MODELING AND SIMULATION OF ELECTRIC PROPULSION CONCEPTS FOR A MULTIMODAL PROTOTYPE DEMONSTRATOR

By:

J.D. Herbst
A. Gattozzi
J. Uglum
J. Chalfant
C. Chryssostamidis
J. Langston
M. Steurer
M. Andrus

2009 Conference on Grand Challenges in Modeling and Simulation (GCMS'09), Part of the 2009 Summer Simulation Multiconference (SummerSim'09), Part of the 2009 International Simulation Multiconference (ISMc'09), Istanbul, Turkey, July 13-16, 2009.

PN 327

Center for Electromechanics
The University of Texas at Austin
PRC, Mail Code R7000
Austin, TX 78712
(512) 471-4496

Modeling and Simulation of Electric Propulsion Concepts for a Multimodal Prototype Demonstrator

J. Herbst, A. Gattozzi & J. Uglum
The University of Texas at Austin
Center for Electromechanics

J. S. Chalfant, C. Chryssostomidis
Massachusetts Institute of Technology
Sea Grant College Program

J. Langston, M. Steurer & M. Andrus
Florida State University
Center for Advanced Power Systems

Keywords: Naval electric power systems, microgrids, integrated power systems, multimodal propulsion

Abstract

The Office of Naval Research (ONR) is planning a prototype demonstration of a novel craft envisioned to have three modes of operation:

- Fuel-efficient, good sea keeping mode for open ocean transits
- High-speed, shallow water mode
- Amphibious mode to enable “feet dry on the beach” capability

The disparate operating modes impose discrete requirements on the various elements of the ship propulsion system, opening a wide range of potential solutions. To meet these requirements, each of the contractor teams involved in the T-Craft program is investigating the potential use of advanced electric drive technologies, including medium voltage dc distribution systems. The Electric Ship Research and Development Consortium (ESRDC) conducted a technical evaluation of three electric drive options. This paper discusses the modeling and simulation activities conducted during the initial technical evaluations of the electric drive concepts as well as challenges and potential solutions for higher fidelity modeling of the complex propulsion power systems.

1. BACKGROUND

Beginning in FY06, the Office of Naval Research embarked on an effort to develop “Game Changing” Innovative Naval Prototypes (INPs) for Sea-Basing [1]. Seabase is a loosely defined term that refers to a collection of ships at sea conducting operations that enable forces to operate ashore without a large logistics footprint. ONR solicited proposals for a prototype demonstrator of a Transformable-Craft (T-Craft) which can deploy in an unloaded condition (with range of 2,500 nm) from an intermediate support base to the Sea base and then be used as a Sea base connector, transporting wheeled and tracked vehicles through the surf zone and onto the beach. The craft is envisioned to have four modes of operation:

(1) A fuel-efficient, good sea keeping mode (open ocean transits);
(2) Cargo transfer mode with the ability to mitigate wave-induced motions in Sea State 4/5 to enable rapid vehicle transfer
(3) A high-speed, shallow water mode (40 knots); and
(4) An amphibious mode to traverse sand bars and mud flats, thereby providing a “feet dry on the beach” capability

The BAA requirements result in four basic operating modes that define the configuration and propulsion requirements of the T-Craft. This diversity of missions places a particular research challenge before the Navy. The brute force approach using established technology for each of the missions results in designs that are large and expensive. On the other hand, ONR-funded research into topics such as motors, generators, power electronics, energy storage, power control, and reconfiguration algorithms makes it possible to share propulsion system components and power to make T-Craft a more modern and efficient ship. Effective use of installed power for a variety of missions is a fundamental benefit promised by electric ship architecture. A challenge, however, is to provide the correct balance of emerging technology to provide an effective ship at an acceptable level of risk.

Three contractor teams -- led by Alion Science and Technology, Textron Marine and Land Systems, and Umoe Mandal – were selected to develop preliminary designs under Phase II of the T-Craft program. Not surprisingly, the T-Craft mission requirements that drove the contractor designs resulted in designs with some basic similarities. Each of the designs will use a Surface Effects Ship (SES) configuration for open ocean operations and will transition to a full Air Cushion Vehicle (ACV) mode for amphibious operations on the beach. The SES and ACV operating modes create specific propulsion system requirements to provide the thrust and lift power requirements of the craft. There are three major propulsion loads that can potentially be supplied by the electric propulsion system: conventional propellers or waterjets, lift fans, and air propellers. The ability to reconfigure the power system as needed to supply the various propulsion loads is a key advantage of the electric drive architecture.

