Project: Development of Capability to Model Ship Power Systems

Project Completion: 2014

Output: Modeling approaches for power systems for electric warships and performance predictions in relevant scenarios

Outcome: Navy had confidence in the support modeling needed to design and construct future ships, including emerging concepts like an energy magazine.

Project Motivation: The ESRDC research team was convinced that emerging modeling capability could support the development of more capable and less costly warships, but the documentation of the capability was not available. This project provided a foundation for more targeted approaches, such as S3D.

There were two significant outputs from this investigation. The first was the development of the ESRDC models for ship power systems operating at dc, 60 Hz and 240 Hz. Three different frequencies were studied because there was insufficient information available to select the best. The fundamental topology for this research is shown in Figure 1. This research demonstrated that all frequencies could be modeled and would operate successfully in an electric ship. Furthermore, it provided guidance in the choice of operating frequencies, as it permitted a direct comparison of components and, thus, of size and weight.

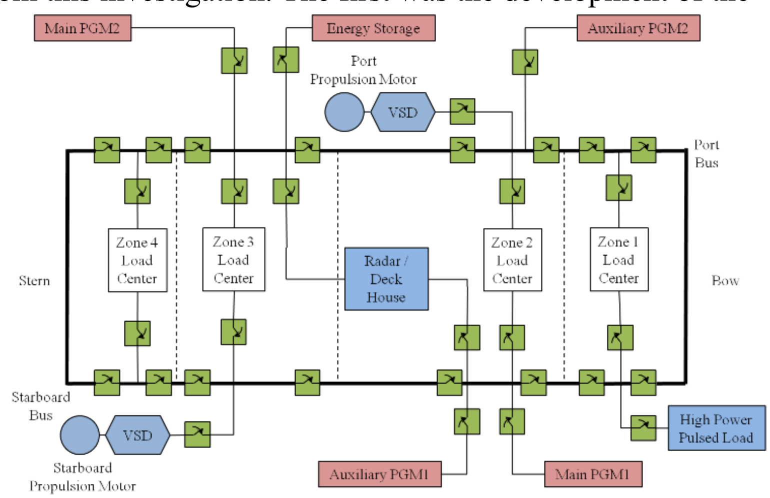


Figure 2: Topology for ship power system modeling.

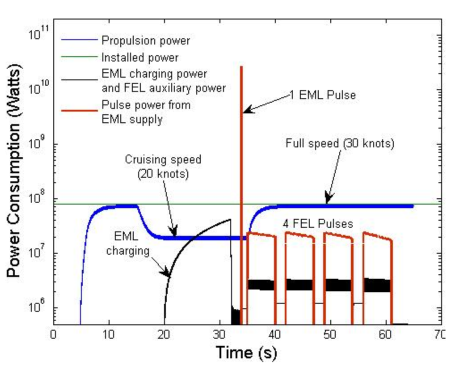


Figure 1: Power consumption from controlled propulsion, electromagnetic launch and laser firing.

The second was the first research documenting the performance of a single storage system that provided power to an electromagnetic gun and high power laser to permit both propulsion and other high power actions. Typical information generated from modeling is shown in Figure 2. The scenario studied in Figure 2 had the ship coming up to cruising power, firing an electromagnetic gun, being detected, firing the laser defensively, and maneuvering at maximum speed. This scenario was developed in collaboration with ESRDC collaborators at the Naval Postgraduate School. This was the first simulation of the multiple use of high power storage on a naval ship, and as such, foreshadowed the current interest in an energy magazine. In addition, it was demonstrated that the storage system could be used to improve power quality at times when the electromagnetic gun and the laser are not needed.

An important part of the project was the development of the modeling capability that led to these research outputs. The initial simpler topology that was used to develop and demonstrate capability is shown in Figure 3. This model, albeit simpler than those used in later work, was important because it includes most of the key components in a realistic topology. This model was initially solved in Matlab/Simulink, a commercial solver. To address concerns about the effectiveness of commercial codes, the same ship system was modeled in three appropriate computer programs. As expected, the three provided the information within the expected uncertainty of the process. Matlab/Simulink was selected for the preponderance of this work at the request of a committee representing the ship yards. Since it appeared that a range of commercial codes were applicable, they preferred that Matlab/Simulink be used when possible because it was familiar to nearly all of their engineers.

