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EVALUATION OF SYNCHRONOUS GENERATOR REACTANCE USING FINITE ELEMENT METHOD (FEM)

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ABSTRACT

For synchronous 3-phase electrical generator machine design, the ability to predict the synchronous reactance of a particular machine design is of prime importance. The synchronous reactance has a significant impact on the magnitude of the fault currents generated within the machine during an event such as a 3 phase short-circuit. Power system designers routinely use the generator synchronous reactance as a key parameter to aid in the design of the complete power generation system. For new generator designs the synchronous reactance is routinely tested for as part of a thorough evaluation of the generator performance characteristics. In the paper, the author is presenting comparatively the application of: numerical method based on the FEA of magnetic field distribution, computed by using FEM; analytical traditional method.

Keywords: *Synchronous Generator, Reactance Evaluation, Numerical methods, Finite Element method (FEM)*

1. INTRODUCTION

Internal winding faults resulting from the degradation of generators winding insulation can be catastrophic and hence expensive. In the new environment of deregulation, utilities therefore need inexpensive methods employed to detect such faults in the incipient stage. However, the implementations of the existing monitoring methods tend to cost too much to be applied to generator. The development of an accurate internal fault diagnostic technique for to generator must be based on the analysis of quantities from fault scenarios. Considering the safety of personnel, the damage that will occur in the generator, the consumed time, and related cost, simulation involving the modeling of generator at various incipient fault stages is the best way to generate these fault cases. Several generator models have been developed for the study of with generator internal short circuit winding faults and some research work on the representation of insulation material was done in the past.

However, none of them discussed how to simulate an internal incipient fault in generator. This paper presents a new methodology developed to model internal incipient winding faults in based generator on the author's earlier work involving the development of a two-dimensional (2-D) nonlinear finite element analysis internal short circuit fault model. The degrading insulation model was combined with the internal short circuit model, developed in our earlier work, to simulate internal winding incipient faults. The generator internal incipient fault model was implemented using commercially available finite element analysis software. Various incipient fault scenarios at different degrading levels of the generator winding insulation were simulated. In these fault scenarios, the terminal voltages and currents of the generator were analyzed in both time domain and frequency domain. The characteristics obtained from the simulation were compared with the characteristics obtained from some experimental fault cases that conveyed incipient behavior.

One of the most common faults in the generator is the inter-turn short circuit in the one of the stator coils. The increased heat due to this short circuit may also lead to turn-turn and turn to ground faults. The inter-turn fault is mostly caused by mechanical stress, moisture and partial discharge, which is accelerated for electrical machines. Modeling, study and determining the parameters of generators with insulation inter-turn fault is first step in the development of fault diagnosis and fault tolerant machine design. These models exhibit a trade-off between simplicity and precision. Study of transient and steady-state behavior of generator under fault conditions by these fault models enable correct evaluation of measured data of diagnostic

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techniques. Fault study of generator can be operated either by physical experiments or computer-based analysis. Obviously, studying fault in electrical machine by computer based simulation is preferred because of economical, flexibility and safety problems. The most used methods for modeling and detection of faults in generator are: Winding function method (WFM), dynamic circuit base method (DCM) and finite element method (FEM). The winding function based method uses generator geometrical parameters and does not take to account the core saturation.

