

Propulsion Drive Models for Full Electric Marine Propulsion Systems

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Abstract—Integrated full electric propulsion systems are being introduced across both civil and military marine sectors. Standard power system analysis packages cover electrical and electromagnetic components but have limited models of mechanical subsystems and their controllers. Hence, electromechanical system interactions between the prime movers, power network, and driven loads are poorly understood. This paper reviews available models of the propulsion drive system components: the power converter, motor, propeller, and ship. Due to the wide range of time constants in the system, reduced-order models of the power converter are required. A new model using state-averaged models of the inverter and a hybrid model of the rectifier is developed to give an effective solution combining accuracy with speed of simulation and an appropriate interface to the electrical network model. Simulation results for a typical ship maneuver are presented.

Index Terms—Electromechanical interactions, marine, propulsion, rectifier models.

I. INTRODUCTION

INTEGRATED full electric propulsion (IFEP) systems for marine applications are being intensively developed in both commercial and military shipping sectors. Replacement of direct mechanical couplings between the prime mover and propeller with an electrical network offers potential benefits including reduced fuel consumption, enhanced dynamic performance, increased reliability, reduced maintenance costs, and greater flexibility in the ship layout. These benefits depend on the operational duties of the ship and the nature of any other electrical loads.

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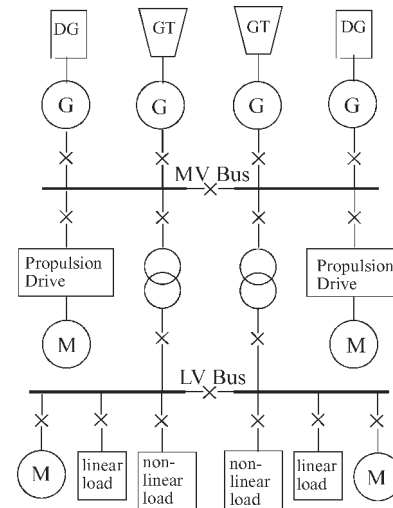


Fig. 1. Overview of an integrated full electric propulsion system.

Simulation tools for marine propulsion systems have been developed for through-life energy management, ship handling, and electrical network analysis [1]–[4]. However, interactions between the dominant mechanical systems and the electrical network are poorly understood. Hence, there is a need to include the prime movers and driven loads with the network model [5]–[7] in order to develop integrated control and protection strategies. Hitherto, research has either focused on improving the accuracy of a very particular part of the drive or ship subsystem (neglecting the difficulty of interfacing such a detailed model to the rest of the system) or adopted a broad-brush approach to the system (neglecting system fidelity). The Advanced Marine Electric Propulsion Systems (AMEPS) project is a collaboration between three U.K. universities (Strathclyde, Cranfield, and Manchester), bringing together expertise in gas turbines, power systems, machines, and drives to develop appropriate models of the complete IFEP system. This paper concentrates on models of the propulsion system and their interface with the electrical network.

II. SYSTEM OVERVIEW AND CONSTRAINTS

Fig. 1 shows an overview of an IFEP system, where the gas turbine alternators (GT) and driven loads are connected to a fixed-frequency ac power network. This allows the gas turbines to be optimized for a single speed. Diesel generation (DG), e.g., for in-port operation, is also shown. Other than the main

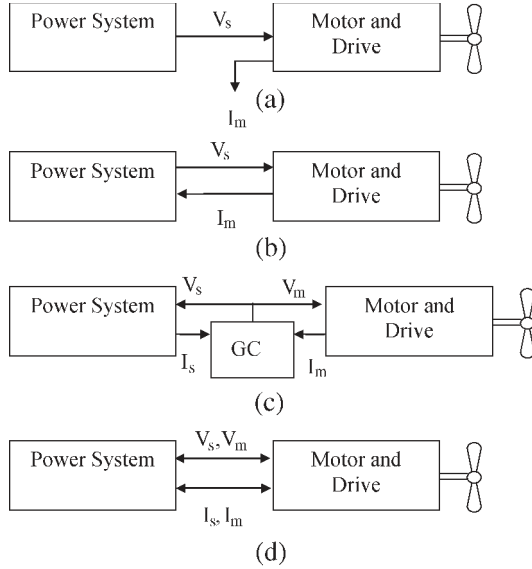


Fig. 2. Data flow at the drive–network interface. (a) Unidirectional interface. (b) Bidirectional interface with unidirectional variables. (c) Variable matching at the interface. (d) Bidirectional interface with bidirectional variables.

propulsion drives, there may be additional electrical loads, including hotel loads and pump and hoist drives.

