Integrated Simulation Framework For Crash Back Operation

S. Brizzolara  
University of Genova  
Dept. of Naval Architecture, Marine and Electrical Engineering  
Genova, Italy, 16145  
currently visiting MIT MechE  
stebriz@mit.edu

P. Prempraneerach  
Dept. of Mechanical Engineering  
Rajamangala University of Technology Thanyaburi, Pathumthani, Thailand 12110  
prradva@gmail.com

G. Karniadakis  
Brown University,  
Division of Applied Mathematics, Providence, RI, USA, 02192  
and also  
MIT Sea Grant College Design Lab  
george_karniadakis@brown.edu

C. Chryssostomidis  
Sea Grant College Program  
Massachusetts Institute of Technology  
292 Main Street, 02139  
Cambridge (MA) – USA  
chrys@mit.edu

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Abstract  
We formulate a modeling and simulation framework that integrates models of an all-electric ship (AES) with ship and propeller hydrodynamic models. In particular we present the first simulation study about the transient behavior of the propulsion system of AES during crash stop and backing maneuvers. A time domain model of all electric propulsion system of a notional destroyer has been coupled with a simplified transient model of the hull and propeller hydrodynamics. The integrated power system of the integrated power system (IPS) includes all main elements of the chain, i.e. from power generators to control units down to frequency controlled electric motors. The simplified unsteady hydrodynamic model of the hull and twin shaft lines with fixed pitch propellers is based on semi-empirical quasi static data corrected with complimentary CFD simulations. The transient behavior of the electrical power distribution and motor control are analyzed and the relevant implications that these kind of violent transient maneuvers have on the engineering of the main electrical components are outlined in the paper.

1. INTRODUCTION  
In the new All-Electric Ship (AES) Integrated Power System (IPS), there is an increasing demand for ship system automation, electrical weaponry, electric propulsion, and ship service distribution. The AES power system can be broadly separated in five main sections: power generation, power conversion and distribution, propulsion loads, ship service loads, and advanced system loads. Figure 1 gives a high-level description of the IPS. In particular, here we focus on the medium voltage DC system (MVDC) which is directly involved in power generation and supply to the main propulsion system. About 70% to 90% of power from the generator units in the fully integrated power system is consumed in the propulsion systems. The power distribution must yield the most efficient power usage to maintain continuity of service in the case of large power demand or critical situations, such as crash-back operations.

A crash back is a standard emergency maneuver the board has to perform in the need of rapid stopping and reversing of the ship advance speed from the full head to the full astern condition. The rapid deacceleration, induced by the propeller stopping and reverse motion, is one of the most violent maneuvers that can be imagined from different perspectives: propeller and shaft dynamics and strength, transient loads on prime movers and powering supply modules and even structural strength and vibrations in the stern structures above the propellers and thrust bearings. The complicated transient phenomena involved in the maneuver are regulated by the propeller and hull hydrodynamics from one side and by the electric propulsion system dynamics from the other. These dynamics have completely different time scales, especially in the case of all electric propulsion systems, but they can interact together conditioning the final result of the maneuver that can contain harmful conditions for both systems. In particular the logic of the torque and powering control of the electric drive is influencing the propeller hydrodynamics and vice versa. Some components as braking resistors are designed just from loads coming out for these kind of maneuvers, so an effective design procedure must include correct modeling of propellers and ship hydrodynamics. Recently different CFD studies just on the unsteady propellers/hull hydrodynamics during crash back maneuvers have appeared, as for instance in [Hur et al. 2011]. The authors after concentrating on the modeling issues of the IPS are here considering an integrated simulation framework that can accurately solve both the IPS and ship/propeller hydrodynamic transients together. This work is the first step towards this goal, featuring a simplified hydrodynamic module, yet consistent in its main components, which can already give interesting indications to the designer, as it will be illustrated in the following sections.
2. ALL-ELECTRIC SHIP SIMULATOR

The governing equations for all major components of a MVDC system are described in [Marden et al. 2010], where first results were presented with very simplified hydrodynamic models. The synchronous machine (SM) produces 21 MW while the unidirectional rectifier converts AC to DC voltage such that the nominal value of the MVDC bus voltage is 5 kV. In particular, in the first generation of an end-to-end simulator for AES we used a constant-slip approach to control the induction machine (IM), see Figure 1. For crashback operations the use of a proper AC drive applied to the induction machine is particularly important. The constant-slip current control optimizes the machine torque for a specified stator current by maintaining constant slip frequency. It has been used widely due to its implementation simplicity and robustness to disturbances. Nevertheless, magnetic saturation of the machine might occur in this control technique, thus the rotor flux linkage must be kept below a threshold limit. Here we will use the direct torque control approach for IM, which has also been widely employed to control the induction machine because of its fast torque response to loads and supplied voltage changes, and its capability to operate with a four-quadrant AC drive. By maintaining the magnitude and phase of the stator current constant and choosing a proper inverter state from a switching table, this technique can control the stator flux and torque directly and independently.

