High speed machines using advanced magnetic materials analyzed by appropriate finite element models

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Abstract: - The paper presents a methodology for electrical machine modeling enabling to exploit new magnetic material characteristics. The proposed models enable analysis of high speed electrical machines, favored in recent marine applications. The materials considered are thin magnetic laminations, amorphous alloy ribbons as well as Neodymium alloy permanent magnets involving very low eddy current losses. Such materials enable electric machine operation at high frequencies compared with the standard iron laminations used in the traditional magnetic circuit construction. Moreover, simpler winding configurations are adopted, taking into consideration that there will be a power electronics converter ensuring the connection of the machine to the electric installation.

Key-Words: - Advanced magnetic materials, finite element method, induction motor, iron losses.

1 Introduction

Recent technological trends favor ‘All Electric’ ship strategy development in marine engineering applications. This strategy, envisages the use of long life, fuel efficient, advanced cycle marine gas turbine alternator sets in an integrated electric population system driving appropriate generators, [1],[2]. In this paper, the study of asynchronous and permanent magnet machines based on such materials is undertaken in three steps. In a first step the typical design procedure is conveniently adapted in order to include the new magnetic material properties [3],[4]. In a second the designed machine characteristics are checked by means of a detailed field calculation through finite element modeling associated to sensitivity analysis techniques [5]. In a third step a prototype is constructed in order to validate the machine performance [6],[7]. Low losses and high volumic power associated with high speed and converter machine operation are the main advantages of such applications [8],[9].

2 Finite Element Modeling

The method of finite elements, is based on a discretisation of the solution domain into small regions. In magnetostatic problems the unknown quantity is usually the magnetic vector potential $A$, and is approximated by means of polynomial shape functions. In two dimensional cases triangular elements can easily be adapted to complex configurations and first order elements exhibit advantages in iron saturation representation. The size of elements must be small enough to provide sufficient accuracy. In this way the differential equations of the continuous problem can be transformed into a system of algebraic equations for the discrete problem. The practical problems necessitate usually several tenths of thousands of unknowns. However, appropriate numerical techniques have been developed, enabling to obtain the solution of such systems within reasonable time, even when personal computers are used. It should be mentioned that the 3D problems require considerably higher computational resources than the 2D ones. In the present paper the 2D finite element model adopted, involves vector potential formulation, while the magnetic flux $\Phi_m$ per pole can be calculated as follows:

$$\Phi_m = \int A \cdot dS = \oint A \cdot dl = (2A_{gap}) l_0$$

where $l_0$ is the length of the magnetic circuit in m, $A$ is the magnetic vector potential, $A_{gap}$ is the vector potential value in the middle of the air-gap, $B$ is the flux density in Tesla, $S_1$ is the cross-sectional area normal to the direction of flux flow in m$^2$ and $C_1$ is
the contour surrounding the surface $S_1$ in m. The electromotive force at no load can be calculated as follows:

$$E = -\frac{d\Phi_m}{dt}$$  \hspace{1cm} (2) 

The value of voltage at full load can be calculated by relation (3):

$$V = E - RI - j\omega L_\sigma I$$ \hspace{1cm} (3)

where $V$ is the voltage on stator windings in V, $E$ is the electromotive force at no load in V, $R$ is the stator resistance in $\Omega$, $L_\sigma$ is the stator leakage inductance in H, $\omega$ is the rotor angular velocity in rad/sec and $I$ is the stator current in A. Then the magnetic flux and electromotive forces can be derived by using equations (1) and (2).

Furthermore, the total resistance of stator winding can be calculated by the following relations:

$$R = \rho \frac{1}{S}$$ \hspace{1cm} (4)

where $\rho$ is the electric resistivity of copper, $l$ the winding total length and $s$ the conductor cross section. The winding length $l$ can be estimated from relation (5):

$$l=2*(l_{ax}+l_p)*N_w*P$$ \hspace{1cm} (5)

where:

- $l_{ax}$: machine's axial length (m)
- $l_p$: polar step length (m)
- $N_w$: total number of series connected turns
Finally, we calculate the iron losses for this machine at the low and high frequency operation by the equation:

\[
P_{\text{iron}} = P_{\text{total}} - P_{\text{Cu}}
\]

where \( P_{\text{Cu}} = P_{\text{Cu rotor}} + P_{\text{Cu stator}} \) (6)

### 3 Results and Discussion

The permanent magnet machine analysis procedure described previously has been applied to construct a 2.5 kW, 26 rad/sec generator to be connected to a six pulse diode rectifier bridge. The air-gap width has been chosen 1 mm while a multipole “peripheral” machine structure has been adopted (Fig. 1). The geometry of the permanent magnet machine is shown in Fig. 1a giving also the mesh employed for the two dimensional finite element program of the machine involving approximately 2100 nodes 4000 triangular elements. The corresponding magnetic field distribution at no load is shown in Fig. 1b. The field distribution at full load is given in Fig. 1c. In these figures the disymmetry caused in the field distribution by the loading current can be observed.