The Electric Ship Research and Development Consortium (ESRDC) was tasked with an evaluation of electric propulsion concepts developed by the contractors for the T-Craft program. The ESRDC evaluation identified key issues with electric propulsion concepts under study by the T-Craft contractor teams and provided qualitative assessments of feasibility and technical risk for each design. Recommendations for technology development activities to support the T-Craft concepts were also developed. To support ONR's evaluation of the T-Craft concept designs and guide technology development investments early in the program, the ESRDC was asked to complete the evaluations within 3 months. The short duration of the initial evaluation project precluded detailed modeling and simulation of the electric drive concepts; however, some initial modeling was done to verify contractor calculations and demonstrate the benefits of higher fidelity modeling and simulation.

2. HYDRODYNAMICS

The ESRDC conducted an independent review of the lift and propulsion power requirements in each of the three primary operating modes. The vessels operate in a fourth mode during cargo transfer at sea; however, power requirements in this mode were not calculated because the propulsion requirements will not drive the basic design of the power distribution system.

Lift fans are used in both the SES and ACV modes. To maintain the ship on cushion, air is pumped into a cavity below the ship and then escapes through a gap below the skirt fore and aft. The power to lift the vessel is thus based upon the weight and size of the ship and the size of the air gap. From Mandel [2], the ideal cushion power is the cushion pressure times the air volume flow rate:

$$P_c = p_c Q = \left(\frac{W}{A_c}\right)\left(V_c S_g D_c\right) = \left(\frac{W}{A_c}\right)\left(\sqrt{\frac{2p_c}{\rho_a}} S_g D_c\right)$$

where W is the lifted weight of the vessel, A_c is the cushion area, V_c is the air discharge velocity ρ_a is the air density at pressure p_c, S_g is the area of the gap, and D_c is the discharge coefficient. The discharge coefficient compensates for the contraction of a jet after passing through an orifice. According to Harris [3], this value is approximately 0.6 for a typical SES; Daugherty [4] recommends a value of 0.62 for a generic orifice.

Propulsion power is the power required for the propulsors to counter the resistance to the vessel's movement; it includes thrust and losses. The resistance of a surface effect ship is mainly comprised of hull friction, wave generation, air drag, and added resistance due to increased Sea State. There are also resistance effects from such things as spray, appendages, and the change in momentum of the air pumped into the cushion; however, these effects pale in comparison to the four mentioned above. In ACV mode, the friction drag is eliminated as the ship no longer penetrates the water surface. However, momentum drag and trim drag become more important.

Friction drag, or viscous water resistance, is caused by the friction force on the wetted hull. In 1957 the International Towing Tank Conference (ITTC) adopted a standard model-ship correlation line which describes a friction coefficient, C_f, as [5]

$$C_f = \frac{0.075}{(\log_{10} \mathrm{Re} - 2)^2},$$

which corresponds to turbulent flow along a flat plate. Re is the non-dimensional Reynold's number; flow is turbulent at Re values above about 10^6. For the T-Craft, flow is always turbulent, with Re ~ 10^8 at 1 knot. Frictional resistance can then be calculated as

$$R_f = \frac{1}{2}\rho_w S_w U^2 C_f,$$

where S_w is the wetted surface area, U is the speed, and ρ_w is the water density. In our calculations, wetted surface area is estimated based upon the length, sidehull beam, and draft on cushion.

Roughness effects. Friction drag is calculated assuming a smooth hull; surface roughness must be considered for a realistic calculation of friction resistance. Increased friction coefficient calculated by Bowden and Davison and presented in Faltinsen [6] is given by

$$10^3 \Delta C_f = 44\left[\left(\frac{AHR}{LBP}\right)^{1/3} - 10\,\mathrm{Re}^{-1/3}\right] + 0.125$$

where AHR is average hull roughness and LBP is length between perpendiculars. All units are in meters. We use AHR = 150μm, which is an upper limit for a newly built ship [6].

Wave drag is caused by the energy expended by the ship in generating waves. Wavemaking resistance increases with speed due to the increased wave size and interaction of the waves with the ship. As the wavelength of the generated waves approaches the length of the ship, the bow tends to rise and the stern to sink, greatly increasing resistance. For a displacement hull, this resistance increases at a very rapid rate such that a significant increase in power results in a very minor increase in speed. The most reliable method of determining wave drag is to perform appropriate model testing. Barring that, there are theoretical solutions to wave drag which can be applied. Using energy arguments, Newman [5] derives the following equation for wave resistance in unbounded water of infinite depth:

$$D = \frac{1}{2}\pi\rho U^2 \int_{-\pi/2}^{\pi/2} |A(\theta)|^2 \cos^3\theta d\theta$$

where A(θ) is the amplitude of the wave at angle θ, the angle between the ship's bow and the direction of wave propagation. The factor $\cos^3\theta$ indicates that the majority of the resistance will be caused by the transverse waves.

