Modelling of 15-Phase Induction Motor Drive for Electric Ship Propulsion System

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Abstract: - The naval integrated power systems (IPS) often utilize electrical machines with large number of phases and magnetic poles. This paper describes a coupled-circuit physical-variable modelling of a 15-phase 20 MW baseline induction motor driven by a voltage source inverter (VSI). The equations for the self and mutual inductance matrices for a machine with an arbitrary number of phases and/or phase groups on the stator and rotor are presented. Detailed simulation studies include normal balanced/symmetrical operation as well as abnormal operation caused by loss of two phases/windings from the same phase group. The proposed models can be used for other transient studies involving inverter-motor interaction, switching harmonics, torque ripple, multiple faults, system-level studies, survivability, reconfiguration, etc.

Key-Words: - naval electric systems, electric ship, propulsion, induction motor drives.

1 Introduction

The integrated power system (IPS) of a future electric ship, such as Canadian Navy Joint Support Ship, Single Class Surface Combatant, Royal Navy's T-45, etc., represent a finite inertia electromechanical system with many power-electronicbased modules and various controls. A simplified diagram (port side) of a typical IPS is shown in Fig. 1, wherein several diesel-electric generators and two propulsion motors are considered [1]. The system layout and appropriate switching gear are designed for operational redundancy and increased reliability. With installed propulsion power in the range of 30 -40 MW, the propulsion motors are typically operate in 0 - 180 rpm speed range. To satisfy the design and operational specification of the ship, the propulsion motors with large number of phases and magnetic poles are often considered [2], [3]. Both synchronous as well as induction motors are presently being actively researched and tested for applications with modern electric ships [4]-[6].

Computer simulation represents a powerful mechanism for predicting the dynamic performance of electrical subsystems under various conditions. In particular, accurate dynamic/transient models can be used for investigating complex survivability scenarios involving, for example, a complete loss of



Fig. 1: Port side of a typical integrated power system.

one main bus (port or starboard) and featuring the subsequent dynamics of the automatic system reconfiguration. Other scenarios might involve investigating a fault caused by a missile hit of any major electrical equipment such as a generator or a converter and predicting its impact on the overall system stability. Overall, interests include: (i) stability and dynamic performance under faults and pulsed loads, (ii) power quality, (iii) efficiency, (iv) automatic reconfiguration, and (v) survivability, which is the ultimate goal.

Results of such studies in the preliminary design phase of any ship can provide very valuable information about how to physically configure the vital electrical subsystems and/or modules in order to increase the survivability of the vessel. Moreover, considerable savings of time and funding can be achieved if, instead of building the real hardware demonstrators for concept validation, the investigation of various survivability scenarios is performed using the appropriate models and simulation tools.

There are numerous simulation languages and programs that can be used to create a detailed model of an induction machine and the corresponding power electronic inverter system. However, a nonstandard multiphase machine models are not commonly available and/or often difficult to implement using the existing library components of commonly used simulation packages (EMTP, PSCAD, VTB, etc.). This paper extends the modelling approach introduced in [7] to a 15-phase baseline propulsion motor for the transient and/or system-level studies. The developed dynamic model can be readily used for investigating various survivability scenarios that may be of interest to the Canadian Navy.

2 Detailed Model of the System

A simplified circuit diagram of the 15-phase induction motor drive considered in this paper is depicted in Fig. 2, for which the model is developed as follows.



Fig. 2: Fifteen-phase induction motor drive system simplified circuit diagram.

2.1 Coupled-Circuit Modelling Approach

A power electronic circuit containing electrical machines can be defined using branches composed of simple elements as depicted in Fig. 3. The first two branches are topological duals. Simple resistors, inductors, or sources can be represented by setting the appropriate parameters of the elementary branch types to zero.



Fig. 3: Branches: (a) inductive, (b) capacitive, (c) switch.

Based on this approach, a simulation package has been developed [8], wherein a complex circuit can be defined by a branch list composed of statements such as

$$L_branch(bn, pn, nn, r, L, e, Iic);$$
 (1)

which defines an inductive branch, for example. Here, **bn** is the branch number; **pn** and **nn** are the positive and negative nodes; **r**, **L**, and **e** are the branch series resistance, inductance, and the voltage source; and **lic** is initial inductor current, respectively. A mutual inductance between any two branches can be specified using a statement

$$\mathbf{L}_{\mathbf{mutual}(\mathbf{b1}, \mathbf{b2}, \mathbf{Lm});}$$
(2)

where: **b1** and **b2** are the inductive branch numbers and **Lm** is the mutual inductance. Other circuit branches may be defined using similar syntax.