The dynamic circuit based methods uses the generalized theory of electrical machines incorporating *qdo* axis. The same transformation process is applied in asymmetrical generator. The circuit based model uses Linearized magnetic parameters in fault analysis and detection and therefore, is not very precise and accurate. However, this method is faster and takes shorter time for computation. Finite Element Method (FEM) can be used for machine modeling especially under fault conditions. FEM gives much more precise information of the machine than other analytical analysis, which uses magnetic Linearized parameters. FEM is based on magnetic field calculation using machine geometry dimensions and materials. FEM is capable to consider the magnetic field saturation effect based on generator performance. Therefore, it can be applied in modeling and analysis of machines with fault and unbalanced cases. The study of machines in steady state, transient and fault conditions requires accurate knowledge of the equivalent circuit parameters. Furthermore, when a fault occurs the current and flux density distribution is more or less modified as a function of fault severity. Therefore, it is necessary to study the electromagnetic flux and machine parameters for machine under stator and rotor faults. Finite Element Method (FEM) is widely used for generator model and parameter identification especially under different fault conditions. In the stator inter-turn fault of generator is studied and analyzed by FEM. FEM is used to analysis the generator with rotor broken bars. The magnetic field is obtained for healthy and faulty machine and compared. Finite element coupled circuit method is capable to study the transient performance of electrical machines. Previously, the steady state analysis of generator was applied, but thank to the availability of powerful computers the transient FE analysis of generator can be carried out by applying time stepping coupled circuit method. In this thesis, a two-dimensional FEM is performed for modeling analysis of a generator with insulation failure inter-turn fault using ANSYS software. The turn fault in stator winding is considered in 25% of one phase winding Comparing the magnetic flux distribution of healthy and faulty machines helps to detect the influence of turn fault. The machine parameters are obtained for generator with inter-turn fault. Finally, the FEM machine model is used for studying the machine under different fault condition. Study results including phases and fault currents express the behavior of machine with inter-turn faults.

2. EVALUATION OF SYNCHRONOUS REACTANCE:

The mathematical formulation for magnetic field problems description is based on the system of relevant Maxwell's equations, by which the magnetic field is described in closed and bounded system. In our case the problem is 2D and here one can suppose that the axial length of the machine is infinite and the machine geometry is invariant along the z-axis. In the mathematical formulation there are two types of magnetic field problems according to the frequency of the problem:

Magneto static problems – the frequency of the problem is zero; and

Time harmonic problems – at non-zero frequency

Magneto static Problems-

Magneto static problems are problems in which the fields are time -invariant. The field intensity H and flux density B must obey

$$\nabla \times H = J \rightarrow \qquad (2.1)$$

And

$$\nabla . B = 0 \rightarrow \qquad (2.2)$$

We now that subject to a constitutive relationship between B and H for each material

$$B=\mu H \qquad (2.3)$$

In the case of electric machines the stator and rotor core are made from saturating iron and therefore the permeability μ is a function of B. The finite element analysis uses the magnetic vector potential approach about finding a field that satisfies Eq. (1) - (3). The relationship between flux density and vector potential is

$$B = \nabla \times A \rightarrow \qquad (2.4)$$

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And from (4) we can express the distribution of the magnetic field by the following nonlinear partial differential equation- (2.5))

Assuming the Coulomb gauge

$$\nabla * A = 0 \qquad (2.6)$$

If there are no currents in the domain under consideration, the right side term is zero. In the general 3D case, *A* is vector with three components, but in our case, which is considered as 2D planar, two components are zero, leaving just the component in the “out of page” direction. The use of vector potential formulation is an advantage that all the conditions to be satisfied have been combined into a single equation. We can notice that if *A* is found, *B* and *H* can then be deduced by differentiating *A.*

Synchronous Reactance

The direct and quadrature axis synchronous reactance are important in steady state performance of a synchronous generator.

Numerical method

In the case of direct axis synchronous reactance *Xd* the currents in the armature winding are distributed sinusoidal such that the field produced peaks at the direct axis because the armature current peaks at the quadrature axis. The field winding is not energized. Magnetic flux distribution for this case is presented in Fig. 2.1.

Inductance is calculated as a ratio of flux linkage to current:

$$L = \frac{\phi}{I} \rightarrow (2.7)$$

We can calculate the flux linkage as product of the number of turns *N*, the depth of the problem *l* and the difference in the vector potential ∇A at the location of the two coil sides

$$\psi = NL\Delta A \qquad (2.8)$$

Here the difference in the vector potential ΔA is obtained directly from the finite element vector potential solution. If we assume that the fictitious winding on the direct axis has the same number of turns as the phase winding we need another factor to find the direct axis inductance. For an 3-phase machine, the current in the direct axis would have to be 3/2 times as great as the phase current to produce the same magneto-motive force in the direct axis as the 3-phase winding.