Michell's thin ship theory introduced an expression for the wave amplitude under the assumption that the beam is small compared to all other lengths of the problem:

$$A(\theta) = \frac{2g}{\pi U^2}\sec^3\theta \iint \frac{\partial\zeta}{\partial x}\exp[(\frac{g}{U^2}\sec^2\theta(y - ix\cos\theta)]dxdy.$$

Where g is the gravitational acceleration and z = ζ(x,y) is the positive local half-beam of the hull surface. The sidehulls of the SES configuration meet this definition; therefore we will use Michell's theory to calculate the wavemaking resistance of the sidehulls with respect to speed.

The pressure cushion creates an indentation in the surface of the water which creates waves as well. Faltinsen [6] presents the following equation for the wave amplitude of an air cushion of an SES or ACV; this wave amplitude can be used in the wave resistance equation to calculate wavemaking resistance:

$$|A(\theta)|^2 = \frac{4g^2}{\pi^2 U^8}\frac{(P^2+Q^2)}{\cos^8\theta}$$

where

$$P + iQ = \frac{1}{2\rho g}\iint_{A_b} p(x,y)\exp(i\frac{g}{U^2\cos^2\theta}(x\cos\theta + y\sin\theta))dxdy.$$

Here A_b is the is the cushion area (length times beam) and p(x,y) is the gage pressure in the air cushion.

Air drag is not normally a major consideration in ship resistance analysis, but the high operational speeds of SES and ACV vessels can make it a factor in this mission description. Air drag can be estimated using [3]

$$R_a = \frac{1}{2}\rho_a S_a U^2 C_a,$$

Where ρ_a is air density, S_a is the frontal area of the vessel above the waterline, U is the vessel speed, and C_a is an air drag coefficient. C_a is best estimated using wind tunnel experiments. Lacking that, a value of 0.5 can be used [6].

Added resistance due to increased Sea State is a major factor for SES ships. SES ships in waves have periods in which the distance between the flexible skirts and the sea surface is increased, causing increased air loss. In this condition, the cushion pressure will decrease, causing the vessel to sink into the water, increasing wetted surface area and correspondingly frictional resistance [6].

In regular head sea waves, the vertical motion of the bow relative to the water can be described as $\eta_R\sin(\omega_e t)$, where η_R is the amplitude of the relative motion and ω_e is the encounter frequency. Whenever η_R exceeds d, the vertical distance needed for the bow seal to be out of the water, extra air escapes; in a sinusoidal description this occurs between t_1 and t_2. The mean leakage area over one oscillation is [6]

$$E(A_L) = \frac{\eta_R b_c}{2\pi}\int_{\omega_e t_1}^{\omega_e t_2}\left(\sin(\omega_e t) - \frac{d}{\eta_R}\right)d(\omega_e t).$$

Where b_c is the cushion beam. In irregular head seas we apply a typical sea wave spectrum to determine the following dynamic change in leakage area [6]:

$$E[A_L\} = b_c\left\{\frac{\sigma_R}{\sqrt{2\pi}}\exp\left(\frac{-d^2}{2\sigma_R^2}\right) - \frac{d}{2} + \frac{d}{\sqrt{\pi}}\int_0^{d/\eta_R}\exp(-t^2)dt\right.$$

where σ_R is the standard deviation of the relative vertical motion.

MIT's 5 degrees of freedom seakeeping program (MIT5D) was used to determine the relative vertical motion in irregular waves. This program determines motion in five degrees (surge excluded), using a strip-theory approach for a given hull form. This follows the theory presented in Salvesen [7].

Figure 1 is an example of the ESRDC calculated resistance compared to the baseline calculated by the contractor. Calculations include wavemaking resistance of the hulls (Rwh) and cushion (Rwc) calculated separately, frictional resistance of the wetted surface area of the hulls (Rf) with roughness effects (Rdf) calculated separately, and air resistance of the above-water portions of the vessel (Ra). Rtot is the sum of all calculated resistances.

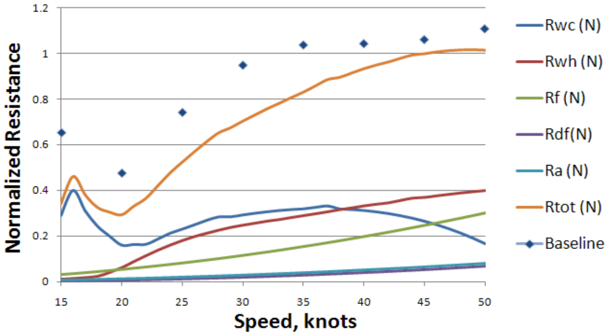

Figure 1. ESRDC calculated resistance compared to contractor baseline

Resistance values calculated by the ESRDC correlate quite well with the contractors projections despite the inherent assumptions, especially at higher speeds. At lower speeds, between 15 and 25 knots, the values correlate less well. In this regime, wavemaking resistance is the dominant portion of the overall resistance. SES wavemaking, especially for the cushion and its interaction with the hulls, is the least well understood component, both in theoretical computations and in model test scaling. While the exact value of the resistance in this regime is not completely substantiated, two points are certain: first, there exists a resistance hump followed by a hollow, and this hump occurs at approximately 16 to 18 knots; second, there is sufficient installed power to overcome this hump and proceed to higher speeds.