In the classical direct torque control, two hysteresis controllers for controlling flux and torque are used to maintain the stator flux and the electromagnetic torque within both hysteresis bands. However, the hysteresis controllers are similar to a bang-bang control, containing discontinuous action, and as a result, the direct torque control produces large torque ripples.

The power generation unit using a 3-phase, 60-Hz, 21 MW synchronous machine, driven by gas turbine, supplies electrical power to the induction motor, which acts as a propulsor for a full-scale USS DDG-51 Arleigh Burke-Class destroyer. The MVDC bus voltage is maintained at 5 kV by the type-AC1A exciter [IEEE 2006]. A detailed description and model of individual components are given in [Marden et al. 2010]. The command-following comparison between constant-slip current control and direct torque control is performed using a ramp torque command from 0.110 to 0.359 MN-m and to 1.129 MN-m, corresponding to steady-state ship speed of 8, 15 and 20 knots, respectively. To reach 15 and 20 knots ship speed, 3.502 and 8.199 MW total propulsion power is required, respectively. Therefore, each of the two propulsion set driven by the induction machine must correspondingly produce about the half if this to propel the ship at these two forward speeds. The simulation results suggest that the direct torque control produces more torque ripple than the constant-slip control since the inverter voltage produced by the switching table generates a lower harmonic frequency compared to that produced by the current hysteresis. The propeller thrust has similar characteristics as the induction machine torque. The ship speed is initially set at 8 knots and ramps up to 15 and 20 knots within 150 and 275 seconds respectively, as shown in Figure 4.

Figure 1: One line diagram of Medium Voltage DC

Using a 3-phase, 15-Hz, 19 MW induction machine, the constant slip current control is compared to the direct torque control based on control characteristics and dynamics response, including a torque-command tracking and torque and current ripple. The results are shown in figures 2 and 3. The induction motor shaft is directly coupled with a five-blade, fixed-pitch, highly skewed propeller [Boswell 1971].

Figure 2: Constant-slip current control : Induction Machine (IM) torque (first row), speed (second row), and stator flux (third row).

Figure 3: Direct-Torque Control : Induction Machine (IM) torque (first row), speed (second row), and stator flux (third row).
3. HYDRODYNAMICS OF CRASH BACK

The dynamic model of the all electric propulsion system has been coupled with a preliminary transient model for ship and propeller hydrodynamics to test the functional characteristics of the main electrical components during crash back maneuvers. To the scope, the unclassified DTMB 5415 combatant hull was taken as reference in the preliminary tests of the simulator, as the closest public version of the notional destroyer under consideration. In fact the hull, presented in Figure 5, is similar to the one actually built in the DDG-51 series, being used for preliminary series of studies and recently openly released in occasion of several workshops about marine CFD [Various, 2010] and maneuvering simulation [Various, 2008]. The full scale ship is a 142m x 19m x 6m (LpPxBxT) guided missile destroyer and her full load displacement measures about 8500tons. The hull has a pronounced sonar dome integrated in the bulbous bow and a narrow stern transom, with a quite fine entrance body (low entrance angles) and a pronounced flare of the sections above its design waterline.

Hull appendages actually vary between different design studies made on this hull: in our case they consist of a bow sonar dome, two pairs of bilge keels, a small skeg, twin shafts, struts, fairwaters and twin rudders with rudder-shoes.

The resistance of the appendages was considered by the addition of a friction and form resistance components calculated with the exact Reynolds number and form factor of each appendage. For crash back simulations, the ship resistance needs to be estimated also in reverse speeds. Preliminary CFD simulations of the hull, free to sink and trim, advancing in steady astern motion indicated that the bare hull resistance in these condition is nearly two times higher than the corresponding value at forward speed, when including also the suction effect of the propellers. The final resistance curve assumed in the studies is given in Figure 6.
Main geometrical data of the different propellers used for manoeuvring tests in model scale are given Table 1. A fixed pitch propeller with the same pitch ratio of that selected by FORCE but with increased expanded area ratio of $A_d/A_o=0.7$ and a smaller hub diameter $d_h/D=0.18$, was assumed in order to be more similar to values usually taken by modern propeller designs of high speed destroyers.