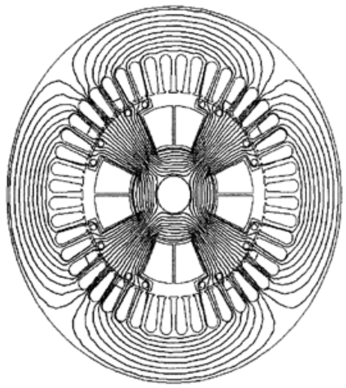

Fig 2.1 Magnetic flux distribution for Xd calculation.

Hence

$$Xd = \frac{i_{fs}}{i_{f0}} \rightarrow$$

$$Ld = L/(3/2) \rightarrow \qquad (2.9)$$

And the per unit value of *Xd* is

$$\nabla \times \left(\frac{1}{\mu} \times A\right) = j \qquad (2.10)$$

The quadrature axis synchronous reactance *Xq* can be calculated in similar way as we calculated the direct axis synchronous reactance. The only difference is that the armature field is moved forward in space for 90^0 el. So, the field produced peaks at the quadrature axis and the current peaks on the direct axis. The field winding is also open circuited. Magnetic flux distribution for this case is presented in Fig. 2-2.In this case the quadrature axis synchronous inductance is the ratio of quadrature axis flux linkage to quadrature axis current.

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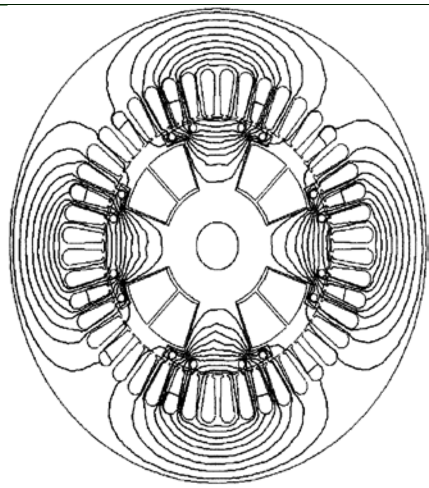

Fig. 2.2 Magnetic flux distribution for Xq calculation.

Analytical Method

The analytical determination of direct and quadrature axis synchronous reactances are based on the equations:

$$Xd = Xad + X la \rightarrow \quad (2.11)$$

And $$Xq = Xaq + Xla \rightarrow \quad (2.12)$$

X ad and *X aq* are reactances of the armature reaction along the direct and quadrature axis respectively, and *X la* is armature leakage reactance. They are calculated in the design procedure of the machine.

Experimental Method

We can experimentally determine direct axis synchronous reactance from both the open circuit and three-phase short circuit characteristics. In this case from the open circuit characteristic $E = f(I_f)$ have to take the value of the field current $f = i_{f0}$ for rated voltage. Also, from the three-phase short circuit characteristic $I = f(I_f)$ we have to take the value of the field current i_{f0} for rated armature current of the synchronous generator. The direct axis synchronous reactance (in p.u.) is the ratio of the equation 2.13:

For calculation of the quadrature axis synchronous reactance *Xq* we should energize the armature winding by external a.c source and the rotor runs at speed, which is very close to the synchronous one. As the rotor is running at asynchronous speed it slowly moves its position with respect to the armature field. When its direct axis is in correspondence with the direction of the armature field, the current has minimum value min *I* and the voltage has maximum value max *U*. When the quadrature axis of the rotor is in the direction of the armature field, the current has maximum value max *I* and the voltage has minimum value min *U*. If we take these values the quadrature axis synchronous reactance can be computed by the equation 2.14:

$$X_d = \frac{ifs}{ifo} \longrightarrow \quad (2.13)$$

$$X_q = X_d \cdot \frac{U_{min}}{U_{max}} \cdot \frac{I_{min}}{I_{max}} \rightarrow \quad (2.14)$$