3. QUASI-STATIC MODELING

Quasi-static models were developed to enable calculation of fuel consumption during each mission segment for a range of sea states. For the quasi-static modeling, a notional mission profile was developed for the long-range transit and high-speed connector mission segments covering a range of wave heights from Sea States SS3 to SS5. The mission profile can be modified to reflect varying sea and weather conditions. The models use propulsion power requirements calculated by each of the contractors based on vessel displacement, Sea State and speed. Using a detailed map of the prime mover characteristics, the quasi-static models convert the propulsion power demand to specific fuel consumption and then integrate over the mission segment. Changes in displacement and the consequent reduction in propulsion power demand in response to fuel consumption over the long range mission segment are captured by the models. As expected, the quasi-static models present good agreement with fuel consumption estimates provided by the contractors. Figure 2 is an example of the output from one of the quasi-static models over the long-range transit mission segment. This particular simulation is based on an average speed of 20 knots over the 2,500 Nm long-range transit mission. The reduction in required propulsion power due to the impact of fuel consumption on vessel displacement is evident during the portions of the long range transit mission segment where a constant sea state condition has been modeled. The reduced power demand during these periods is also reflected in the increase in the specific fuel consumption of the notional gas turbine prime mover.

Using theory, the evaluations independently confirmed the resistance values for the vessels in SES mode and substantiated the power requirement calculations for propulsion and lift. In the amphibious mode, the calculations approximated the ACV resistances and confirmed that installed power was sufficient to propel the vessels as required. The quasi-static models confirmed the fuel consumption projections provided by the contractors.

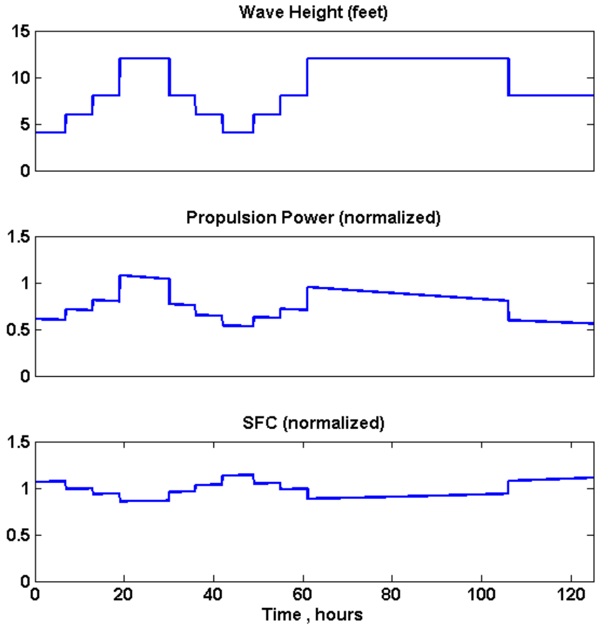

Figure 2. Sample results from quasi-static model for the long-range transit mission segment

4. PROPULSION SYSTEM MODELING

The ESRDC also conducted preliminary modeling of some notional propulsion configurations to illustrate potential issues with the electric propulsion concepts. One concept explored by the ESRDC was synchronous connection of a gas turbine driven generator to a synchronous motor without the use of an intermediate variable speed motor drive. Concerns about the dynamic behavior of the synchronous drive configuration can be exacerbated by the use of PM machines for the motor and generator in that they do not allow active control of the field. A significant issue in this assessment was the transient behavior of the system during initial startup of the driven motor. Without active field control or power conversion equipment, the motor is effectively being started across-the-line which can create significant in-rush currents and current oscillations in the distribution system. Misalignment of the rotor and armature fields at startup can lead to large torque oscillations with no net torque delivered and a corresponding oscillation in the motor current. Unlike a motor start across the line on a large scale utility power system, the cross-connect drive motor and generator are nominally the same power rating and the oscillations in the system are potentially quite severe.

A basic model of two synchronous PM machines was developed in Simulink to illustrate dynamic system issues of the cross-connect concept. The model simulated across-the-line start of a megawatt level synchronous PM motor with power provided from an identical PM generator. Figures 3 through 5 show the starting transient as the motor is pulled into synchronization with the generator output frequency. In these examples, the motor starting load was modeled by increasing the motor rotor inertia by 20% to represent the inertia of the load reflected through a speed-reduction gearbox. As can be seen in the figures, the transient impact on this notional system can be significant, with currents approaching two per unit and system voltage drooping to 0.4 per unit. Power oscillations on the bus can be seen in figure 5; note the “negative” power as motor regenerates power back to the bus.