A. Interface Constraints

In order to investigate interactions between these mechanical and electrical systems, the interfaces between these systems must be bidirectional. When an event occurs in one subsystem (for example, a change in operating point or a fault condition), then connected subsystems may be affected. The simulation should represent both the effect on other connected subsystems and their interaction with the part where the event originated.

Fig. 2 shows the interface requirements between the electrical network and propulsion drives. The four cases show increasing levels of complexity.

In (a), the electrical network voltage at the drive terminals may be time varying, but because the drive current is not fed back into the network model, there is no way of computing the network response to changes in the propulsion system. Many averaged-value rectifier models essentially follow this pattern, assuming ideal voltage sources and fixed network impedances, which do not respond to changes in the driven load [8]. Even where the averaged-value rectifier models have been extended to determine ac-side current waveforms and incorporate generator characteristics [9], these rely on calculating a lumped-parameter equivalent circuit (EC) of the power network. This is not suitable in the present application because it does not allow for connection or disconnection of additional loads and generators.

Case (b) allows two-way data flow but with unidirectional variables: Voltage is set by the network, and the returned current is defined by the driven load. This case is desirable because it is easy to implement, avoiding arithmetic loops and convergence problems.

In case (c), both subsystems source currents, and an additional general control (GC) block is required to match currents

TABLE I
PROPULSION DRIVE TIMINGS

Source	Time
Semiconductor commutation	$\sim 1\mu\text{s}$
Stator leakage time constant	1-10ms
Rotor time constant	50ms-1s
PWM period	0.5-2ms
PWM resolution (12 bit)	$\sim 1\mu\text{s}$
DC link ripple period	2.8ms
Propeller run-up time	20-60s
Ship run-up time	60-500s
Wave disturbance interval	10-100s

* Based on 0.5-20MW Industrial drives and rapid response ship.

at the interface. GC might represent a network with line reactance, using capacitive snubbers for current matching between the power network and the drive system. In [10], GC is an explicit current-matching control element.

Case (d) is the most complex since either side of the interface may define the voltages and currents and the interface must control how this occurs. An example is the diode rectifier, where turn-on is defined by voltage and turn-off is set by current.

B. Timing Constraints

Table I shows typical timing values within the marine propulsion drive, based on a generic 20-MW propulsion motor, and rapid-response ship. The discrepancy between time constants in the power converter and the driven load is apparent. If the entire system is modeled at a time step to suit the power semiconductors, for the duration of a mechanical transient, simulation run times become excessive. One solution is to have reduced-order models of the power converter to allow a larger step size. Multirate simulation may be used to minimize the number of calculations at the highest rate.

C. Software Constraints

The Simulink SimPowerSystems toolbox was selected as the simulation environment for the power network. Other parts were modeled directly in Simulink or via its interface to Fortran in order to take advantage of existing validated models.

III. SIMULATION MODELS

An overview of the propulsion drive model is shown in Fig. 3. This combination was selected from a range of possible technologies [7] for its immediate relevance to U.K. marine users. However, the model has been structured in subblocks to allow future extension to alternative motors or power converters. From the rectifier onward, the connections between model elements are deterministic, with no conflicts between inputs and outputs. Bidirectional data flow is achieved with unidirectional variables, as outlined in Section II-B. The main models are discussed in the following.