2.1 How the Finite Element Method Is Implemented

The solution of a continuum problem by the finite element method always follows an orderly step-by-step process. To summarize in general terms how the finite element method works we will succinctly list these steps now:

i. Discretize the Continuum: The first step is to divide the continuum or solution region into elements.The stator of synchronous generator has been divided into triangular elements that might be used to find the temperature distribution or stress distribution in the blade. A variety of element shapes may be used, and different element shapes may be employed in the same solution region. Indeed, when analyzing an elastic structure that has different types of components such as stator and rotor, it is not only desirable but also necessary to use different elements in the same solution. Although the number and the type of elements in a given problem are matters of engineering judgment, the analyst can rely on the experience of others for guidelines.

ii. Select Interpolation Function: The next step is to assign nodes to each element and then choose the interpolation function to represent the variation of the field variable over the element. The field variable may be a scalar, a vector, or a higher-order tensor. Often, polynomials are selected as interpolation functions for the field variable because they are easy to integrate and differentiate.

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The degree of the polynomial chosen depends on the number of nodes assigned to the element, the nature and number of unknowns at each node, and certain continuity requirements imposed at the nodes and along the element boundaries. The magnitude of the field variable as well as the magnitude of its derivatives may be the unknowns at the nodes

iii. Assemble the Element Properties to Obtain the System Equation: A unique feature of the finite element method is that the system equations are generated by assembly of the individual *element* equations. In contrast, in the finite difference method the system equations are generated by writing nodal equations.

iv. *Impose the Boundary Conditions.* Before the system equations are ready for solution they must be modified to account for the boundary conditions of the problem. At this stage we impose known nodal values of the dependent variables or nodal loads

v. Make Additional Computations if desired: Many times we use the solution of the system equations to calculate other important parameters. For example, in a structural problem the nodal unknowns are displacement components. From these displacements we calculate element strains and stresses. Similarly, in a heat-conduction problem the nodal unknowns are temperatures, and from these we calculate element heat fluxes.

2.2 Procedure of Fault Analysis Using FEM

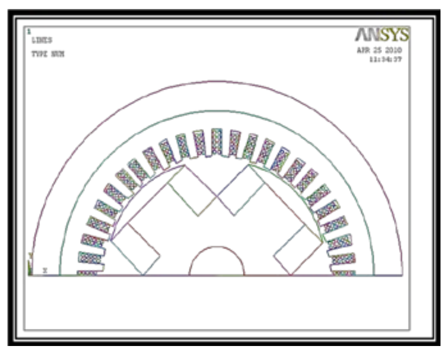
The procedure for numerical computation of magnetic field problems, by using the finite element method is divided into three steps:

Pre-processing - the derivation of the FE model of the electric machine under consideration, defining material properties, boundary conditions and mesh generation;

Processing - solving the problem by the relevant Maxwell's equations and obtaining the field distribution in the analyzed domain of the electric machine.

Post-processing - calculation of characteristics, as well as parameters, of the analyzed electric machine.

After the problem geometry is defined we have to complete the entire domain of the electric machine by defining the material properties and boundary conditions. The basic idea of FEM application is to divide that complex domain into elements small enough, under assumption to have linear characteristics and constant parameters. Usually, triangular elements are widely accepted shapes for 2D FE models. After this step is completed, the output is always generation of finite element mesh. It is recommended to make mesh refinements in the regions carrying the interfaces of different materials, or with expected or presumed significant changes in the magnetic field distribution. In Fig4-3 is presented the 2D mesh of the tested machine, which is consisted of 97272 nodes and 96704 elements.