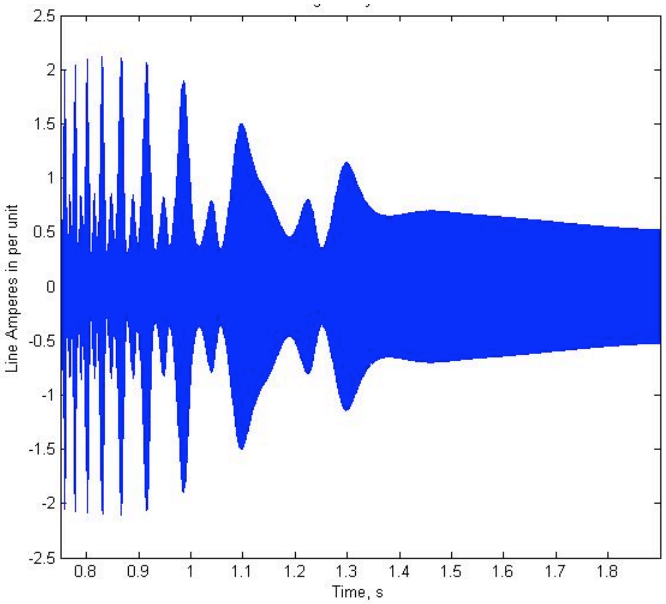

Figure 3. Bus current during motor starting transient

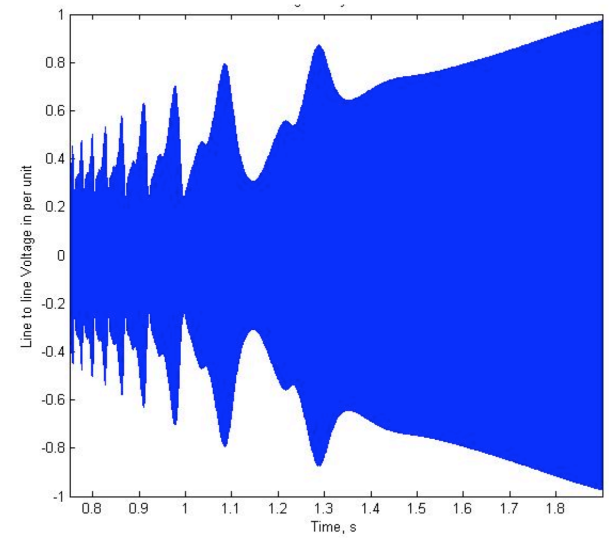

Figure 4. Bus voltage during motor starting transient

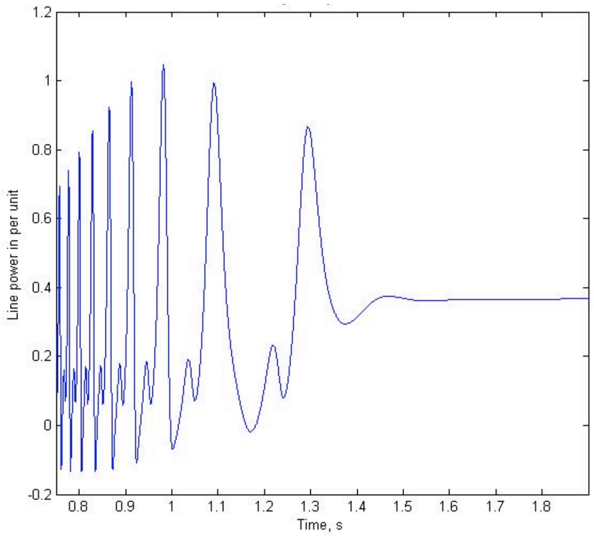

Figure 5. Bus power during motor starting transient

Using the U.S. Navy’s Next Generation Integrated Power System (NGIPS) technology roadmap as a guide, the ESRDC developed a model of a notional T-Craft propulsion system using medium voltage dc (MVDC) distribution. Gas turbine prime movers and high speed motors and generators were assumed to maximize the power density of the electric propulsion system components; active power converters (rectifiers, inverters) were used throughout the system to provide control flexibility. The notional system was then used to perform dynamic modeling in order to illustrate the use of such a tool in assessing the magnitude of potential responses in an integrated electric power plant due to system disturbances.

Figure 6 shows sample simulation results for sudden unloading and reloading of a propeller, for example due to broaching in high sea states. After reaching steady-state operation, the torque signal representing the loading of the starboard propeller was removed with a 5 ms time constant. After three seconds, the torque signal was reapplied to the motor, again, with a 5 ms time constant. These timing factors for the unloading were arbitrarily selected. Figure 6 shows the deviations in electrical signals within the starboard power plant occurring during the disturbance.

