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Comparative leakage field analysis of electromagnetic devices using finite element and fuzzy methods

Ajay Kumar [a,*], Sanjay Marwaha [b], Amarpal Singh [a], Anupama Marwaha [b]

[a] *Department of Electronics & Communication Engineering, Beant College of Engineering & Technology, Gurdaspur, Punjab, India*
[b] *Department of Electrical & Instrumentation Engineering, Sant Longowal Institute of Engineering & Technology, Longowal, Punjab, India*

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ABSTRACT

To get a better design of electromagnetic devices it is important to understand the relationship between core configurations and leakage flux distributions. The possibility of increasing weight and dimensions of electrical machines requires more and more care in the evaluation of magnetic field distribution. This paper presents a method for calculating the steady-state leakage flux distributions for electromagnetic devices. Finite element method (FEM) has been used to carry out the field behavior of permanent magnet (PM) generator in terms of magnetic vector potential (MVP) A, as A is the preferred potential to obtain the field variables like magnetic field density (B) and magnetic field intensity (H). Then fuzzy model of the generator is developed using adaptive neuro-fuzzy inference system (ANFIS), for carrying out its leakage field analysis. Performance is evaluated by comparing finite element model with fuzzy model and good correlation is achieved between them.

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1. Introduction

For electrical designs, not only accuracy of calculations but also appropriate determination of configurations of stator and rotor cores to meet the machine specifications is required. Determination of the magnetic fields in the rotating machines, which is quasi-stationary in nature, is quite helpful in optimal design of the same (Marwaha, Hudiara, & Marwaha, 2001). The remarkable increase in power unit size of electrical machines within the limits of the possibilities of increasing their weight and dimensions requires more and more care in the evaluation of magnetic field distribution. The knowledge of such leakage magnetic field is the major step to determine the best geometry and suitable material for the design of electromagnetic devices. Values of sub-transient inductances that affect control responses and values of sudden short-circuit currents are determined mainly by the leakage flux in the machines (Flores, Buckley, & McPherson, 1984). It necessitates understanding the relationship between core parameters and leakage flux distributions in order to get a better design of low cost and highly controllable machines with small short-circuit currents. The goal of finite element analysis and modeling is to find the flux distribution in the interior domain, from which the steady-state reactances, load angle and several components of loss may be computed. Calculation of the magnetic field in the air-gap of machines with slotted stators due to the stator currents have been documented in the literature Polinder and Hoeijmakers (1997), Zhu and Howe (1993) and Zhu, Howe, and Chan (2002). The approach here is to use an equivalent surface current density, located at the stator surface. This approach is not valid for a slot less stator. Circuit models for synchronous machines have been studied by Canay (1969), Boldea and Nasar (1988), Tahan and Kamwa (1995), Slemon (1990) and Escarela-Perez and Macdonald (1998) to predict behavior of high-power generators or control systems of motors. In order to make accurate machine models with magnetic saturation, it is desirable that structures or parameters of the models are determined so that they reflect the actual flux distributions in the machines (Escarela-Perez & Macdonald, 1998). Modeling and control techniques based on fuzzy sets attempt to combine numerical and symbolic processing into one framework. On the one hand, fuzzy systems are knowledge-based systems consisting of linguistic if–then rules that can be constructed using the knowledge of experts in the given field of interest. On the other hand, fuzzy systems are also universal approximators that can realize non-linear mappings. This duality allows qualitative knowledge to be combined with quantitative data in a complementary way. Compared to other non-linear approximation techniques, fuzzy systems provide a more transparent representation of the non-linear system under study, and can also be given a linguistic interpretation in the form of rules.

In this paper, firstly the finite element model of the generator is developed to carry out its leakage field analysis using a finite

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[*] Corresponding author. Tel.: +91 9855559956.
E-mail address: ajaykm_20@yahoo.co.in (A. Kumar).

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element based package. Then fuzzy model of generator is developed for its leakage field analysis to validate the results obtained with FEM.

2. Modeling of the generator

2.1. Finite element modeling

Fig. 1 shows the model of the generator used for analysis. The center of rotor consists of annealed medium carbon steel, which is a material with high relative permeability. The center is surrounded with several blocks of permanent magnet made of samarium cobalt, creating a strong magnetic field. The stator is made up of same permeable material as the center of the rotor. The winding is wound around the stator poles. The winding used in the stator is single turn winding. Length of the generator is 0.4 m. Area of winding in the stator is 0.001257 m^2. Relative permeability in permanent magnets is 1.

The symmetry of the generator has been exploited to reduce the model size to 1/8th of the original size. The smallest possible model of the generator is obtained by cutting only the cross section between *d*-axis and *q*-axis as shown in Fig. 2.