A. Inverter

A voltage-source inverter with a diode or thyristor rectification stage is modeled. For the inverter stage, an

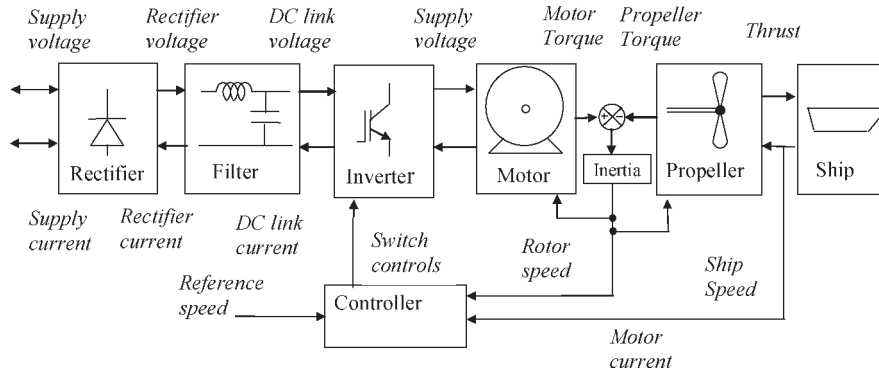


Fig. 3. Marine propulsion drive simulation structure.

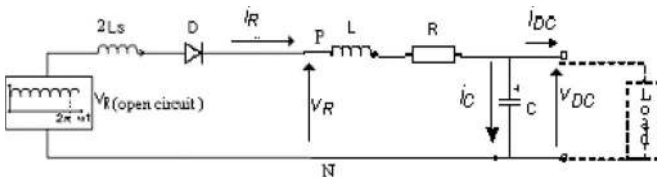


Fig. 4. EC model of the rectifier.

averaged-voltage-vector approach is proposed. Space-vector pulsewidth modulation approximates the desired voltage vector by using a sequence of switch states over the switching period. The time for which each state is asserted is weighted to give the desired average voltage over the switching period. A model using the averaged voltage vector instead of the switch states avoids the need to accurately locate switching edges but neglects the effects of PWM harmonics. Inverter dead time has not been included, although it could be added using the analysis in [11]. The resulting model thus loses some accuracy but can be run at a fixed rate equal to the inverter switching period (typically 0.5–2 ms). This is a significant improvement in time step and can also be used to include control loop delays.

B. Rectifier

The averaged-voltage-vector technique cannot be applied to the diode rectifier, because the turn-on and turn-off instants depend on the circuit conditions rather than external control signals. Averaged-value rectifier models which assume fixed power network conditions were rejected because they do not meet the interface constraints discussed in Section II.

1) *EC Model*: Two models have been considered for the ship propulsion drive. The first uses separate EC models for the ac and dc sides. The dc-side voltage is calculated, assuming that there are only two diodes conducting at any time, neglecting overlap. In this case, the rectifier and dc link can be represented by the circuit model in Fig. 4, where the voltage source (V_R) represents the maximum envelope of the three-phase supply voltages; L , R , and C are the dc-link inductance, resistance, and capacitance, respectively; and L_s is the line inductance. This is similar to the averaged-value rectifier models (e.g., [8] and [9]), except that the voltage source is defined from terminal connections rather than assumed network conditions. The circuit equations can be used to compute dc output voltage (V_{DC}) and rectifier current (i_R) for a defined load current (i_{DC}).

Two methods have been considered for calculating the ac-side currents. In either case, additional circuit components are required to interface the current sources to SimPowerSystems. Fig. 5 shows the connection to the ac network. The measured envelope of the network voltages (V_s) is used by the dc-side circuit, from which the ac-side currents (I_s) can be calculated. The currents are injected into the power network using controlled current sources. The RC circuits allow current matching across the interface, as discussed in case 2(c). The RC component sizes are discussed in Section III-B3.

The simplest alternative is the power balance model, which equates input and output powers. This assumes unity power factor, which is almost true for a three-phase rectifier [12], but neglects the poor form factor. Hence, the model is not valid for peak current calculations, particularly with a stiff supply. The supply-side currents are calculated assuming a balanced star-connected resistive load equivalent to the output power.

Alternatively, a logic block may be used to assign the current drawn by the rectifier (I_R) to the supply lines that are conducting, assuming that there are only two diodes conducting at any time. A full six-diode model was also considered, with an extended logic block which allowed three diodes to conduct simultaneously, but was found to give complicated algebraic loops; loop-breaking solutions caused erroneous commutation in continuous conduction mode.