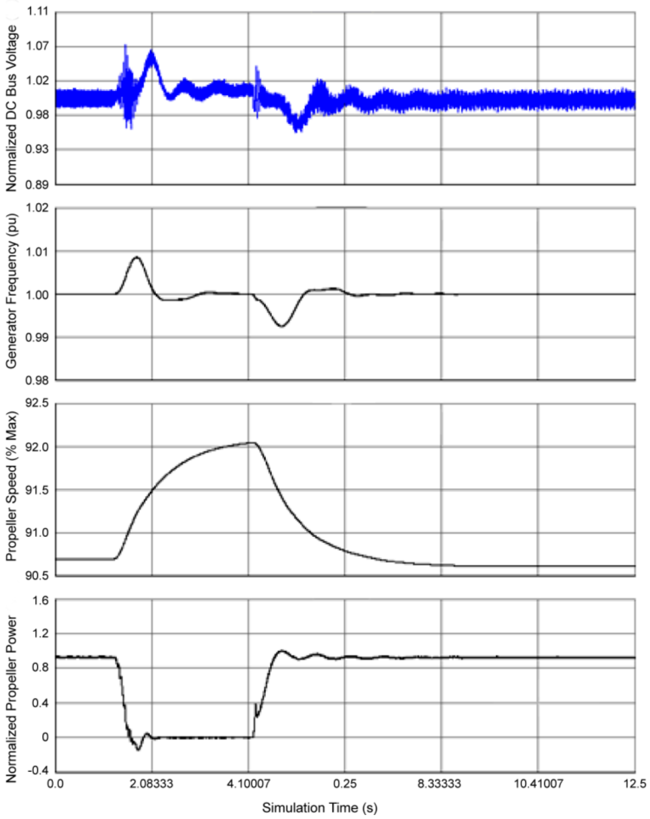

Figure 6. Sample results from dynamic simulation of propeller unloading/reloading event

Another case considered in this study involved applying a 10 milliohm rail-to-rail fault to one dc distribution bus. The 0.5 s duration of the fault was selected to be long relative to the system response – the protection system trips off the generators and their rectifiers well within 0.5 s. A di/dt protection threshold of 1000 kA/s was applied to the dc current out of the rectifier's filter. Upon detection of a fault, the firing pulses for the active rectifiers are blocked and an open command signal is sent to the generator's circuit breaker. The valves are blocked almost instantaneously, but they continue to conduct until dc current through the fault reduces to zero allowing the thyristor currents to reach zero. An open command signal is sent to the generator's circuit breaker upon fault detection, but the breaker does not actually open until the breaker advance time of 50 ms (typical value) is reached. Figure 7 shows the response of the notional system to the short circuit fault.

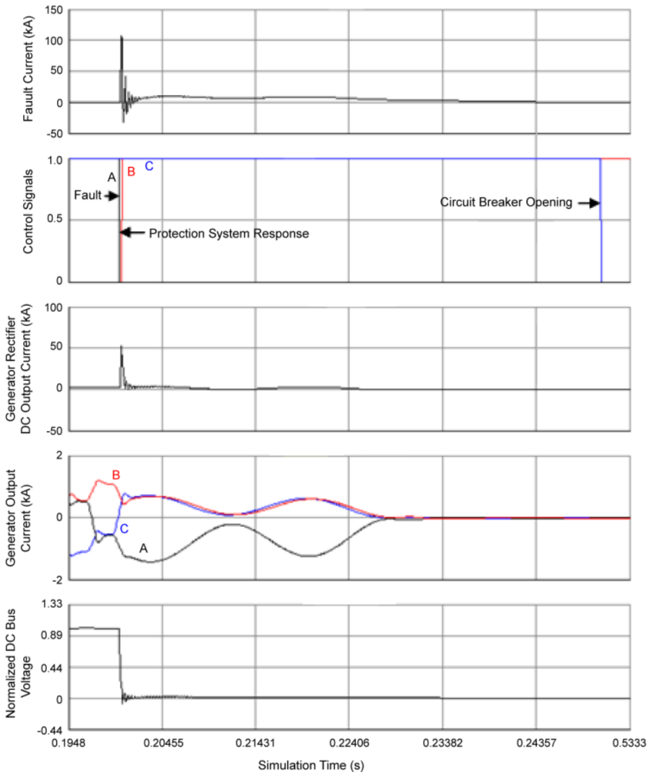

Figure 7. System response to dc bus short circuit fault

5. FAULT TOLERANCE

The ESRDC team also conducted fault tolerance analyses to provide an assessment of the response of the various contractor concepts to single point failures of critical components. The analysis was cast as a maximum flow problem for a directed graph, in which prime movers were modeled as source nodes and loads were modeled as sink nodes. The equipment connecting the prime movers to the loads comprised the edges of the graph, for which the equipment ratings provided limits on power flow. Component failures were considered by removing edges associated with the faulted components, eliminating these paths for power flow. Each mission provided a different scenario in terms of the power demanded by each of the loads. The performance of a topology under faulted conditions was assessed by the proportion of the demanded power that could be delivered to each group of loads. Figure 8 shows the results of one of the fault tolerance analyses. The component numbers correspond to selected components of the proposed propulsion system; the specific components are not identified to protect contractor proprietary information. The plot shows the normalized power available to loads based on a single component failure in each of the three operating modes.

