Prediction of Performance Characteristics of Salient Pole Synchronous Generators by Finite Element Method

K. S. Jiji*, Jayadas N. H. ** and C. A. Babu**

* Department of Electrical engineering, Rajiv Gandhi Institute of Technology, Kottayam – 686 501, India

** School of Engineering, Cochin University of Science and Technology, Kochi – 682 022, India

jiji.sajeev@rit.ac.in
jayadasnh@cusat.ac.in and cababu@cusat.ac.in

Abstract— Performance prediction in electrical machines is often carried out by traditional methods which combine analytical and empirical knowledge. These methods lack accuracy as the calculation of magnetic field pattern and characteristics yield approximate results due to complicated machine geometry and nonlinear characteristics of magnetic materials associated with the machine. Finite element method is a numerical tool being extensively used as a design tool for prediction of machine parameters by electromagnetic field analysis. In this paper an attempt is made to predict the performance characteristics of salient pole synchronous generators by finite element method.

Index Terms— Synchronous generators, Total harmonic distortion, FEM, Armature windings, Maxwell’s equations.

I. INTRODUCTION

Salient pole synchronous generators coupled to IC engines are being extensively used as standby power supply units for meeting industrial power demands. Design of such generators demands for high power to weight ratio, high efficiency and low cost per KVA output. Moreover, the performance characteristics of such machines like voltage regulation, short circuit ratio (SCR) etc. are critical when these machines are put into parallel operation and alternators for critical applications like defence, aerospace etc demand very low harmonic content in the output voltage. While designing such alternators, accurate prediction of machine characteristics is essential to minimize development cost and time.

Performance prediction in synchronous generators is often carried out using traditional methods which combine analytical and empirical knowledge. These methods lack accuracy due to complex geometry and nonlinear characteristics of magnetic materials associated with the machine and performance characteristics such as magnetization characteristics, losses, currents, voltage etc. are calculated based on averaging assumptions for the magnetic field in the air gap and the core. Hence, the results of machine performance characteristics by analytic methods are enough accurate only at steady state operation of the machine and the results are unreliable for transient operation. Hence numerical field computation methods like Finite Difference Method (FDM), Boundary Element Method (BEM) and Finite Element Method (FEM) have been deployed for prediction and analysis of machine characteristics [1] by electromagnetic field analysis. However, FEM is increasingly used by designers due to its ability to handle complex geometry and presence of nonlinear magnetic materials. Due to advancements in computational capabilities over recent years FEM has become an attractive alternative to well established semi analytical and empirical design methods as well as to the still popular trial and error approach [2-3].

This paper presents the FEM based prediction of performance characteristics of a salient pole brushless synchronous generator and comparison of output voltage harmonics of the machine provided with two different layouts for the armature winding.

II. SYNCHRONOUS MACHINE DESIGN – SIGNIFICANCE OF ARMATURE WINDING LAYOUT

The synchronous generators used in diesel generating units are normally designed with different winding layouts based on the desired machine parameters like THD, transient characteristics like transient voltage diprise (TVD/TVR), transient time constants etc. The simplest type of armature winding provided for such machines is the full pitched winding which has got the advantages like single layer structure which reduces the labor put for winding process, maximum voltage induced in the windings owing to high winding factor which ultimately leads to lower size of the machine for the same KVA output and hence reduced cost. But, this type of winding is having a disadvantage like high harmonic content in the output voltage across line and neutral which may have ill effects on the sophisticated single phase loads connected across these machines. To circumvent the problem of high total harmonic distortion (THD) in the output voltage, conventionally, the main winding is wound for 2/3rd pitch which introduces complexity in winding due to arrangement of the winding in two layers leading to increased labor cost and additional insulation requirements in the slots and in the winding overhang. This type of winding results in reduced KVA due to poor winding factor and hence increase in size by about 13%.
III. FEM BASED DESIGN OF ELECTRICAL MACHINES

FEM is being extensively used as a design tool for modeling of electrical machines [4-7] and prediction of machine parameters like open circuit voltage distortion [8-11], direct axis and quadrature axis synchronous reactances [12] etc. In this paper, the performance characteristics of a 45 KVA brushless alternator like open circuit characteristics (OCC), zero power factor Characteristics (ZPFC) and air gap flux density distribution at no load and full load conditions are plotted and harmonic content in the output voltage of the machine with two different winding layouts are analyzed by finite element method.

A. FEM Formulation

The mathematical modeling of magnetic field problems in closed and bounded systems is based on Maxwell’s equations and constitutive relationships as detailed below.

\[ \nabla \times H = J + \frac{\partial D}{\partial t} \]  
\[ \nabla \times E = -\frac{\partial B}{\partial t} \]  
\[ \nabla \cdot B = 0 \]  
\[ \nabla \cdot D = \rho \]

where \( H \) = Magnetic field strength  
\( J \) = Current density  
\( D \) = Electric displacement  
\( E \) = Electric field intensity  
\( B \) = Magnetic flux density  
\( \rho \) = Volume charge density

The constitutive relationships are

\[ B = \mu H \]  
\[ D = \varepsilon E \]  
\[ J = \sigma E \]

where \( \mu \) = Magnetic permeability  
\( \varepsilon \) = Electric permittivity and  
\( \sigma \) = Electric conductivity

The field properties of the machine are invariant along the z-axis and hence 2D FEM formulation is sufficient for analysis of electrical machines thereby considerably reducing the computational time. The distribution of magnetic field in the 2D machine structure is expressed by the nonlinear partial differential equation,

\[ \frac{1}{\mu} \nabla^2 A_z = -J_z \]  
\[ \text{i.e., } \frac{\partial^2 A_z}{\partial x^2} + \frac{\partial^2 A_z}{\partial y^2} = -\mu J_z \]

where \( \mu \) = absolute permeability of magnetic field  
\( A_z \) = Magnetic vector potential in Z direction and  
\( J_z \) = Current density vector normal to the section (in Z direction)

The current density vector \( J \) has z-axis component only and the magnetic vector potential \( A \) being parallel to \( J \) has components only in the z-direction.

