Inter-turn Fault Analysis of Synchronous Generator using Finite Element Method (FEM)

B. Jagadeesh Chandra Prasad, B. V. Sanker Ram

***Abstract:** A turn fault in the stator winding of a generator causes a large circulating current to flow in the shorted turns. If left undetected, turn faults can propagate, leading to phase-ground or phase-phase faults. Incipient detection of turn's faults is essential to avoid hazardous operating conditions and reduce down time. At present the synchronous generators are protected against almost all kind of faults using differential methods of protection. All kind of faults develops into inter winding fault by damaging inter winding insulation. So it is necessary to protect the synchronous generator from inter winding faults which represents the protection against all kind of faults. There are different method based techniques for analyzing generator incipient/inter turn faults on stator side. They are circuit based, field based, wavelet based, artificial intelligence based, fuzzy based, artificial neural networks based. Machine performance characteristics that could be monitored to diagnose the stator inter-turn fault in generator include line current, terminal voltage, torque pulsations, temperature rise due to excessive losses, shaft vibrations, air-gap flux and speed ripples. So in this 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. The main Objective is to develop a mathematical model or method based on online/offline condition monitoring system by analyzing various conditions (i.e. normal and abnormal) for protection of generators against faults (i.e. means incipient/inter turn faults) on stator side.*

***Keywords:** Synchronous generator, windings, internal winding faults, fault detection, fault diagnosis, incipient faults, ANSYS*

I. INTRODUCTION

The challenging and competitive energy market makes utilities tend to operate the generators harder, longer, and closer to their capabilities in order to reduce cost and generate the most amount of profit. Generators are more likely to fail under such a stress besides regular aging and insulation deteriorating processes. Therefore, utilities are calling for an economical yet reliable fault detection system to help with the maintaining and extending the life of their existing assets and equipment to provide affordable and reliable electric power. The detection systems and diagnosis methods developed previously either require the generators to be taken out of service, which means more operational cost to the utility, or are expensive to implement. Therefore, a low-cost, on-line, non-destructive fault diagnosis and detection system is highly demanded to provide immediate and accurate assessment of the conditions of the equipment in the field.

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There are different method based techniques for analyzing generator incipient/inter turn faults on stator side. They are circuit based, field based, wavelet based, artificial intelligence based, fuzzy based, artificial neural networks based. Machine performance characteristics that could be monitored to diagnose the stator inter-turn fault in generator include line current, terminal voltage, torque pulsations, temperature rise due to excessive losses, shaft vibrations, air-gap flux and speed ripples. So in this 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 drawing the performance characteristics and protection of generators against faults (i.e. means incipient/inter turn faults) on stator side. Finite element analysis (FEA) techniques are useful to obtain an accurate characterization of the electromagnetic behavior of the magnetic components, such as synchronous generators. Once a model of the magnetic component is defined, the values of its parameters can be calculated using the FEA techniques. Finite element analysis has typically been coupled to circuit simulation using time-stepped field solutions. This approach can be very accurate, but it involves long simulation times. Therefore, the use of the finite element method in modeling a short circuit fault in a synchronous generator provides a significant advance in the degree of accuracy. In this paper, finite element analysis is applied to calculate the parameters for an equivalent circuit of the synchronous generator with an internal short circuit fault on stator side using ANSYS Software.

II. SYNCHRONOUS GENERATOR FAULT ANALYSIS

A modern generating unit is a complex system comprising the generator stator winding, associated transformer and unit transformer (if present), the rotor with its field winding and excitation system, and the prime mover with its associated auxiliaries. Faults of many kinds can occur within this system for which diverse forms of electrical and mechanical protection are required. The amount of protection applied will be governed by economic considerations, taking into account the value of the machine, and the value of its output to the plant owner.

Stator winding faults- These types of faults occur due to the insulation breakdown of the stator coils. Different types of stator windings faults are:

a) Phase to earth fault
b) Phase to phase fault
c) Inter turn fault

a) Phase to Earth faults

The most probable mode of insulation failure is phase to earth.