Consistently also the non-dimensional thrust and torque coefficients are referred to the undisturbed speed relative to the 0.7R blade section, in such a way:

$$C_T = \frac{T}{1/2 \rho (V_A^2 + (0.7\pi n D)^2) \pi D^2/4} = \left(\frac{8K_T}{\pi (J^2 + (0.7\pi)^2)}\right)$$

$$C_Q = \frac{Q}{1/2 \rho (V_A^2 + (0.7\pi n D)^2) \pi D^2/4} = \left(\frac{8K_Q}{\pi (J^2 + (0.7\pi)^2)}\right)$$

in which $T$ is the thrust, $Q$ the torque, $n$ the rpm and $D$ the diameter of the propeller; $V_A$ is the ship advance speed defined in terms of the wake fractions as $V_A = V \cdot (1-w)$.

### Table 2: Quadrant definition for $\beta C_T^*$ $C_Q^*$ coordinate system

<table>
<thead>
<tr>
<th>Quadrant Number</th>
<th>Quadrant Description</th>
<th>Beta ($\beta$) [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ahead</td>
<td>0 - 90</td>
</tr>
<tr>
<td>2</td>
<td>Crashback</td>
<td>90 - 180</td>
</tr>
<tr>
<td>3</td>
<td>Backing</td>
<td>180 - 270</td>
</tr>
<tr>
<td>4</td>
<td>Crashahead</td>
<td>270 - 360</td>
</tr>
</tbody>
</table>

The final propeller $C_T$, $C_Q$, $\beta$ diagram used in this study is presented in Figure 8, as estimated on the basis of a B4.70 propeller, tuned in such as way to match the thrust needed by the hull at the design speed of 30 knots.

It is worth noting that some propeller geometric characteristics have a relevant influence on the maximum propeller thrust and torque during crash back maneuvers. The analysis of the B-series propeller tests results in the four quadrants [van Lammeren et al. 1969], it can be argued that the expanded area ratio has a major influence on the maximum $C_T^*$ and $C_Q^*$ that a fixed pitch propeller generate in the diagram, while the pitch ratio has a prevalent effect on the maximum $C_Q^*$ only in stopping and backing.

Indeed, also the actual blade design in terms of chord, skew and rake distribution along the radius is to be considered for the correct estimation of the propeller forces during these transient maneuvers.

For the above reasons, it is desirable to use the exact designed propeller for the calculation of the four quadrant diagrams needed in the final assessment of propulsion transient behavior. In this respect Numerical flow solvers [Luo et al. 2010] [Brizzolara et al. 2008] able to fully consider separation and turbulence, seems to be a valid tool to obtain accurate predictions. A validation study is in fact currently under completion.

So simulator integrates the ordinary differential equation for the speed of the ship advancing in rectilinear decelerated motion, and it is considering in it the variable propeller thrust deriving from the ship speed and propeller rpm changes during the maneuver. An example of the values taken by the advance angle $\beta$ during a crash stop...
maneuver with constant torque set to one third of the maximum torque in forward speed, is presented in Figure 9.

Figure 8: Torque and Thrust Coefficient curves estimated for the assumed propeller

Due to the completely different time scales between the two dynamics, propeller and ship, the quasi steady approach followed to estimate propeller thrust and torque seems well justified. An estimate of the ship added mass for the surge motion is instead considered, using classical relations.

Figure 9: Advance angle change during the crash stop maneuver with given constant torque on the propellers.

4. CRASH ASTERN OPERATION

To avoid an accumulation of heat in the braking resistors during the crash astern operation, a braking chopper is added to maintain the MVDC bus voltage at maximum threshold level of 6 kV. If the MVDC bus voltage rises above this maximum threshold, the braking chopper turns on the crowbar to draw current through the braking resistors with a switching frequency of 100 Hz. According to Table 3, there exist braking resistors in the market with oil cooling system of various power ratings and maximum voltage, which can be applicable to the MVDC integrated power system. In this case, three braking resistors are connected in parallel to synergistically dissipate the surplus energy, as shown in Figure 10. Different resistance values have been investigated to minimize the instantaneous power dissipation using the braking chopper.