2) *Hybrid Model*: The second model is a hybrid, combining the library model of a rectifier from SimPowerSystems with a Simulink state-space model of the dc link (Fig. 6). V_R is the output of the diode bridge library model, and I_{DC} is set by the load. The state variables of the dc link are the dc-link voltage V_{DC} and rectifier current I_R . A controlled current source of value I_R is connected to the SimPowerSystems rectifier model. This moves the interface between the power system circuit model and the drive from the ac side to the dc link and reduces it to the form of interface given in case 2(b). As Fig. 6 shows, the supply defines the voltage applied to the rectifier, and the dc side defines the current returned. Within the SimPowerSystems rectifier library block, local snubber values are specified for each power diode. These were sized to reflect realistic component values at 1 μ F and 1 k Ω .

3) *Evaluation of Rectifier Models*: The models were implemented and compared with an independent model using the PLECS simulation package [13]. For the tests, three values of supply impedance were considered: an ideal source with

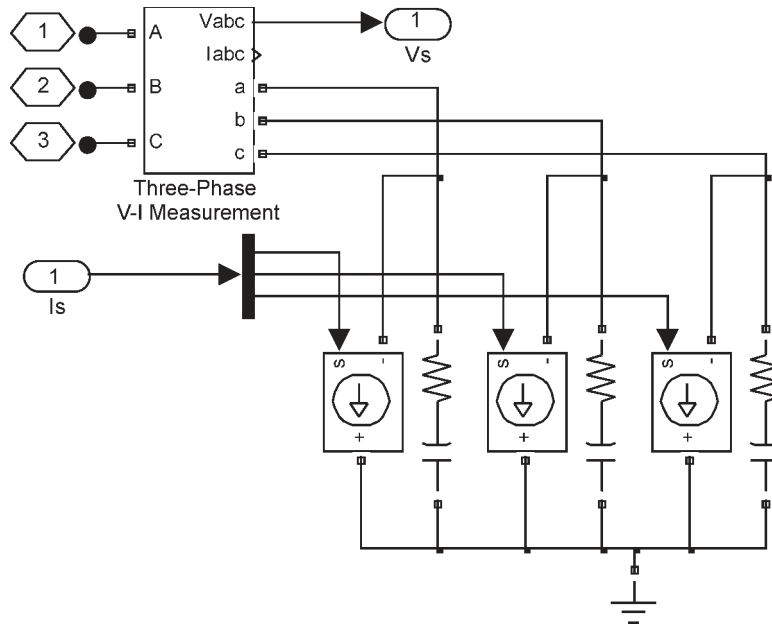


Fig. 5. Circuit components to interface with SimPowerSystems.

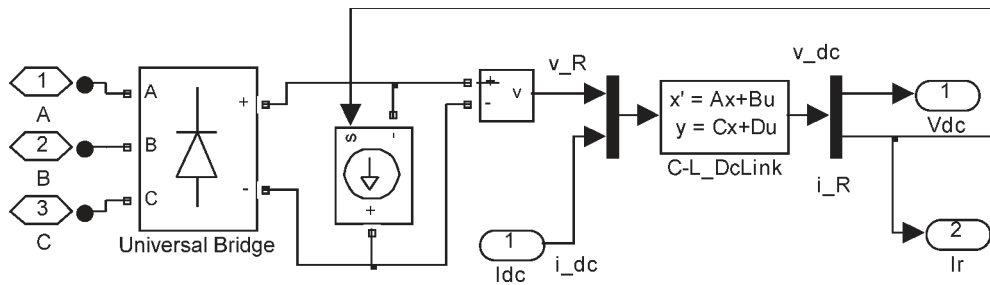


Fig. 6. Implementation of the hybrid rectifier model.

TABLE II
COMPARISON OF SUPPLY CURRENT HARMONIC DISTORTION BETWEEN THE PLECS AND EQUIVALENT CIRCUIT MODELS

Conditions	Model	$I_{R\ fund}$ (A)	THD ₁ (%)
Ideal source, discontinuous I_R	Plecs	997.3	79.28
	E.C.	997.3	79.28
Ideal source, continuous I_R	Plecs	2418	48.88
	E.C.	2418	48.88
Stiff source, discontinuous I_R	Plecs	1009	82.73
	E.C.	1009	82.82
Stiff source, continuous I_R	Plecs	2424	54.56
	E.C.	2418	48.89
Weak source, discontinuous I_R	Plecs	144.3	79.76
	E.C.	143.1	78.72
Weak source, continuous I_R	Plecs	2208	22.38
	E.C.	2397	29.99

no line impedance, a stiff source with 1.5% reactance, and a weak source of 15% reactance (with a 20-MV · A base). The ODE23tb integration method was used, with a maximum step size of 100 μ S.