The topology of the overall system is changing depending on the state of each inverter leg. A basic algorithm for generating the corresponding state equations has been set forth in [9]-[12]. The final state equation for the i^{th} topological instance has the following implicit form

$$\mathbf{M}^{i}(\boldsymbol{\theta}_{r})\frac{d\mathbf{x}^{i}}{dt} = \mathbf{F}^{i}\left(\mathbf{x}^{i},\boldsymbol{\theta}_{r}\right) + \mathbf{g}^{i}\left(\mathbf{u}\right)$$
(3)

where $\mathbf{M}(\theta_r)$ is a positive-definite mass matrix, $\mathbf{F}(\mathbf{x}, \theta_r)$ is a term that contains state-self dynamics, and the forcing term $\mathbf{g}(\mathbf{u})$ accounts for external inputs from independent sources. For the inductive network with time-varying parameters, the terms of the state equation may be expressed

$$\mathbf{M}^{i}\left(\mathbf{x}^{i},t\right) = \mathbf{B}_{b}^{i}\mathbf{L}_{br}\left(\mathbf{B}_{b}^{i}\right)^{T}$$
(4)

$$\mathbf{F}^{i}\left(\mathbf{x}^{i},t\right) = -\mathbf{B}_{b}^{i}\left(\mathbf{R}_{br} + \frac{d\mathbf{L}_{br}}{dt}\right)\left(\mathbf{B}_{b}^{i}\right)^{T}\mathbf{i}_{\text{link}}$$
(5)

Here, \mathbf{B}_b^i is a basic loop matrix that relates the branch and link currents as $\mathbf{i}_{br} = (\mathbf{B}_b)^T \mathbf{i}_{\text{link}}$. The diagonal elements of the network inductance matrix \mathbf{L}_{br} represent the branch self inductance, and the off-diagonal elements, if nonzero, represent mutual coupling between the branches. In general, any of the parameters can vary with time.

A although the rotor windings are not explicitly shown in Fig. 2, the stator and rotor windings are magnetically coupled. This coupling should be specified in terms of inductive coupling among the respective stator and rotor circuit branches, which in turn can be conveniently expressed as the machine inductance matrix

$$\mathbf{L}_{br_machine} = \begin{bmatrix} \mathbf{L}_{s} & \mathbf{L}_{sr}(\theta_{r}) \\ \mathbf{L}_{sr}^{T}(\theta_{r}) & \mathbf{L}_{r} \end{bmatrix}$$
(6)

In (6), the matrix \mathbf{L}_s represents the stator windings self- and mutual-inductances. Similarly, \mathbf{L}_r represents the rotor windings self- and mutualinductances. Since the induction machines are assumed to be round and symmetrical, these two matrices do not depend on the rotor position and are assumed constant. The mutual coupling between the rotor and stator windings is represented by $\mathbf{L}_{sr}(\theta_r)$, which is a matrix with dimensions 15×15 with entries that dependent on the rotor position θ_r .

To complete the model, the developed electromagnetic torque can be calculated as

$$T_e = \frac{P}{2} \mathbf{i}_{abcs1-5}^T \frac{\partial \mathbf{L}_{sr}(\theta_r)}{\partial \theta_r} \mathbf{i}_{abcr1-5}$$
(7)

where: *P* is the number of magnetic poles, $\mathbf{i}_{abcs1-5}$ and $\mathbf{i}_{abcr1-5}$ are the vectors consisting of the stator and rotor phase currents

$$\mathbf{i}_{abcs1-5} = [i_{as1}, i_{bs1}, i_{cs1}, \dots, i_{bs5}, i_{cs5}]^T$$
(8)

$$\mathbf{i}_{abcr1-5} = [i_{ar1}, i_{br1}, i_{cr1}, \dots, i_{br5}, i_{cr5}]^T$$
(9)

which are the subsets of \mathbf{i}_{br} , respectively.

2.2 Machine Inductances

When 6 and more phases are considered, the phases may be grouped for better utilization of the

phase zones [7]. Other advantages may include possible reconfiguration and increased reliability when considered together with inverter operation.