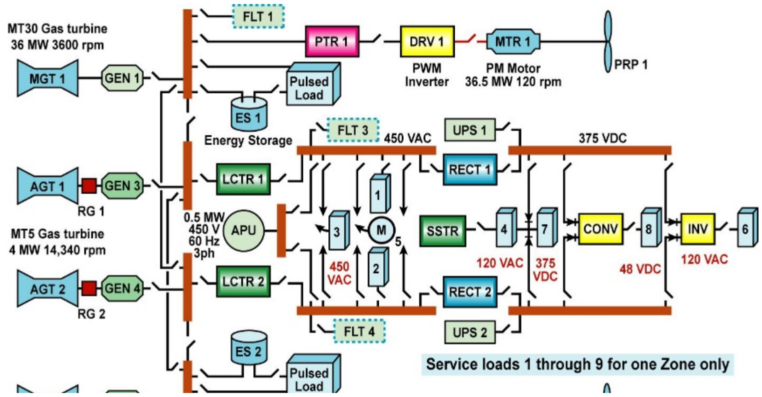


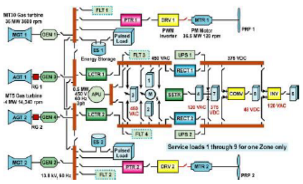
Figure 3: Initial system used to develop and demonstrate modeling capability.

Project Extent: This project involved researchers from four ESRDC member institutions as well as the Naval Postgraduate School and is documented in ten technical papers and reports.

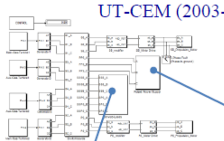
Technical Point of Contact: Dr. A. Ouroua, a.ouroua@cem.utexas.edu

Modeling and Simulation of Electric Ship Power Systems (1/2)

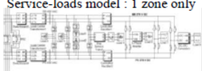
INITIAL DEFINITION OF ESRDC NOTIONAL (DD) ELECTRIC SHIP POWER SYSTEM (SYNTEK ~2003)



Initial Model Implementation in Matlab\Simulink UT-CEM (2003-2004)



Waveform-level Matlab\Simulink model using commercial pre-programmed component models.

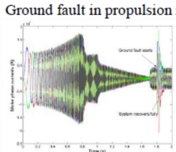


Service-loads model : 1 zone only

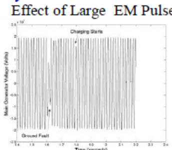
Initial EM gun power supply model

Initial Analyses

Ground fault in propulsion motor



Effect of Large EM Pulses



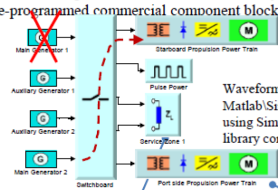
Computer simulation time to complete 10-second-long analysis (2004-desktop) ~ 48 HOURS

Publication

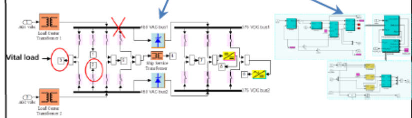
J. Beno, A. Ouroua, and M. Flynn, "Effect of EM weapons requirements on the electric ship power system," presented at the Engine as a Weapon Symposium, Bristol, UK, 2004.

POWER MANAGEMENT ANALYSIS (2005-2006)

To improve simulation time: Models built from components' equations using Matlab\Simulink native library components only. Pre-programmed commercial component blocks were not used.

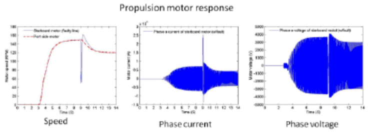


Waveform-level Matlab\Simulink model using Simulink native library components only.



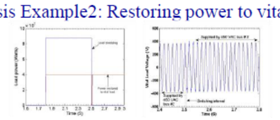
Analysis Example1: Rapid transfer of power

Propulsion motor response



Speed   Phase current   Phase voltage

Analysis Example2: Restoring power to vital load

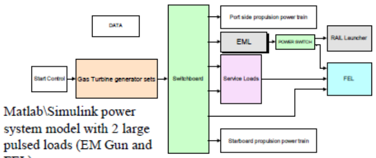


Computer simulation time to complete 10-second-long analysis (2005-desktop) ~ 8 HOURS

Publication

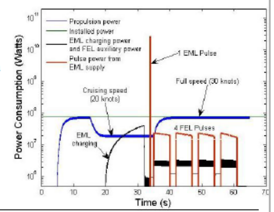
A. Ouroua, L.N. Domaschk, and J. Beno, "Electric ship power system integration analysis through modeling and Simulation", ESTS 2005.