Table 3: Oil cooled power resistor from GINO AG (http://www.gino.de/download/download/71_prospekt_oil_cooled_power_resistors_en.pdf)

<table>
<thead>
<tr>
<th>Continuous Load (kW)</th>
<th>Current (A)</th>
<th>Voltage up to (kV)</th>
<th>Oil Volume (l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>400</td>
<td>10</td>
<td>145</td>
</tr>
<tr>
<td>100</td>
<td>400</td>
<td>12</td>
<td>205</td>
</tr>
<tr>
<td>150</td>
<td>630</td>
<td>12</td>
<td>355</td>
</tr>
<tr>
<td>270</td>
<td>630</td>
<td>12</td>
<td>500</td>
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<tr>
<td>400</td>
<td>630</td>
<td>24</td>
<td>775</td>
</tr>
<tr>
<td>540</td>
<td>630</td>
<td>24</td>
<td>1080</td>
</tr>
<tr>
<td>800</td>
<td>630</td>
<td>24</td>
<td>1600</td>
</tr>
</tbody>
</table>

A crash astern scenario is performed to examine the interaction among all different electric machines and components as well as to evaluate the power consumption and regeneration. Moreover, different values of three-parallel braking resistors are compared to minimize power dissipation in each individual resistor. For the crash astern operation, as previously described, the propeller hydrodynamics is directly coupled and driven by the induction machine. The results of these tests are shown in figures 11-16.

Figure 10: Three parallel braking resistors are controlled by the braking chopper to maintain the MVDC bus below the maximum threshold voltage of 6 kV. The braking chopper is operated at 100 Hz.

Initially, the ship speed is kept at 15 knots and then increased to 25 knots within 50 seconds. Subsequently, the induction machine undergoes the braking operation by applying a ramp negative torque to the propeller shaft from 981.1 kN-m to -0.4 MN-m within 25 seconds. The rotational speed of the propeller or motor shaft gradually
decreases and reaches zero speed in about 43 seconds, as shown in figure 12. During this braking period, the ship still cruises in forward direction [Hur et al. 2011], see figure 14, and the induction motor operates as a generator that supplies the regenerated power back to the MVDC bus, which causes the gas turbine (GT) and synchronous machine (SM) to become idle or SM torque drops to zero in figure 11. In addition, the MVDC bus voltage rises and limits at the maximum threshold of 6 kV by switching on-off the braking chopper, shown in figure 13, thus a large instantaneous current is drawn from the MVDC bus current intermittently. The synchronous machine phase current decreases to zero during this period. This regenerative power must be consumed by the three-parallel braking resistors of 75 Ω for a short period of 24.6 second. Once the rotational speed of the induction machine (IM) becomes negative, the IM again operates in the motor mode, drawing power from the MVDC bus, at 93.4 seconds. As a result, the MVDC bus voltage suddenly drops and the gas turbine and synchronous machine start to supply more energy to the MVDC bus once again after idling.

To minimize the dissipated power in each braking resistor, five different resistance values of 15, 30, 45 60 and 75 are compared in terms of peak instantaneous power and average power dissipations, as shown in Table 4. Figures 15 and 16 show the time histories of the peak electrical power drawn from the MVDC bus for two representative cases during the regenerative duration. As a result, the larger value of braking resistor, the smaller the peak instantaneous power dissipation. Therefore, the existing power resistor from Table 3 could be employed when the braking resistor size is above 45 Ω. However, the average power dissipation over the regenerative period for all resistor values is comparable at 4.8-4.9 MW.

<table>
<thead>
<tr>
<th>Individual Resistor (Ω)</th>
<th>15</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Power (MW)</td>
<td>4.90</td>
<td>4.78</td>
<td>4.80</td>
<td>4.81</td>
<td>4.81</td>
</tr>
<tr>
<td>Peak Instantaneous Power (MW)</td>
<td>2.41</td>
<td>1.22</td>
<td>0.82</td>
<td>0.62</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Figure 11: Gas Turbine (GT) torque (first row), Synchronous Machine (SM) torque and rotational speed (second and third rows).

Figure 12: Induction Machine (IM) torque (first row), speed (second row), and stator flux (third row).

Figure 13: Bus voltage and current (first and second rows), SM phase current (third row), and IM phase current (fourth row).

Figure 14: Propeller thrust (first row) and ship speed (second row).
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REFERENCES