Solving the nonlinear partial differential equation by FEM yields the magnetic vector potential \( A \) from which the magnetic flux density \( B \) having components only in the (x,y) plane is computed using the relation

\[ B = \nabla \times A \]

From the calculated value of \( B \) at each and every point in the 2D machine structure, all field values and hence machine parameters can be computed.

B. FEM Modeling and Analysis

The FEM modeling of the synchronous machine is done using the geometrical data, material properties, winding data, period of symmetry and the boundary conditions. The specifications and the main geometrical data of the machine modeled are given in Table I. The winding data are prepared separately for full pitched machine and the 2/3 pitch pitched machine. The FEM models of the two machine configurations are analyzed separately for the harmonic content in the output voltage to ascertain the effect of the two different winding layouts on the output voltage harmonics.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SPECIFICATIONS AND GEOMETRICAL DATA OF THE MACHINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>45 KVA</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>415 V</td>
</tr>
<tr>
<td>Number of poles</td>
<td>4</td>
</tr>
<tr>
<td>Number of phases</td>
<td>3</td>
</tr>
<tr>
<td>Number of stator slots</td>
<td>36</td>
</tr>
<tr>
<td>Air gap</td>
<td>0.9 mm</td>
</tr>
<tr>
<td>Inner diameter of stator</td>
<td>240 mm</td>
</tr>
<tr>
<td>Outer diameter of stator</td>
<td>356 mm</td>
</tr>
<tr>
<td>Inner diameter of rotor</td>
<td>90 mm</td>
</tr>
<tr>
<td>Outer diameter of rotor</td>
<td>238.2 mm</td>
</tr>
<tr>
<td>Stack Length</td>
<td>130 mm</td>
</tr>
<tr>
<td>Core material</td>
<td>M43C4</td>
</tr>
</tbody>
</table>
IV. RESULTS AND DISCUSSION

The FEM models of the 45 KVA machine with the two different winding layouts are simulated for 0.8 pf, full load and the output voltage harmonics are analyzed in each case. The performance characteristics of the full pitched machine like OCC, ZPFC and air gap flux density distributions for no load and full load conditions are plotted.

The winding layouts of the two configurations are shown in Figs. 1 and 2.

![Winding layout of the full pitched machine](image1)

Fig. 1. Winding layout of the full pitched machine

![Winding layout of the machine with 2/3rd pitch winding](image2)

Fig. 2. Winding layout of the machine with 2/3rd pitch winding

The FEM models of the synchronous generator with the two different winding layouts are shown in Figs. 3 to 4.

![FEM model of 45 KVA full pitched generator](image3)

Fig. 3. FEM model of 45 KVA full pitched generator

![FEM model of the 45 KVA 2/3rd pitched generator](image4)

Fig. 4. FEM model of the 45 KVA 2/3rd pitched generator

First order triangular elements are used to discretize the field region and the finite element mesh applied to the machine models are shown in Figs. 5 to 6.

![FEM model of the full pitched generator after meshing](image5)

Fig. 5. FEM model of the full pitched generator after meshing

![FEM model of the 2/3rd pitched generator after meshing](image6)

Fig. 6. FEM model of the 2/3rd pitched generator after meshing

Flux distribution and the flux density plots of the generator with two different winding layouts are shown in Figs. 7 to 10.

![Flux distribution of 45 KVA full pitched generator](image7)

Fig. 7. Flux distribution of 45 KVA full pitched generator
Fig. 8. Flux density plot of 45 KVA full pitched generator with rotor rotted through 15°

Fig. 9. Flux distribution of 45 KVA full pitched generator

Fig. 10. Flux density plot of 45 KVA 2/3rd pitched generator with rotor rotated through 13.5°

The air gap flux density plot of the machine under no load and full load conditions are shown in Figs. 11 to 12 and the open circuit characteristics (OCC) and the zero power factor characteristics (ZPFC) are shown in Fig. 13.

Fig. 11. Air gap flux density plot at no load

Fig. 12. Air gap flux density plot at full load

Fig. 13. Open circuit characteristic (OCC) and the zero power factor characteristics (ZPFC) of the generator

The output voltage waveforms and their harmonic spectra for the two different cases are shown in Figs. 14 to 17.

Fig. 14. Output voltage waveform of 45 KVA full pitched generator

Fig. 15. Harmonic spectra of output voltage waveform of 45 KVA full pitched generator

Fig. 16. Output voltage waveform of 45 KVA 2/3rd pitched generator
On analyzing the harmonic spectra of the output voltage of the generator with full pitched winding it is observed that there is high harmonic content especially of orders third and fifth. The simulation results confirm that by introducing 2/3rd pitch armature winding; the third harmonic components are completely eliminated from the output voltage.

V. CONCLUSIONS

In this paper, a simple, fast and efficient method based on 2D FEM for predicting the performance characteristics of a salient pole brushless synchronous generator is presented. FEM proves to be an efficient numerical tool for prediction of performance characteristics of electrical machines in the design stage thus saving development time and cost by avoiding expensive and time consuming prototyping. This method can also be used for predicting machine parameters like TVD/TVR, transient time constants, transient reactances etc. without resorting to sudden short circuit test which is hazardous to the machine.

REFERENCES