SFig 2.3 Model created from the given data

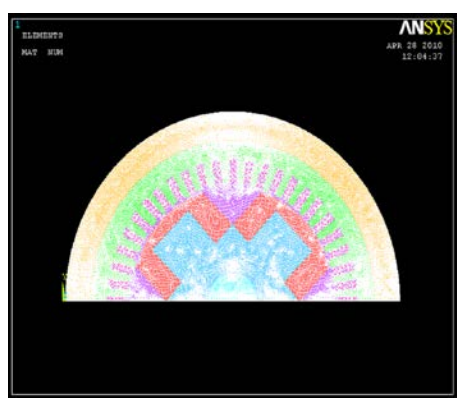


Fig 2.4 Creating Areas.

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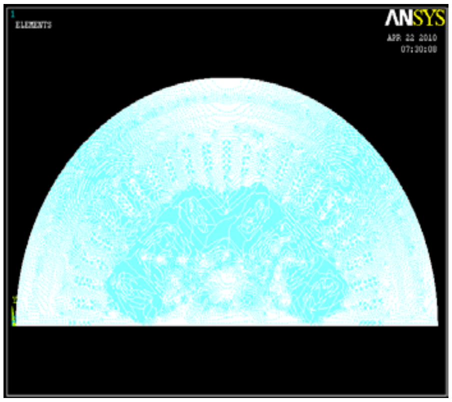

Fig 2.5 Finite Element Mesh.

Solution-

The solution of the problem, when the magnetic vector potential *A* is used, as an output from the 2D computations offers the values $A\{x, y\}$. The equipotential lines, $A = const.$ represent flux lines and the magnetic field distribution along any surface is obtained. As an example, in Fig.2-4 is presented the distribution of the field flux per pole.

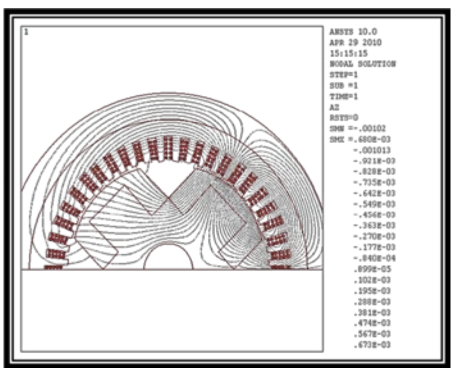

Fig. 2.6 Field flux distribution at no-load of SG.

Post-Processing

This is the final and most important step of the FEM application. In this step we have possibility to compute various types of line and surface integrals numerically in terms of the magnetic vector potential *A*. This enables to determine different electric, magnetic and mechanic quantities and characteristics. In fact all the reactance of the tested synchronous generator in this project is computed in the step of post-processing.

3. SIMULATIONS AND RESULTS

The particular generator design used for these analyses is a, 3 phase, 50 Hz, 400 V synchronous generator. The generator rotor is a 4-pole rotor with a normal operating speed of 1500 RPM. The generator is rated for 25 kVA of output power .The following is the data used for fault analysis and calculation of synchronous generator. According to this data the reactance is calculated using the output energy obtained after the analysis. By using the data model of synchronous generator is created on a graph paper and the coordinates are calculated and then the steps as described above for the analysis are followed.

Data on 3-Phase Synchronous Generator
(All dimensions are in mm)

Rating, Kva	-25
Voltage, Volts	-400
Current, Amps /ph	–36.084991
Speed, Rpm	– 1500
Number of poles	- 4
Stator ID	- 290
Stator OD	–400
Number of slots	-48
Slot size	– 32 x 12
Slot type	- open
Number of conductors per slot	- 10
Conductor radius	–2 x10^{-5}
Parallel paths in winding	-1
Phase current	–same
Path current	–same
Air gap	- 2
Pole shoe height	- 18
Pole body width	-70
Pole body height	– 135
Shaft diameter at center	-70
Shaft diameter at bearing	-55

After using the coordinates as calculated above are used for modeling as shown in the fig 2.2 and creation of areas and meshing is shown in the fig.2.3.