INTEGRATION/COORDINATION OF LARGE PULSED LOADS WITH SHIP POWER SYSTEM (2006-2007)



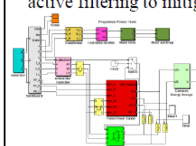
Matlab\Simulink power system model with 2 large pulsed loads (EM Gun and FEL).

Demonstrated feasibility for EM gun and FEL to operate intermittently using a common storage module.

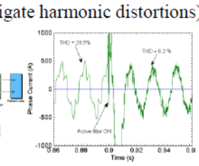


Component Multi-function

Possible use of EM Gun/ FEL power electronics and storage module for secondary function (e.g. active filtering to mitigate harmonic distortions)



Active filtering circuit



Simulation of active filtering performance

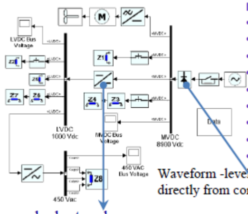
Publication

L. Domaschk, A. Ouroua, R. Hebner, O. Bowlin, and W. Colson, "Coordination of large pulsed loads on future electric ships", IEEE Transactions on Magnetics, Jan. 2007, vol. 43, no. 1, pt. 2, pp. 450-455

Modeling and Simulation of Electric Ship Power Systems (2/2)

MVDC MODELING AND SIMULATION (2009)

Initial assessment of MVDC performance through simulations of anticipated fault events



Model Components

- Synchronous generator
- 3-phase AC breaker
- 6-pulse passive rectifier
- PM propulsion motor
- PWM motor drive
- DC-DC step-down converter
- DC-AC converter
- DC interrupts
- 8 resistive loads

Waveform -level Matlab\Simulink model built directly from component model equations.

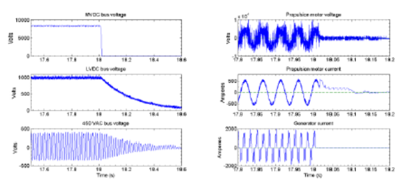
dc-dc step-down converter model

$$i_b = i_{b1} + i_{b2}$$
$$i_{b1} \cdot R_{bonoff} = i_{b2} \cdot R_{bs}$$
$$v_d = v_1 - i_{b1} \cdot R_{bonoff}$$
$$i_{d1} \cdot R_{donoff} = i_{d2} \cdot R_{ds}$$
$$i_d = i_{d1} + i_{d2}$$
$$i_b = i_d + i_L$$
$$v_2 = v_d - L\frac{di_L}{dt}$$
$$i_c = C\frac{dv_2}{dt}$$
$$i_L = i_c - i_{Load}$$

6-pulse rectifier model

$$\frac{di_{D1}}{dt} = \frac{+v_{ac}}{L_s} - \frac{R_s + R_{D1}}{L_s} i_{D1} - \frac{R_s + R_{D2}}{L_s} i_{D2} + \frac{R_s}{L_s} i_{D4} + \frac{R_s}{L_s} i_{D5} - \frac{di_{D1}}{dt} + \frac{di_{D4}}{dt} + \frac{di_{D3}}{dt} - \frac{v_d}{L_s}$$
$$\frac{di_{D2}}{dt} = \frac{-v_{cb}}{L_s} - \frac{R_s + R_{D2}}{L_s} i_{D2} - \frac{R_s + R_{D3}}{L_s} i_{D3} + \frac{R_s}{L_s} i_{D5} + \frac{R_s}{L_s} i_{D6} - \frac{di_{D3}}{dt} + \frac{di_{D5}}{dt} + \frac{di_{D6}}{dt} - \frac{v_d}{L_s}$$
$$\frac{di_{D3}}{dt} = \frac{+v_{ba}}{L_s} - \frac{R_s + R_{D3}}{L_s} i_{D3} - \frac{R_s + R_{D4}}{L_s} i_{D4} + \frac{R_s}{L_s} i_{D6} + \frac{R_s}{L_s} i_{D1} - \frac{di_{D4}}{dt} + \frac{di_{D6}}{dt} + \frac{di_{D1}}{dt} - \frac{v_d}{L_s}$$
$$\frac{di_{D4}}{dt} = \frac{-v_{ac}}{L_s} - \frac{R_s + R_{D4}}{L_s} i_{D4} - \frac{R_s + R_{D5}}{L_s} i_{D5} + \frac{R_s}{L_s} i_{D1} + \frac{R_s}{L_s} i_{D2} - \frac{di_{D5}}{dt} + \frac{di_{D1}}{dt} + \frac{di_{D2}}{dt} - \frac{v_d}{L_s}$$
$$\frac{di_{D5}}{dt} = \frac{+v_{cb}}{L_s} - \frac{R_s + R_{D5}}{L_s} i_{D5} - \frac{R_s + R_{D6}}{L_s} i_{D6} + \frac{R_s}{L_s} i_{D2} + \frac{R_s}{L_s} i_{D3} - \frac{di_{D6}}{dt} + \frac{di_{D2}}{dt} + \frac{di_{D3}}{dt} - \frac{v_d}{L_s}$$
$$\frac{di_{D6}}{dt} = \frac{-v_{ba}}{L_s} - \frac{R_s + R_{D6}}{L_s} i_{D6} - \frac{R_s + R_{D1}}{L_s} i_{D1} + \frac{R_s}{L_s} i_{D3} + \frac{R_s}{L_s} i_{D4} - \frac{di_{D1}}{dt} + \frac{di_{D3}}{dt} + \frac{di_{D4}}{dt} - \frac{v_d}{L_s}$$
$$\frac{dv_{dc}}{dt} = \frac{(i_{D1} + i_{D3} + i_{D5})}{Cd} - \frac{i_{load}}{Cd}$$
$$v_d = L\frac{d(i_{D1} + i_{D3} + i_{D5})}{dt} + v_{dc}$$