For the 15-phase motor considered, the stator is composed of five 3-phase winding groups. The corresponding stator winding magnetic axes are shown in Fig. 4, wherein the angular displacement between the phases in the same group is $\alpha_s = 2\pi/3$ (120 electrical degrees), and the displacement between adjacent groups is $\beta_s = 1\pi/15$ (12) electrical degrees). Although various arrangements can be made regarding the neutral point of each group of windings, herein all neutral points are assumed connected to a common point that is left floating. In this case, each winding (and the corresponding inverter leg) has to carry about 1/5 of the phase current on an equivalent 3-phase motor. This arrangement of the neutral points is preferred when considering failure of one or more phases (windings). In particular, it was shown in [13] that in order to reconstruct the same rotating mmf with equal and minimal magnitude of currents in the remaining healthy phases, the connection of the neutral points is required. The rotor winding groups are assumed to be similar, $\alpha_r = 2\pi/3$ and $\beta_r = 1\pi/15$.

In general, entering the mutual inductances using statements like (1) and (2) for an electrical machine with a large number of phases and coupled windings can be quite tedious. Instead, a set of new function has been developed. The inductance matrices in (6) can be expressed in terms of smaller block-matrices corresponding to each of the group as



Fig. 4: Stator winding magnetic axes considering five Y-groups.

$$\mathbf{L}_{s} = \begin{bmatrix} \mathbf{L}_{s1s1} & \mathbf{L}_{s1s2} & \cdots \\ \mathbf{L}_{s2s1} & \mathbf{L}_{s2s2} & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}$$
(10)

$$\mathbf{L}_{sr} = \begin{bmatrix} \mathbf{L}_{s1r1} & \mathbf{L}_{s1r2} & \cdots \\ \mathbf{L}_{s2r1} & \mathbf{L}_{s2r2} & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}$$
(11)

$$\mathbf{L}_{r} = \begin{bmatrix} \mathbf{L}_{r1r1} & \mathbf{L}_{r1r2} & \cdots \\ \mathbf{L}_{r2r1} & \mathbf{L}_{r2r2} & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}$$
(12)

The expressions for the self- and mutualinductances can be obtained using the magnetic axes of the respective windings shown in Fig. 4. The key is to first express the spacial angle $\gamma_{i,j}$ between any two i^{th} and j^{th} magnetic axes in terms of the indices corresponding to the phases (l, n) the phase groups (k,m). With this in mind, the entries of the stator and rotor inductance matrices are defined as

$$\gamma_{i,j}^{s} = \alpha_{s}(n-l) + \beta_{s}(m-k);$$

$$\mathbf{L}_{s}(i,j) = \begin{cases} L_{ms} + L_{ls}, & \text{if } i = j \\ L_{ms} \cos(\gamma_{i,j}^{s}) \end{cases};$$
where
$$\begin{cases} i = 3(k-1) + l \\ j = 3(m-1) + n \end{cases};$$
(13)

where

k, m = 1...5, and l, n = 1...3

$$\gamma_{i,j}^{r} = \alpha_{r} (n-l) + \beta_{r} (m-k);$$

$$\mathbf{L}_{r} (i, j) = \begin{cases} L_{ms} + L_{lr}, & \text{if } i = j \\ L_{ms} \cos(\gamma_{i,j}^{r}) \end{cases};$$
(14)

where $\begin{cases} i = 3(k-1)+l\\ j = 3(m-1)+n \end{cases}$;

$$k, m = 1...5$$
, and $l, n = 1...3$

The rotor-to-stator mutual inductance matrix can be expressed as

$$\gamma_{i,j}^{sr} = -\alpha_{s} (l-1) - \beta_{s} (k-1) + + \alpha_{r} (n-1) + \beta_{r} (m-1);$$

$$\mathbf{L}_{sr} (i, j) = L_{ms} \cos(\theta_{r} + \gamma_{i,j}^{sr})$$

where
$$\begin{cases} i = 3(k-1) + l \\ j = 3(m-1) + n' \\ k = 1...5, \text{ and } l = 1...3 \\ m = 1...5, \text{ and } n = 1...3 \end{cases}$$
 (15)

Note that implementation of (13)-(15) results in 4th order nested loops, which is readily implemented in computer code. These functions have been implemented with the syntax similar to (1), (2). In particular, the stator or the rotor inductance matrices (8) and (10) can now be entered as

L_selfmx(B, Nph, Ng, Lm, Ll, beta); (16)

where **B** is an array containing the respective branches; Nph is the number of phases; Ng is the number of phase groups: Lm and Ll are the mutual and the leakage inductances, respectively; and beta is the angular displacement between the phase groups. The rotor-to-stator mutual inductance matrix (9) can be specified using the function

L mutmx(B1,Nph1,Ng1,beta1,

B2,Nph2,Ng2,beta2, theta); (17)

where **B1** and **B2** are the arrays containing the respective stator and rotor branches; Nph1 and Nph2 are the number of phases in each; Ng1 and Ng2 are the number of phase groups in each; beta1 and **beta2** are the respective angular displacements; and theta is the angle between the B1 and B2 (stator and rotor) windings.