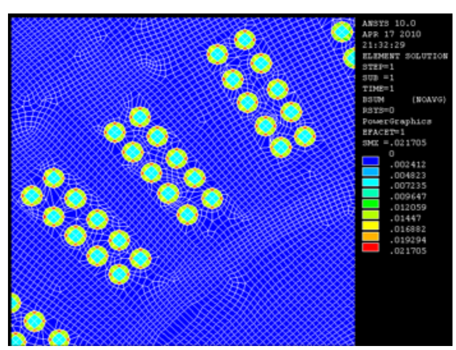

Fig.3.1 shows both the areas and meshing.

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The following figures show the generator model based on above data and fig 3.2 shows the solution after the load is applied

Fig 3.2 shows the generator model based on above given data after applying the load across the boundary vector potential with flux

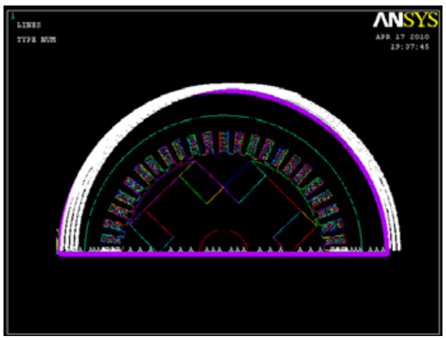

Fig 3.3 Excited conductors of 3-Phase Synchronous Generator at normal condition.

When the generator is subjected to excitation the flux produced in normal condition is shown in following fig 3.4.

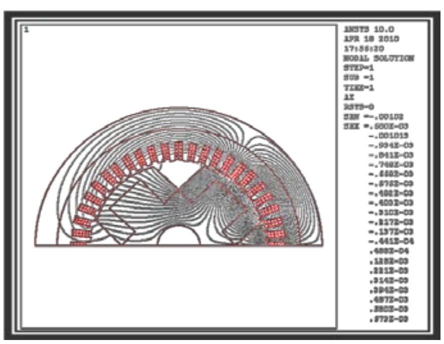

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fig 3.4 Ten Conductor Flux Excitation Output in normal condition.

The fig3.1 parallel and then applying magnetic current density on the areas of the conductors. After that fig 3.3 shows the flux pattern with normal condition and fig 3.4 shows the flux pattern in normal condition.

Calculation of Reactance-

Current (I), $I = \frac{KVA}{\sqrt{3} * V_L}$

$$I = \frac{25*10^3}{\sqrt{3}*400},$$

I=36.08439182A

Current density (J),

For first phase,

Unit value=$1\angle 90^0$

J=I/10*area of conductor,

$$J = \frac{36.08439182}{10*\prod*0.02^2},$$

J=2871.504664amp/m^2

For second phase,

Unit value=$1\angle 120^0$

J=0.9*2871.504664

J=2584.354198 amp/m^2

For third phase,

Unit value=$1\angle 180^0$

J=-2871.504664amp/m^2

Now by applying magnetic flux density on areas of stator conductor we get the stored energy as follows,

Stored energy for normal condition = 0.877862 J,

[Since from fig 3.3, 3.4]

$$\text{As, } E = \frac{1}{2} L I^2$$

Using above values,

Inductance at normal condition,

$$0.877862 = \frac{1}{2} * L_N * 36.0893216^2$$

$$L_N = 1.348027677*10^{-3}\text{H}$$

Reactance at normal condition,

$$X_N = \omega \mathrm{L}_\mathrm{N}$$

$$X_N = 0.4234953847\ \Omega$$

- The Reactance at normal condition X_N=0.4234953847Ω

4. CONCLUSION:

This thesis presented a new generator model to simulate an internal incipient winding fault. we are developing a mathematical model or method based on online/offline condition monitoring system by analyzing various conditions and collecting various samples of voltage and current (i.e. normal and abnormal) for protection of generators against faults (i.e. means incipient/inter turn faults) on stator side. In future work, the incipient fault generator model will be used to generate a database of incipient internal winding faults in generator for the development of intelligent generator fault detection techniques.

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