Analysis Example: Fault in load (Z1) connected to MVDC bus

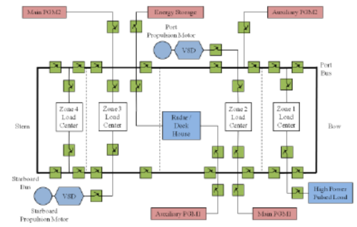


Publication

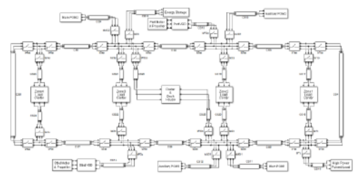
A. Ouroua, J. Beno, and R. Hebner , "Analysis of Fault Events in MVDC Architecture," ESTS 2009.

ESRDC NOTIONAL ARCHITECTURE MODEL DEVELOPMENT

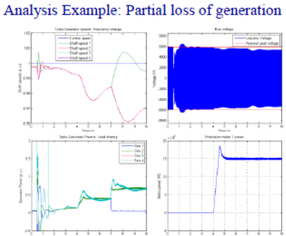
- ESRDC Modeling team: Purdue, FSU, USC, & UT
- UT-assigned architecture = HFAC (240Hz)
- UT-participant = Hamid Ouroua (UT-CEM)
- Developed HFAC dynamic model (waveform-level)
  - ESRDC 2012 Task
  - Matlab\Simulink , 10 µs fixed-step solver
  - 11-second-long scenario runs in ~ 4 hours
- Developed HFAC reduced-order average-value model
  - ESRDC 2013 Task 2.2
  - Matlab\Simscape, variable-step solver
  - 1-hour-long scenario runs in ~ 6 minutes



HFAC notional dynamic model



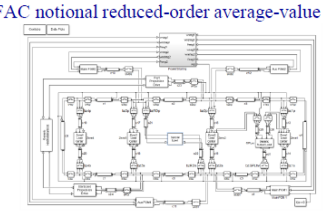
Analysis Example: Partial loss of generation



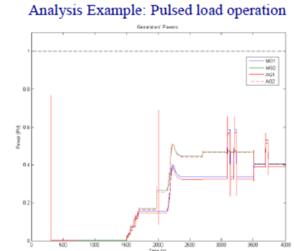
Publications

- ESRDC modeling team, ESTS2011.
- ESRDC modeling team, GCMS2012, Genoa Italy.
- A. Ouroua et al., "High –frequency power generation and distribution in multi-megawatt power systems," ESTS 2011.
- A. Ouroua et al. "Dynamic simulations of a large high-frequency power system," GCMS2011, The Hague, Netherlands.

HFAC notional reduced-order average-value model



Analysis Example: Pulsed load operation



Publications

- ESRDC modeling team, ESTS 2013
- ESRDC modeling team, Report ,"Notional component models," 2013
- ESRDC modeling team, Final report in preparation – 2014.