2.2. Theory

The magnetic field prevailing in the interior of the machine can be described in terms of MVP. The vector fields *B* and *H* vary with position in a medium. With every such field a potential may be associated where the field relates to the potential and some combination of its positional derivatives. Depending on the nature of the vector field, this potential can either be a scalar potential or a vector potential. The following advantages of using the magnetic vector potential *A* are identified:

- Finding *A* is a very convenient way to obtain *B* in any region with no constraints on current density (*J*).
- For two-dimensional fields, the magnetic field lines are simply the equipotential curves of *A* (Haus & Melcher, 1989).
- The flux linkage and consequently inductance and no-load voltage can be obtained directly from *A* (Haus & Melcher, 1989).

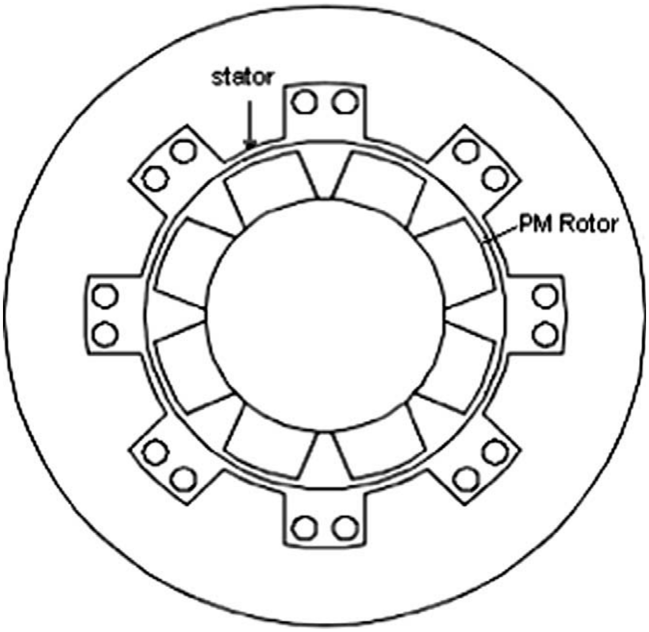

Fig. 1. Model of generator.

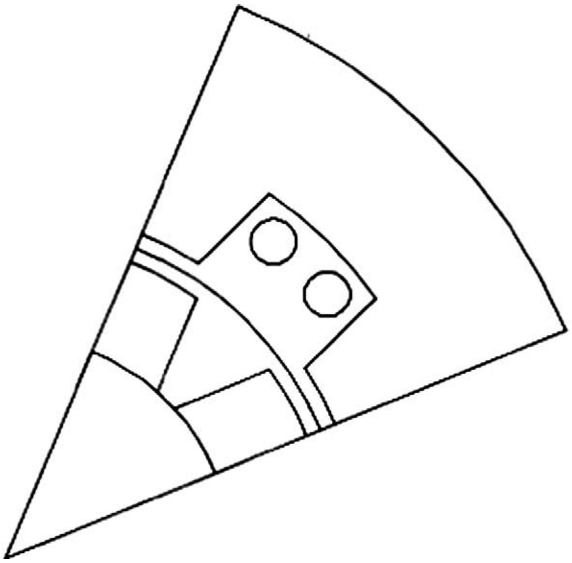

Fig. 2. Reduced model of the generator.

In order to apply finite element method to turbo alternators, across curved boundaries (Marwaha et al., 2001), following assumptions are made:

(1) The non-magnetic end fingers and non-magnetic retaining ring are ignored.
(2) The rotor end windings are represented by a ring whose current is assumed to be constant in the circumferential direction.
(3) The stator ends are simulated with *N* current rings, whose current is supposed as constant in the circumferential direction, although the actual current distribution in the rings is sinusoidal.

The magnetic field prevailing in the interior of the machine can be described in terms of magnetic vector potential (Salon, 1985). The two-dimensional diffusion equation is

$$\nabla \times v\nabla \times A = J \tag{1}$$

where current density *J* and vector potential *A* are assumed to be *z*-directed and independent of *z*. *v* is the reluctivity of the material. The current density *J* consists of three parts: one due to applied source second due to the induced electric field produced by time varying magnetic field and third due to motion-induced or speed voltage.

$$J = \sigma \frac{U_b}{l} - \sigma \frac{\partial A}{\partial t} + \sigma \upsilon \times B \tag{2}$$

where σ is the electrical conductivity, *l* is the length of the problem in *z*-direction, U_b is the voltage applied to finite element region and *v* is the velocity of the conductor w.r.t. *B*.

Flux density *B* is related with MVP as

$$B = \nabla X A \tag{3}$$

Therefore diffusion equation (1) can be written as

$$\nabla \times v\nabla \times A = \sigma \frac{U_b}{l} - \sigma \frac{\partial A}{\partial t} + \sigma \upsilon \times \nabla \times A \tag{4}$$

By employing the frame of reference that is fixed w.r.t. the component under consideration, the relative velocity becomes equal to

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