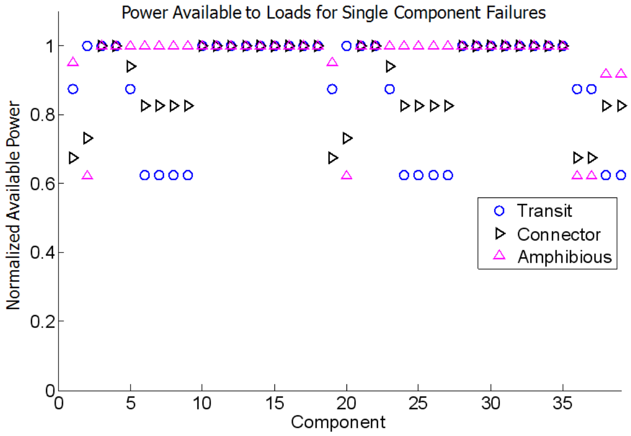

Figure 8. Sample of fault tolerance analysis results

6. NEXT STEPS

As part of the original technical evaluations of the T-Craft electric power system concepts, the ESRDC was asked to identify critical technology development and demonstration activities to mitigate program risk. High fidelity modeling of the various electric power system concepts was identified as the most cost effective risk mitigation activity. High fidelity modeling will require detailed information about the components and configuration of the power distribution systems, but will provide valuable information to guide component selection, define circuit protection approaches and requirements, and develop control algorithms for power system operation.

One scenario in which high fidelity modeling can play a major role is the study of system response to the loss of one phase in a power converter or motor. Loss of a phase may not prevent continued operation, whether at reduced load or, perhaps, even at full load at least for some time, provided the fault is promptly identified, contained, and isolated. It will, however, subject the system to a major transient event that may become destabilizing. A detailed study of the dynamics of a phase loss in any of the major components of the power system will highlight potential weaknesses and point the way to possible design alternatives that would make the whole system much more fault tolerant. This issue has been discussed especially in the last decade, but most of the work has been carried out within the realm of land based systems, where the parameters of interest are at least a couple of orders of magnitude different than those envisioned for T-Craft, and where carrying the mission to completion is not of vital importance as the task can be deferred to later times. Thus, the assurance of a survivable system under a prospective phase loss and the definition of the level of redundancy required to achieve it are of major importance for T-Craft.

Another operational scenario in which high fidelity modeling and simulation may prove to be of great value is the specified operation of T-Craft as an amphibious vehicle. In such mode, seawater will not be available for cooling the equipment on board. Although the amphibious mode is expected to be of relatively short duration, the reduced cooling ability may be tolerated by the rotating machines but it may prove fatal for the power electronics whose thermal excursions have time constants in the range of a few seconds at best. Therefore, the aim of high fidelity modeling here is not so much to study the thermal transient for the electronic equipment but the identification of possible strategies to reduce losses in the power electronics components while the vehicle is operating without the benefit of a major source of cooling. One such strategy, for example, may be the reduction of the switching frequency to a level that may allow continued operation of the power converters, albeit at the cost of increased harmonic content of the output waveform. This will result in effectively shifting some of the losses from the electronic converters to the load motors but, as mentioned, the latter are intrinsically more tolerant of temperature rise. In fact, it may be possible to design the motors to be able to handle the additional harmonics with relatively small penalty of size and cost. Other strategies may be explored and high fidelity modeling and simulation will make it possible.

7. CHALLENGES AND SOLUTIONS FOR THE FUTURE

The ESRDC activities presented here were focused on evaluation of electric propulsion concepts; however, the evaluation and selection of propulsion technologies – electrical, mechanical, or hybrid – is continuing at each of the contractor teams. Preliminary modeling of the various T-Craft propulsion concepts effectively supported the initial technical evaluations and demonstrated the potential value of high fidelity modeling for assessing the dynamic performance of electric power distribution systems.

By the standards of land based power systems, a ship can be considered a small microgrid. Islanded power systems with multiple power sources – such as a ship power system with multiple paralleled generators – have characteristics that must be considered to ensure stable, reliable operation. These systems differ from utility power distribution systems in that the power sources and connected loads are of the same order of magnitude. T-Craft electric power system concepts are even more challenging due to the relatively few number of components comprising the power grid. Thus, a disturbance at any location is more difficult to absorb and stabilize than in a system with more components and more averaging capacity.