Table II compares harmonic distortion between the reference PLECS model and the EC (diode logic) model. Results for the hybrid model have been omitted because they were indistinguishable from the reference PLECS model in all cases. As might be expected, the assumption that overlap can be neglected is not significant for a stiff source and with discontinuous

conduction but makes a significant difference to line currents in continuous conduction mode, particularly with a weak source. This is shown in Fig. 7, which compares supply-side line to neutral voltages and line currents, for a stiff source in continuous conduction mode.

The results presented so far are for the Simulink-only model, with the voltage source represented as an ideal signal. When the model was embedded in the power network, using the interface shown in Fig. 5, the model gave increasing problems as the line inductance was increased. With a stiff source, current-matching RC circuit values of 10 mF and 1 Ω gave a stable simulation. Larger values of resistance and lower values of capacitance gave excessive simulation times or led to convergence problems. However, the resulting current flowing through the current-matching circuits was considerable and caused excessive distortion to waveforms. In the case of a weak source, the current-matching values required for the model to stably run produced such large leakage currents in that they became the dominant feature in the waveforms, making the model ineffective and the EC approach unsuitable.

By contrast, the hybrid model was found to run effectively. Even with continuous conduction and a weak supply, the results were indistinguishable from the PLECS reference model, as shown in Fig. 8. Simulation times were also comparable, for example, within 10% for a strong source.

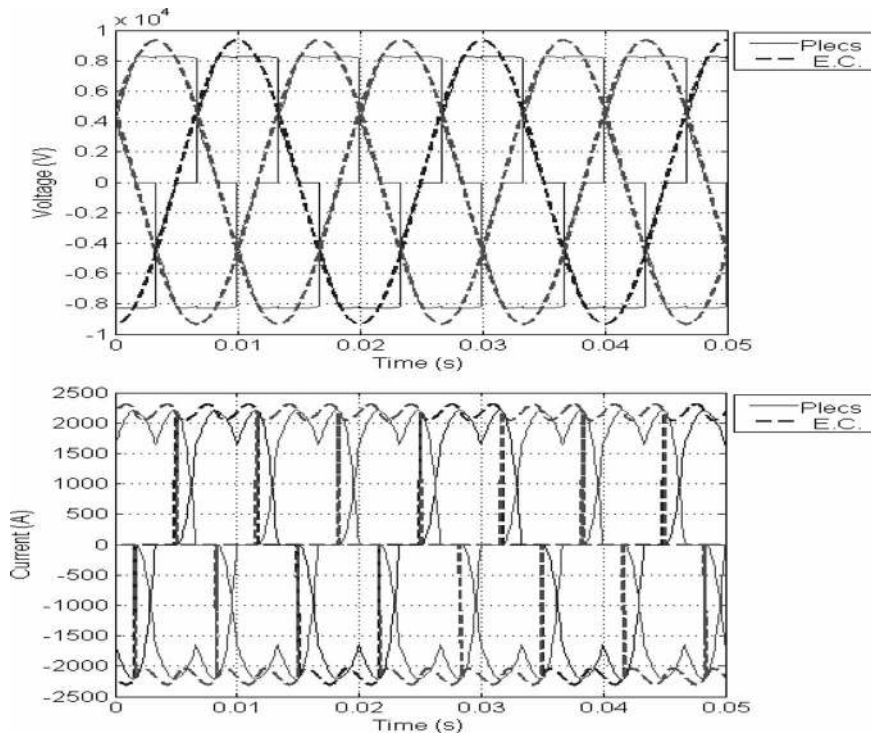


Fig. 7. Comparison of supply line to (upper) line voltages and (lower) line currents between the PLECS and EC models.