Figure 2 gives a comparison of the simulated flux density distribution in the middle of the air-gap with and without rotor skew by 3D FEM simulation and the same distribution obtained by 2D simulation. From the results, it comes up that the magnitude of magnetic flux density is less with rotor skew.

Moreover, measurements were realized for an asynchronous motor, which was supplied by an inverter with variable frequency. The motor is a three phase, 4-pole, machine supplied at a frequency of 400 Hz, at a voltage of 208 V while the nominal, speed is 10.800 rpm. The motor was tested under no load and low load operating conditions, for various frequencies. The test results are presented in table 1. Figure 4a shows the field distribution in the machine supplied at fundamental frequency of 300 Hz, while Fig. 4b gives the field distribution at the switching frequency of 11 kHz.

In table 2 are given the simulated results for motor torque, which are in good agreement with the experimental ones. The experimental and simulated results for the resistance of the stator windings are presented in table 3. Moreover, the iron losses have been calculated and the results of this investigation are tabulated in table 4. From figure 6, showing the respective measured voltage and current spectra, the total power and the iron losses at the switching frequency can be determined.
Fig. 4: Simulated field distribution in the machine
a: fundamental supply frequency of 300Hz, at low-load
b: switching frequency of 11 kHz, at low-load

Table 1: Test results for the 4-pole asynchronous motor

<table>
<thead>
<tr>
<th>f (Hz)</th>
<th>$V_{\text{rms}}$ (V)</th>
<th>$I_{\text{rms}}$ (A)</th>
<th>$T$ (Nm)</th>
<th>$P$ (W)</th>
<th>$n$ (rpm)</th>
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<tr>
<td>50</td>
<td>18</td>
<td>2.7</td>
<td>0.1</td>
<td>10</td>
<td>1183</td>
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<tr>
<td>250</td>
<td>120</td>
<td>5.3</td>
<td>0.4</td>
<td>57.5</td>
<td>7090</td>
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<tr>
<td>300</td>
<td>140</td>
<td>5.9</td>
<td>0.5</td>
<td>55</td>
<td>8488</td>
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<tr>
<td>300</td>
<td>137</td>
<td>8.4</td>
<td>1.1</td>
<td>75</td>
<td>8073</td>
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Table 2: Test and simulated results for the motor torque

<table>
<thead>
<tr>
<th>f (Hz)</th>
<th>$T$ (Nm)</th>
<th>$T$ (Nm)</th>
<th>$T$ (Nm)</th>
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</tr>
</thead>
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<tr>
<td></td>
<td>Experiment</td>
<td>Simulation</td>
<td>Experiment</td>
<td>Simulation</td>
</tr>
<tr>
<td>300</td>
<td>0.5</td>
<td>0.58</td>
<td>1.1</td>
<td>1.21</td>
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<tr>
<td>250</td>
<td>0.4</td>
<td>0.49</td>
<td>1</td>
<td>1.02</td>
</tr>
<tr>
<td>50</td>
<td>0.1</td>
<td>0.12</td>
<td>0.3</td>
<td>0.32</td>
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Table 3: Test and simulated results of the resistance of stator winding

<table>
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<th>$R_1$ (Ω)</th>
<th>$R_2$ (Ω)</th>
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<tbody>
<tr>
<td>Experiment</td>
<td>0.56</td>
<td>0.62</td>
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Fig. 5: Measured supply quantities in the machine for supply frequency of 300Hz, semi-load condition
a: phase voltage time variation
b: phase current time variation

Fig. 6: Measured frequency spectra of the supply at fundamental frequency of 300 Hz and switching frequency of 11 kHz under low-load conditions
a: Frequency spectrum of voltage
b: Frequency spectrum of current
<table>
<thead>
<tr>
<th>semi-load</th>
<th>$f$ (Hz)</th>
<th>$P_{Cu, rotor}$ (W)</th>
<th>$P_{Cu, stator}$ (W)</th>
<th>$P_{wind}$ (W)</th>
<th>$P_{iron}$ (W)</th>
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<td></td>
<td>300</td>
<td>109</td>
<td>39</td>
<td>405</td>
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<td></td>
<td>250</td>
<td>77</td>
<td>32</td>
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<td></td>
<td>50</td>
<td>5</td>
<td>11</td>
<td>15</td>
<td>170</td>
</tr>
<tr>
<td>no load</td>
<td>300</td>
<td>53</td>
<td>19</td>
<td>219</td>
<td>75</td>
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<td>2</td>
<td>4</td>
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Table 4: Results of iron losses of the motor

4 Conclusion
The paper proposes models for high speed electrical machine analysis, favored in recent marine engineering applications. 2D and 3D finite element models have been used and the results presented sufficient accuracy with the measured ones, in a permanent magnet synchronous generator prototype. The simulations performed have shown that the skew of permanent magnets in the rotor results in a reduction of the fundamental component of the electromotive force induced because of the reduction in the flux density in the air-gap. So, the stator current harmonics and torque ripple are estimated to be subsequently reduced in the case with rotor skew.

Moreover, the method of finite elements can efficiently simulate the operating characteristics associated with the fundamental frequency of a three phase asynchronous high speed machine, but the switching frequency losses need further investigation.

References: