodynamic-based and transfer function-based gas turbine models that can be used in power system dynamic analyses is continuing.

Figure 4. Twin-shaft, advanced-cycle, gas turbine engine

Figure 5. Gas turbine model for single-shaft, simple cycle gas turbines
5.2. Modeling of Synchronous Generators

Modeling of high-power turbo-generators also presents challenges, although not as severe as those for gas turbines. The mathematical representation of synchronous generators for dynamic analyses is generally well understood, but there are variances in machine types and machine designs that should be carefully considered before applying a given model. Wound-field synchronous generators with silent or cylindrical rotors, permanent-magnet synchronous generators with rotor bandings and large magnetic air-gaps, and superconducting machines with metallic rotor shields will have different eddy-current structures in the rotor and should be modeled appropriately.

The simplest representation of the effects of induced eddy-current in the rotor is through equivalent damper windings in the rotor frame. For some machines, a single damper winding in the d-axis and a single-damper winding in the q-axis are adequate, but in other machines additional windings may be needed for a more accurate representation.

What model should one use and what are the needed machine parameters? In general, a single winding damper in each axis is used for salient-pole rotors while a single damper in the d-axis and two damsers in the q-axis are used for cylindrical rotors such as those found in turbo-generators. Ultimately, the manufacturer should provide this information along with the various parameters since they are usually calculated during the design process and often verified through testing.

To illustrate the complexity associated with modeling electric machines and the various parameters that are needed for proper descriptions, circuits representing a synchronous generator model with a single damper winding in each axis are shown in Figure 6.

As can be seen in the model circuits, the parameters needed for modeling synchronous machines are various resistances, inductances, and mutual inductances. These parameters are often defined in terms of reactances and time constants which are commonly used by industry. Definitions of these parameters as well as recommendations in modeling and testing procedures can be found in IEEE Standards 1100-2002 and IEEE Standards 115-1995.

As in the case for gas turbines, manufacturers are sometimes reluctant to provide these machine parameters, especially for machines that include proprietary technology such as high-speed machines, superconducting machines, and some permanent-magnet machines. In this situation one has to consider the possibility of measuring these parameters or assume typical parameter values until actual data become available.

![Figure 6. Synchronous generator representative circuit with a single damper winding in each axis](image)

6. INSULATION COORDINATION AND GROUNDING SCHEMES

One important reason for the simulation of shipboard power systems is to evaluate insulation coordination. This is of particular significance because of low damping characteristics of a power system based on short cables. In such systems, the level of transient overvoltage is considerably influenced by reflection and superposition of travelling waves. In order to obtain trustworthy results, each component in the simulation needs to be represented to a level of detail that yields results that are accurate on the time scale of electromagnetic propagation along cables of interest. For cables having scale roughly 10 to 100 meters, this corresponds to time resolutions well below 1 μs. This is substantially more stringent than the time resolution required for transient analysis of 60 Hz power waveforms, and many orders more stringent than the time resolution for power flow studies. The choice of the appropriate type of model, as well as the scope of application of each component in the simulation, needs to be scrutinized and respected. Furthermore, the accuracy of parameterization of each component needs verification. A sensitivity analysis may help focus on the elements of highest importance.

Thus far, models for the cables and the diodes have been studied. The cable model should be able to correctly simulate the phenomenon of propagating waves. A distributed parameter line model is proposed, incorporating the frequency dependence of parameters: capacitance and inductance per unit length, mutual coupling, conduction losses, dielectric losses, and skin effect.

Software packages for the simulation of power systems usually incorporate rather simple diode models in order to reduce the necessary computation effort. These diode models often consist of a resistor with two different values of resistance according to
the respective state: a low resistance while conducting and a high resistance during blocking. In general, these models are static but allow adding a snubber circuit (capacitor and resistor) in parallel to the diode. This snubber circuit is not meant to cope with the dynamic behavior of the diode, but to represent additional components to reduce the rate of change of voltage across the diode. Preliminary results from an ongoing study about high-frequency oscillations during diode switching in a rectifier circuit show that such elementary models are not always appropriate for every kind of circuit or problem to be studied. In some cases, an additional capacitor in parallel to the diode can simulate the effect of stored space charge in the junction during the recovery transition.

Another reason for the simulation of shipboard power systems is to determine a suitable grounding scheme. The main goals of a grounding scheme are to provide personnel safety and operability under single phase to ground faults. Other aspects that factor into the selection of a grounding scheme are overvoltage protection and magnitude of single-phase-to-ground fault currents. Grounding schemes in AC systems have been established and are documented in both standards and technical publications [13]. However, for MVDC systems, this is not the case. In such systems there will be a collection of different frequencies arising from the source generator, the converters and the propulsion drive that will create multi-frequency fault currents. Also MVDC system will be vulnerable to system wide voltage offsets as well as overvoltages during single-phase-to-ground faults. Finally, it is important to determine the impact of the system parasitic elements (EMI filters, capacitances to ground, etc.) in order to account for magnitudes of the expected overvoltages and fault currents. A study we are currently conducting will analyze the impact of different grounding schemes on the system overvoltages and ground current during single-phase-to-ground faults. Similar to insulation coordination, the components of the simulation model used for this study will be carefully validated. These models need to account for the high frequency components expected to be present during fault occurrences. Recommendations based on the results of this study will help select an appropriate grounding scheme for a MVDC shipboard power system.

7. CONCLUSION
This work focuses on specification of the models for a simulation-based design of ship power systems. We address the issues of levels of detail in models, definition of model ports to support substitution of models at increasing levels of detail, and the application of multiple analyses to one set of simulation models. The insulation coordination phenomenon and grounding scheme are considered for the simulation of a ship power system. The article benefits and helps the reader understand the level of information or knowledge required to accurately model and then to simulate the ship power system.

References


Biography

Mohd. Hasan Ali received his Ph.D. Degree in Electrical and Electronic Engineering from Kitami Institute of Technology, Japan, in 2004. He served as a lecturer in EEE dept. of RUET, Bangladesh since 1995 to 2004, and also became an assistant professor in the same university in 2004. Dr. Ali was a Postdoctoral Research Fellow under the Japan Society for the Promotion of Science (JSPS) Program at the Kitami Institute of Technology, Japan, since November 2004 to January 2007. He also worked as a Research Professor in Electrical Engineering Department of Changwon National University, South Korea since February 2007 to December 2007. Also, he was a Postdoctoral Research Fellow with the Electrical and Computer Engineering Department of Ryerson University, Canada, from January 2008 to June 2009. Currently he is working as a Research Assistant Professor at the Electrical Engineering Department, University of South Carolina, USA. His main field of interest includes advanced power systems, grid-connected power electronics, electrical machines and motor drives, renewable energy systems, energy storage systems, and FACTS.

Roger A. Dougal received his Ph.D. in electrical engineering from Texas Tech. University, Lubbock, in 1983. He is currently the Thomas Gregory Professor of Electrical Engineering at the University of South Carolina, where he leads the Power and Energy Systems group. He is a Director of the Electric Ship R&D Consortium, which is developing electric power technologies for the next generation of electric ships, he is co-director of the NSF Industry/University Cooperative Research Center for Grid-connected Advanced Power Electronic Systems, and he leads development of the Virtual Test Bed --- a computational environment for simulation-based design and virtual prototyping of dynamic, multidisciplinary systems. His research interests include power electronics, hybrid power sources, and simulation methods.

Michael “Mischa” Steurer received a Master of Electrical Engineering in 1995 from the Vienna University of Technology, Austria, and his Ph.D. in Technical Science in 2001 from the Swiss Federal Institute of Technology Zurich, Switzerland. Since then, Dr. Steurer leads the power systems group at the Florida State University (FSU) Center for Advanced Power Systems (CAPS) where he focuses on hardware-in-the-loop real-time simulation and modeling of integrated power systems for all-electric ships and future terrestrial power systems. He is a senior member of the IEEE and a member of CIGRE. Dr. Steurer is chairman of the IEEE Task Force on “Fault Current Limiter Testing”, and contributes to several IEEE working groups and one CIGRE working group. Dr. Steurer has authored and co-authored more than 20 peer reviewed technical papers in various areas of electric power apparatus and their system interactions.

Lukas Graber was born in Basel, Switzerland, in 1976. He received the M.Sc. degree in electrical engineering (Dipl. El.-Ing. ETH) and the degree of doctor of science from ETH Zurich in 2002 and 2010, respectively. From 2002 until 2004 he was project leader with Technocon AG, Basel, developing frequency converters for wind power application. From 2004 until 2009 he was assistant at ETH Zurich where he developed algorithms for SF6 leakage detection in Gas Insulated Switchgear. Currently, he is a post doctoral research associate with the Center for Advanced Power Systems at Florida State University, working on insulation coordination and grounding of DC power systems.

John Ciezki is an Associate Professor in the Electrical & Computer Engineering Department at the United States Naval Academy. He has been on the faculty at the Academy for 8 years following 8.5 years serving on the faculty at the Naval Postgraduate School in Monterey, California. Professor Ciezki received his B.S.E.E., M.S.E.E., and Ph.D. from Purdue University in 1988, 1990, and 1993, respectively. His research work has focused on various Department of Defense power system problems. His current research work deals with dc-de converter power density and shipboard grounding strategies.

Michael Andrus received a B.S.E.E. degree from Virginia Polytechnic Institute and State University in 1975. He is an Associate in Research at the Florida
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**Diomar Infante** was born in Bayamo, Cuba, in 1987. He received his B.Sc. degree in electrical engineering from Florida State University in 2009. He is currently working towards a M.Sc. degree at the same institution with prospective graduation date end of this year. He currently holds a graduate research position with Center for Advanced Power System (CAPS). His research interests include grounding schemes for MVDC power systems and design of computer experiments.

**A. Ouroua** is a research associate at the University of Texas, Center for Electromechanics where he works as an analyst of electromechanical systems. He holds a PhD degree in physics from the University of Texas at Austin.

**Robert E. Hebner** is the Director of the Center for Electromechanics at the University of Texas at Austin. The Center develops advanced energy technology and teams with companies to get the technology to market. Previously, he was acting Director of NIST with an annual budget of about $750 million. He worked in OMB on the technology portions of the Administration’s 1990 budget and at DARPA to advance semiconductor manufacturing. He has extensive experience in measurement systems needed to support global trade and in developing government technology programs to stimulate the economy. He is a fellow of the IEEE.

**Damon Weeks, MSEE**, has 25 years experience in prototype development, 15 years experience in development and testing of advanced transportation technologies. Mr. Weeks joined UT-CEM as a full time engineer in 1985. He is Lead Systems Engineer for the Electric Vehicle (EV) program, where he assists with proposals, prepares and manages budgets and schedules, leads technical research efforts, directs CEM staff and consulting engineers, manages subcontractors and outside vendors, interfaces with sponsors, and provides technical guidance to undergraduate and graduate students. Mr. Weeks holds two patents and is author or co-author on 28 technical papers.