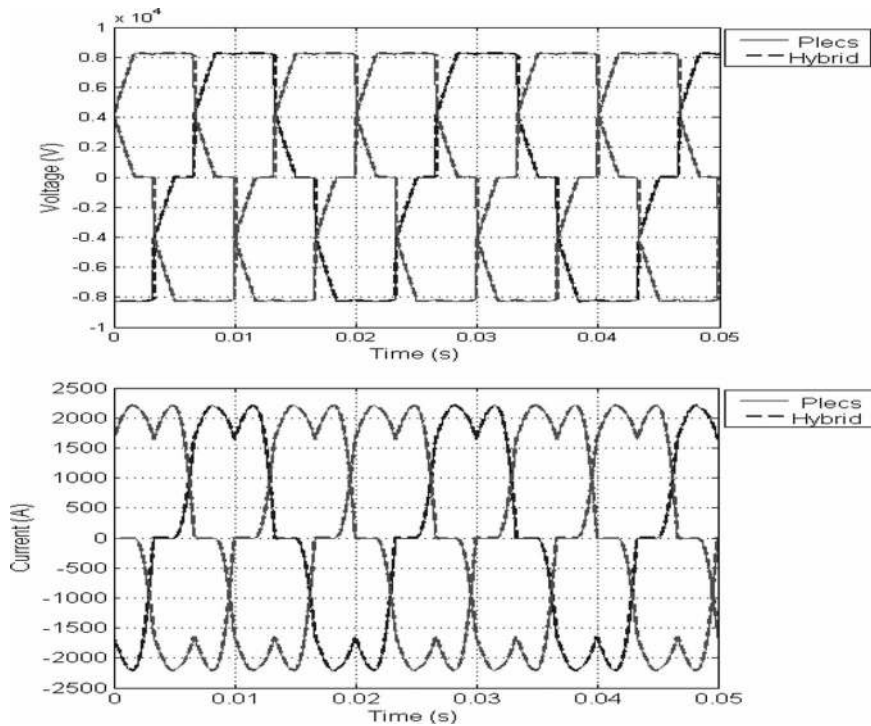


Fig. 8. Comparison of supply line to (upper) line voltages and (lower) line currents between the PLECS and hybrid models.

C. Motor

Multiphase induction machines are used in marine propulsion drives because of their inherent fault tolerance and reduced power rating per phase. They may also give better efficiency and smoother torque. Reference [14] shows that, for a multiphase machine, the Park transformation can be replaced by a general symmetric-component transformation. For an m -phase

machine with an odd number of phases, the stator phases are transformed into $(m-1)/2$ dq sets and one zero-sequence set. For ideal sinusoidal windings, only the fundamental dq set produces a net stator mmf and creates torque. Hence, the multiphase machine may be controlled in the same way as a three-phase machine, with $m-2$ additional constraints in that all higher order and zero-sequence currents are kept to zero

[15], since these sequence sets contribute only to motor losses. For clarity, only the expressions for an odd number of phases are given in the following:

$$\mathbf{x}_{dq0} = \mathbf{T}\mathbf{x}_{abc} \quad (1)$$

where

$$\begin{aligned} \mathbf{x}_{abc} & [x_a, x_b, x_c, \dots, x_m]^T; \\ \mathbf{x}_{dq0} & [x_{d1}, x_{q1}, x_{d3}, x_{q3}, \dots, x_{d(m-2)}, x_{q(m-2)}, x_0]^T; \\ T_{k,l} & \sqrt{2/m} \cos[(k+1)(l-1)\alpha/2] \text{ for } k \text{ odd}; \\ T_{k,l} & \sqrt{2/m} \sin[k(l-1)\alpha/2] \text{ for } k \text{ even}. \end{aligned}$$

k and l vary from one to m , and the displacement between phases is $\alpha = 2\pi/m$. \mathbf{x}_{abc} and \mathbf{x}_{dq0} may represent any motor electromagnetic variable (for example, voltage, current, and flux linkage) in the winding and transformed coordinate spaces, respectively.

The fundamental dq motor equations are identical to those for a three-phase machine. The additional higher order and zero-sequence sets do not include any rotor variables since there is no rotor excitation in these sets and they are decoupled in the stationary reference frame

$$v_{dq_s(2n-1)} = R_s i_{dq_s(2n-1)} + p L_s i_{dq_s(2n-1)} \quad (2)$$

where $n = 2, \dots, (m-1)/2$.