It should be pointed out that because (13)-(15)are very general, the statements (16)-(17) can be used to define the inductance matrices corresponding to an induction machine with any number of phases and/or winding groups.

3 Studies

The automated state model generator toolbox [8] interfaced with MATLAB/SimulinkTM [14] has been used to implement the final models. The per-unit parameters of the baseline 15-phase 20-MW motor are summarized in Appendix a). The motor is assumed to be fed from a voltage source inverter (VSI) as shown in Fig. 2.

Because the stator winding groups have a common floating neutral point, the zero sequence is not present in the phase voltages as seen by the stator. For the 15-phase case, the inverter output for the 180 degrees operation will have 30 steps as depicted in Fig. 5. The stator phase voltages are related to the inverter output voltages as

$$\mathbf{v}_{abcs1-5} = (\mathbf{I} - \mathbf{U}/15)\mathbf{v}_{abcg1-5}$$
(18)

where **I** is the 15×15 identity matrix, and **U** is the square matrix of the same dimensions filled with ones. Eq. (18) is similar to the relationship derived for the 3-phase inverter operation [16]. The phase voltages (and currents) are ordered as follows

$$\mathbf{v}_{abcs1-5} = [v_{as1}, v_{bs1}, v_{cs1}, \dots, v_{bs5}, v_{cs5}]^T$$
(19)

The VSI is assumed to operate using the pulsewidth modulation (PWM) with switching frequency of 2kH [5]. A fragments of reference voltage v_{as1_ref} , phase voltage v_{as1} , and phase current i_{as1} are shown in Fig. 6. This operation corresponds to a steady state condition of the motor drive at full load. It can be noticed that although the switching frequency is relatively low, the current ripple is within acceptable range. Moreover, the considered baseline motor is capable of achieving relatively high power factor due to the large number of phases and poles [5]. In particular, as seen in Fig. 5, the phase difference between voltage v_{as1_ref} and current i_{as1} is on the order of 0.0041s, which corresponds to the power factor angle of 26.57° and power factor of 0.89, respectively.

In the following transient study, the motor is assumed to operate in a steady-state under full mechanical load. The propulsion load is assumed to have a predominantly quadratic torque-speed characteristic given in Appendix b). In the following study, a simultaneous loss of phases a1 and b1 from the first group abc1 is considered. At t = 0.15s, the corresponding phase windings are being opencircuited and the resulting transients are shown in Figs. 7 and 8. As can be observed in Fig. 7, the current in the remaining operational phases increases unevenly. This is also followed by an increase of the torque ripple and a momentary reduction of the average torque and speed, as shown in Fig. 8.



Fig. 5: Voltage output waveforms for 30-step 180 degrees VSI operation.



Fig. 6: Steady state stator voltage and current for the phase *as*1.



Fig. 7: Stator currents response to loss of *as*1 and *bs*1 phases from *abcs*1 group.

4 Conclusion

In this paper, a coupled-circuit physical-variable modelling of a 15-phase 20 MW baseline induction motor drive system has been discussed. Presented simulation studies demonstrate the motor operation from VSI with PWM in normal (balanced and symmetric) and abnormal (loss of multiple phases) conditions. The developed model is appropriate for fairly detailed time-domain transient/dynamic studies of electric ship propulsion systems that may be of interest to the Canadian Navy Joint Support Ship and Single Class Surface Combatant programs. This paper also serves as a proof of the modelling concept for the further work related to the integrated electric propulsion projects for the Department of National Defence, Canada, subject to approval of funding.



Fig. 8: Torque and speed response to loss of *as*1 and *bs*1 windings.

Appendix

a) Induction machine per-unit parameters:

$$\begin{split} P_b &= 20MW \; ; \; T_b = 1.0706MN \cdot m \; ; \; \omega_b = 2 \cdot \pi \cdot 18 \frac{rad}{s} \; ; \\ V_b &= 5kV \; ; \; I_b = 461.88A \; ; \; r_s = 0.0080 ; \; x_{ls} = 0.0101 \\ r_r &= 0.0086 ; \; x_{lr} = 0.0133 \; ; \; x_m = 1.76 \; ; \; H = 2.68 \; . \end{split}$$

b) Load torque-speed characteristic in per-unit $T_m = 0.0136 \cdot \omega_r + 1.0158 \cdot \omega_r^2$

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