Analysis of Unbalanced Magnetic Pull in Train-Lighting Alternators with Skewed Rotor under Static Eccentricity and Conical Rotor Motion

K P P Pillai, Achuthsankar S Nair, G R Bindu

Abstract— The paper deals with the electromagnetic forces in inductor type brushless alternators, when the rotor is performing static eccentric and conical motion with respect to the stator. An investigation of the unbalanced magnetic pull (UMP) is highly essential in the case of these machines, since many failures have been reported by Indian Railways mainly due to broken shaft and bearing damage of such alternators used in railway coaches for supplying loads like lights, fans and for charging coach battery. A two dimensional finite element method is proposed for the analysis, in which the rotor skew and conical motions of the rotor are taken into account by multi-slice method.

Index Terms— Electromagnetic analysis, Eccentricity, Finite element methods, Inductor alternators.

I. INTRODUCTION

Frequent breakdowns have been reported by Indian Railways due to breaking of the shaft in three-phase inductor type brushless alternators, used in railway coaches. These failures, besides other mechanical reasons, can be attributed to unbalanced magnetic pull (UMP) due to rotor eccentricity. The paper deals with the electromagnetic forces in such alternators, when the rotor performs static eccentric motion with respect to the stator. In view of the complex geometrical shapes and boundaries, material inhomogenities and nonlinearities involved, rigorous analytical solution is not possible, unless some major assumptions are made. Hence a modified time-stepping finite element method (FEM) is proposed for the analysis, followed by multi-slice method for the modeling of rotor skew and conical motion so that the axial variations of the magnetic field are also taken into account.

II. METHOD OF ANALYSIS

Using two-dimensional finite element analysis, the governing equation is

$$\frac{\partial}{\partial x} \frac{1}{\mu} \left( \frac{\partial A}{\partial x} \right) + \frac{\partial}{\partial y} \frac{1}{\mu} \left( \frac{\partial A}{\partial y} \right) = -J$$

where, $A$ is the magnetic vector potential, $J$ is the current density in the winding and $\mu$ is the magnetic permeability. Moving the rotor mesh in discrete predetermined angular steps as the solution progresses simulates movement at constant speed. Starting from a particular position, the rotor is moved by $\Delta\theta$ degrees each time, till the original rotor-stator relative position is reached [1]. When solving (1) using Galerkin formulation, while taking account of movement, flux linkage distribution in the air gap is obtained [2],[3].

Maxwell’s stress tensor $dF$ is calculated from radial component of flux density $B_r$ by

$$d F = \frac{B_r^2}{2 \mu_0}$$

The total force created by the non-symmetric flux distribution in the air gap is then obtained by integrating Maxwell’s stress tensor around the rotor[4]. For convenience, static eccentricity factor (SEF) is considered to specify the level of static rotor eccentricity[5] as

$$SEF = \frac{\Delta}{g}$$

where, $\Delta$ is the displacement of the rotor centre vertically downwards from the stator centre and $g$ the normal air gap length.

The armature and the field windings of train lighting alternators are both accommodated in the stator. The three-phase armature winding is uniformly distributed in small slots, whereas the field winding is concentrated in two diametrically opposite larger slots. The rotor is of cogged wheel type, with no winding, as shown in Fig.1 and Table I gives the specification of a 3-phase 4.5kW train lighting alternator.
Finite element modeling of an alternator of 4.5 kW is done for different variations of static eccentricities of the rotor, the rotor centre alone being shifted vertically in negative y-direction, by a distance $\Delta$. Each time, the rotor is rotated through discrete angular steps of 5 degrees, till the original stator-rotor relative position is reached at 45 degrees. From the flux distribution so obtained, UMP for an unskewed rotor machine is calculated at no load, for three values of SEF, viz, 0.2, 0.4 and 0.6 by using a combination of FE analysis, and classical equations. Fig.2 shows the flux density distribution in an FE model with a SEF of 0.6. The variation of UMP with SEF for an alternator with unskewed rotor for two excitation values is shown in Fig 3.

In order to investigate the dependence of UMP on excitation, the procedure is repeated for two dc excitation values, at no load. Thus, for each value of SEF, 20 models of the alternator are analysed and UMP is calculated. For this a general-purpose 2D electromagnetic finite element analysis software package is used in conjunction with Microsoft Excel to perform automated simulation.

In the next step, a skew of 72 electrical degrees was introduced in the machine rotor. Rotor skew produces axial variation in the flux density pattern. This together with localized saturation produced by eccentric rotor around the narrowest air gap makes the influence of skew on UMP difficult to quantify using analytical models. The size of the problem and computation time, limit the use of 3D FEM. Hence, an alternative method, which uses multi-slice technique, is employed to model skew in 2D whereby the machine is divided into five equal slices cut by planes perpendicular to stator axis and then coupling the slices together[6]. The values of UMP at no load for three degrees of rotor eccentricities for a train lighting alternator for both unskewed and skewed rotors, at a DC excitation of 1600AT are listed in Table II, for comparison.
The conical motion of the static eccentric rotor can also be modelled likewise [7]. The rotor is divided into three slices of equal length as shown in Fig 4. The first slice is shifted vertically downwards by 0.1 mm, second slice by 0.2 mm and third slice by 0.3 mm, from the stator axis. Each of these slices is modelled by a cross section taken from the middle of the slice. The electromagnetic force acting between stator and rotor was then calculated as a slice force and the net force is the sum of slice forces. The values of resultant UMP for two different dc excitation values in an unskewed rotor machine are listed in Table III. When conical motion occurs under static eccentricity of skewed rotor machines all the techniques detailed, are to be used in unison. The values of resultant UMP for two different dc excitation values in the machine with skewed and unskewed rotors are listed in Table IV.

![Fig. 4. Modeling of Conical Motion of rotor by Multi-Slice Technique](image)

**TABLE III**

VALUES OF UMP FOR CONICAL MOTION OF UNSKEWED ROTOR

<table>
<thead>
<tr>
<th>UMP for a DC Excitation of 400 Ampere turns</th>
<th>UMP for a DC Excitation of 1600 Ampere turns</th>
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<td>342.52 Newtons</td>
<td>889.74 Newtons</td>
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**TABLE IV**

VALUES OF UMP FOR CONICAL MOTION OF SKEWED ROTOR

<table>
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<tr>
<th>UMP for a DC Excitation of 400 Ampere turns</th>
<th>UMP for a DC Excitation of 1600 Ampere turns</th>
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<tr>
<td>325.45 Newtons</td>
<td>879.52 Newtons</td>
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**III CONCLUSION**

For machines like train lighting alternators, which operate under extreme environmental conditions and which are flexible mounted and constantly under the influence of vibrations, contributed by the movement of the coach itself, UMP is too significant to be ignored. Moreover in inductor alternators, air gap is too small for saturation to be neglected, as in classical analysis. Hence the techniques discussed in the paper are extremely helpful, to calculate UMP. The dependence of UMP on rotor skew under both balanced and unbalanced loaded conditions are also to be investigated in future.

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**REFERENCES**