The model assumes rotor-flux-oriented control and orients rotor flux by the slip calculator method as representative of the operating envelope and bandwidth of the machine.

As with the three-phase case, the dq model neglects winding harmonics, although the extension to concentrated winding or synchronous PM machines would be relatively minor, as models for these machines are well documented and the mapping to higher order dq sets and their current control is already in place. For example, [16] is for a synchronous reluctance machine, demonstrating the wider application of the general symmetric-component transformation to other machine technologies. Each additional harmonic increases the order of the motor model by two.

The averaged-voltage-vector approach omits PWM harmonics, which can contribute additional copper losses and pulsating torques. For a given PWM strategy and winding arrangement, pulsating torques may be calculated offline using complex harmonic analysis [17] and injected as a disturbance torque. With a balanced supply and machine, the frequency of these pulsations f_p is an even multiple of the product of the number of phases and the principal excitation frequency f_e . Calculation of the magnitude requires knowledge of both the stator current waveform and the machine winding distribution, as given in [17]

$$f_p = 2m f_e. \quad (3)$$

The omission of stator harmonic losses, iron losses, and also of power electronic switching losses was considered acceptable since the focus was on electromechanical interactions rather than efficiency and loss calculations.

D. Driven Load

The propeller model calculates torque (Q) and thrust (T) from nondimensional torque and thrust coefficients K_Q and

K_T , respectively,

$$T = \rho n^2 D^4 K_T \quad Q = \rho n^2 D^5 K_Q \quad (4)$$

where n is the propeller speed, D is the propeller diameter, and ρ is the water density.

The torque and thrust coefficients are a function of the propeller geometry and the nondimensional advance number J , which is the ratio of ship advance speed V_A to propeller speed, given as nD (in units of $2\pi \text{ m} \cdot \text{s}^{-1}$)

$$J = V_A/n \cdot D. \quad (5)$$

The ship advance speed gives the approach speed of the water at the propeller inlet. It is less than the ship speed V_S due to the wake. Full modeling of wake effects is complex, but the dominant term is frictional. The ship advance speed is calculated from the wake fraction w , which is a ship design parameter

$$V_A = V_S(1 - w). \quad (6)$$

For a family of propellers of similar geometry, torque and thrust can be calculated for a given combination of propeller and ship advance speeds. Tables of coefficients may be obtained from computational models or manufacturers' tests. The results in the following are based on the well-characterized Wageningen (Troost) B series of propellers, for which extensive test data are available [18]. Motor and propeller speeds are calculated using the normal equations of motion.

The test data in [18] are only valid for a limited range of positive advance numbers. For zero or negative propeller and ship advance speeds, modified torque and thrust coefficients are used as a function of advance angle β , which is the angle of the resultant of the propeller velocity and ship advance velocity, normally defined at a point that is 70% along the radius [18], [19]. Expressions for the torque and thrust and values for modified coefficients were obtained from [18]

$$\beta = \tan^{-1} [V_A/(0.7\pi \cdot n \cdot D)]. \quad (7)$$

The ship is treated as an inertial mass m , acted on by the sum of propeller thrusts T , with a resistive drag R_f that is proportional to the square of ship velocity V_S^2 . The normal equation of motion applies. Resistive drag can be calculated approximately from ship dimensions or obtained more accurately from the ship designers.

IV. VALIDATION

The rectifier models were validated against the more-detailed independent commercial software package PLECS [13], as outlined in Section III. Motor and controller models have been tested by implementation on a multiphase laboratory test system [17] with a dSpace controller. The test machine was coupled to a dc load machine, which operated in speed control. Fig. 9 compares simulated and experimental results for a ramp change in flux current followed by a step in torque current for a six-phase machine. There is good agreement in predicted speed and currents.