Another characteristic of T-Craft imposed by the small size of its power system is that the installed capacity of solid state power conversion units may potentially represent a larger percentage of the total installed capacity than in a larger ship, and certainly than in land based systems. In a compact structure like T-Craft the opportunities for electrical isolation among the various converters are limited. It is clear, therefore, that a detailed understanding of the impact of not only actual faults but also of different perturbations is necessary to ensure stable operation. This will allow, for example, the definition of an optimal level of energy storage and filtering elements in the circuit to achieve the most effective plan for noise immunity.

One of the challenges of developing a suitable modeling tool for this analysis is well known to the members of ESRDC and was brought out also by the range of models developed in support of the initial technical evaluations: the need to employ a range of time steps to efficiently model various portions and operating scenarios for a given system. Time steps on the order of 2 μs are needed to accurately model switching events in high frequency solid state power converters, while electric machinery tends to respond electrically in times of the order of seconds and mechanically in even longer times. Modeling of systems with timescales ranging over 6 to 8 orders of magnitude can quickly reach the memory and computational limits for current desktop computers. These issues typically restrict modeling at this level of fidelity to simulation durations of a few seconds. Work is underway at several organizations to develop distributed modeling environments which enable the use of a range of time steps as needed to accurately represent the various elements of the electric power distribution system. For example, quasi-static processes can be modeled using microprocessor based computation with higher frequency events simulated using digital signal processor (DSP) and field programmable gate arrays (FPGA's) models. These innovations can potentially enable the modeling and simulation of electric power systems with very complex interactions in real time, providing an invaluable tool for the designer and operator of the systems.

Hydrodynamic modeling of T-craft would benefit from updated modeling techniques as well. Specifically, improved modeling of air cushion and hull interactions in SES mode and air cushion behavior in ACV mode would improve the seakeeping and resistance calculations in these modes. While we were able to approximate such situations, more accurate techniques would be of great assistance in preliminary ship design and analysis. The traditional approach to calculating wavemaking resistance and seakeeping has solved incident, diffracted and radiation wave potentials for a single hull; however, further analysis is required to properly analyze the proposed T-craft concept of operations to accommodate multi-hull craft, surface-effects ships, air-cushion vehicles, and vessels operating in close proximity to one another while connected but not hard-coupled. Multi-hull ships produce wave patterns that interfere with one another causing additional resistance; the air cushion pressure of surface effects ships modifies the wave pattern within the cushion space. The air cushion itself has a non-uniform shape and contains waves within it which affect both SES and ACV modes. Close-proximity vessels respond at different phases than a hard-coupled, multi-hull vessel. Expansion of current seakeeping codes both within the current realm of linear solutions in a strip-theory format and to a full 3D nonlinear code that solves the 3D inviscid flow equations would assist in such solutions in the future.

The U.S. Navy has conducted extensive research into the development of automated controls for ship systems and the value of modeling and simulation for controls development is well known. A key benefit of accurate modeling is the opportunity to experiment with various control schemes to determine an optimal strategy for automatic reconfiguration of the power system based on realistic operational and fault scenarios. Thus the software development of a comprehensive supervisory control system will not only expedite its implementation but will also ensure its robustness and fault tolerance. This is not necessarily straightforward and may be quite an intensive task but its ultimate payoff in terms of mission success cannot be overemphasized. This is particularly true in a ship like T-Craft that is projected to be operable with a minimal crew.

Acknowledgement

This work is sponsored by the Office of Naval Research under ONR Grant N00014-08-1-0080.

References

[1] http://www.onr.navy.il/02/baa/docs/baa_05_020.pdf

[2] P. Mandel, Water, Air and Interference Vehicles. MIT-B-69-001, 1969.

[3] J. C. Harris and S. T. Grilli. Computation of the wavemaking resistance of a Harley surface effect ship, in Proceedings of the Seventeenth International Offshore and Polar Engineering Conference, Lisbon, Portugal, July 1-6, 2007.

[4] R. L. Daugherty and J. B. Franzini, Fluid Mechanics, 6th ed., McGraw-Hill, New York, 1965.

[5] J. N. Newman. Marine Hydrodynamics. The MIT Press, Cambridge, MA, 1977.

[6] O. M. Faltinsen. Hydrodynamics of High-Speed Marine Vehicles. Cambridge University Press, New York, 2005.

[7] N. Salvesen, E. O. Tuck, & O. Faltinsen. Ship motion and sea loads, Transactions of the Society of Naval Architects and Marine Engineers, 78: 250-287, 1970.

Biography

Mr. John D. Herbst is a Senior Engineering Scientist at The University of Texas at Austin Center for Electromechanics since 1985.