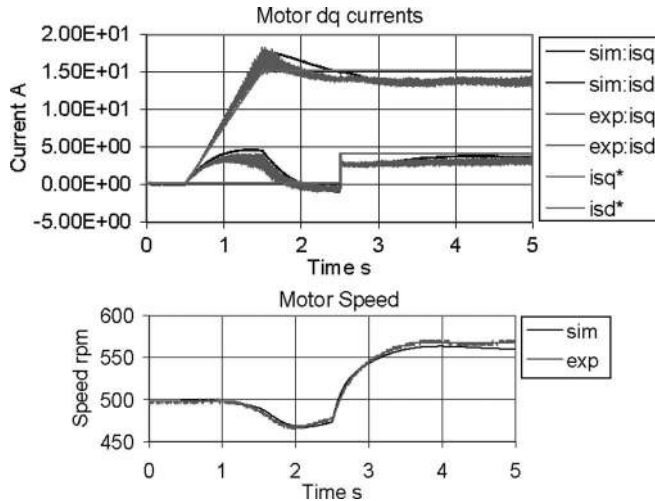


Fig. 9. Comparison of experimental (exp) and simulation (sim) results for a ramp-up in flux current (isd) followed by a step in torque current (isq).

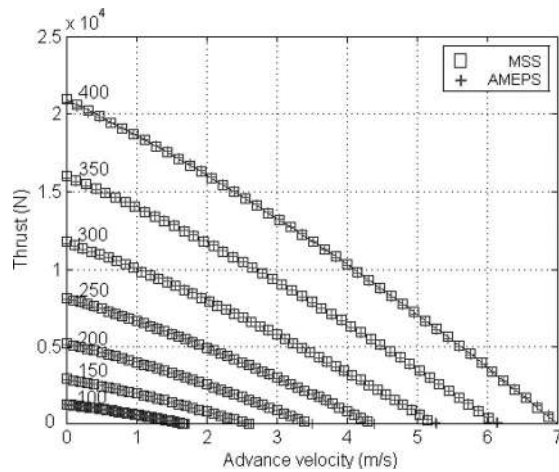


Fig. 10. Verification of calculated propeller thrust as a function of advance velocity.

The propeller models have been validated against the static performance curves in [18] and also compared with the results from the independent Marine Systems Simulator [2]. For example, Fig. 10 shows no discernible difference between the calculated thrusts from the two models.

V. CASE STUDY

Fig. 11 shows results from the propulsion system models for a ship accelerating to full speed. The 20-MW propulsion motor is limited to an operating envelope of 150% rated torque and 100% rated speed. The propeller accelerates much faster than the ship, and maximum torque and thrust occur as the propeller reaches its maximum speed. As the ship approaches full speed, the torque and thrust reduce. After 100 s, a 0.1-Hz thrust disturbance, with magnitude of 10% of the steady-state thrust, is applied. This is used to represent effects of high seas and, in extreme conditions, propeller emergence. Fig. 11 shows that the ship's speed is virtually unaffected because of its high inertia. However, the disturbance is clear in the motor torque and is passed back through to the supply current.

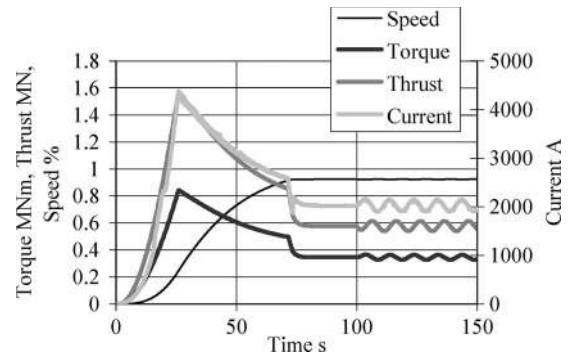


Fig. 11. Ship acceleration to full speed and response to disturbance thrust applied after 100 s.

This has implications for the power network, which has been shown in a separate study [20] to be sensitive to low-frequency changes in load power, demonstrating the value of an integrated electromechanical simulation tool.

VI. CONCLUSION

The limiting element in the propulsion drive model in terms of minimum time step and maximum computation times was found to be the power converter—specifically the interface with the power network. The best solution was found to be to locate the interface between the Simulink and power network models at the dc link, where current matching occurs in the dc-link capacitor. From this point onward, the drive system is deterministic, and reduced-order models can be used successfully. The SimPowerSystems rectifier model gave optimum results, as alternative theoretically better solutions could not be interfaced to the network without making compromises in the design.

The proposed drive system models have been used to show how load perturbations transfer to the electrical network. This is useful in itself for studying dc-link voltage regulation and propeller control strategies. The next step will be to look at the consequences for the complete IFEP system.

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