Use of an earthing impedance limits the earth fault current and hence stator damage. An earth fault involving the stator core results in burning of the iron at the point of fault and welds laminations together. Replacement of the faulty conductor may not be a very serious matter (dependent on set rating / voltage / construction) but the damage to the core cannot be ignored, since the welding of laminations may result in local overheating. The damaged –area can sometimes be repaired, but if severe damage has occurred, a partial core rebuild will be necessary. A flashover is more likely to occur in the end-winding region, where electrical stresses are highest. The resultant forces on the conductors would be very large and they may result in extensive damage, requiring the partial or total rewinding of the generator. Apart from burning the core, the greatest danger arising from failure to quickly deal with a fault is fire. A large portion of the insulating material is inflammable, and in the case of an air-cooled machine, the forced ventilation can quickly cause an arc flame to spread around the winding. Fire will not occur in a hydrogen-cooled machine, provided the stator system remains sealed. In any case, the length of an outage may be considerable, resulting in major financial impact from loss of generation revenue and/or import of additional energy.

b) Phase to Phase faults

Phase-phase faults clear of earth are less common; they may occur on the end portion of stator coils or in the slots if the winding involves two coil sides in the same slot. In the latter case, the fault will involve earth in a very short time. Phase fault current is not limited by the method of earthing the neutral point.

c) Inter turn faults

Interturn faults are rare, but a significant fault-loop current can arise where such a fault does occur. Conventional generator protection systems would be blind to an interturn fault, but the extra cost and complication of providing detection of a purely interturn fault is not usually justified. In this case, an interturn fault must develop into an earth fault before it can be cleared. An exception may be where a machine has an abnormally complicated or multiple winding arrangements, where the probability of an interturn fault might be increased.

Fault analysis using fem-

The finite element method is a numerical technique for obtaining approximation solutions to boundary value problems of mathematical physics. Especially it has become a very important tool to solve electromagnetic problems because of its ability to model geometrically and compositionally complex problems. The potential distribution which satisfies the differential equation in (4.1), subject to proper boundary conditions, will also minimize the stored energy in the field and vice versa. Therefore one practical approach for solving the field problem is to approximate and minimize the stored energy in the field. To construct an approximate solution by finite element analysis, the complicated field region is discretized into a number of uniform or non uniform finite elements that are connected via nodes. The potential within each element is approximated by an interpolation function. Thereafter the potential distribution in the various elements is interrelated to constrain the potential to be continuous across inter element boundaries. The total energy is the sum of the individual element energies. Then, the total stored energy is minimized. Using finite element to solve problems involves three stages. The first consists of meshing the problem space into contiguous elements of suitable geometry and assigning appropriate values of the material parameters-conductivity, permeability and permittivity to each element. Secondly, the model has to be excited, so that the initial conditions are set up. Finally, the boundary conditions for the problem have to be specified. The values of the potentials are suitably constrained at the limits of the problem space. The finite element method has the advantage of geometrical flexibility. It is possible to include a greater density of elements in regions where fields and geometry vary rapidly. There are two different approaches to couple finite element models with circuit equations. One is direct coupling and the other is indirect coupling. In direct coupling, the circuit equations are directly incorporated into the field calculation and solved simultaneously. In indirect coupling, the field calculation is performed by a free standing program, while circuit simulation and coupling between field and circuit models are handled in a separate program. ANSYS Maxwell Software adopted the indirect coupling method. In this approach, the behaviors of a magnetic component can be characterized by a model and the parameters of the model can be calculated using FEA tool. Then the model can be utilized in circuit simulation.

Role of synchronous reactance in FEM-

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 t 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.

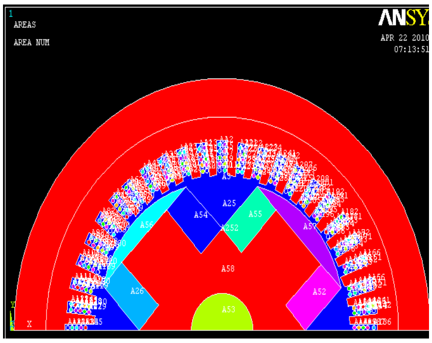
The synchronous reactance, Xd, is the generator internal impedance element that is effective in the first cycles of a transient load event and determines the magnitude of the instantaneous fault current from the generator. The transient reactance, Xd, becomes effective after approximately 6 cycles into a transient load event and determines the amount of voltage change seen at the generator terminals due to the step change in load. As stated, the reactances of a generator have a direct effect on the transient fault currents experienced in an electrical power generation system, as well as the motor starting capability of the generator. The magnitudes of the fault currents need to be calculated so that breakers, etc. can be sized accordingly. The peak magnitudes of the 3-phase fault currents are inversely proportional to the synchronous reactance of the generator. For new generator designs, the transient and synchronous reactances are routinely tested for as part of a thorough evaluation of the generator's performance characteristics.

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.

Pre-Processing

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.



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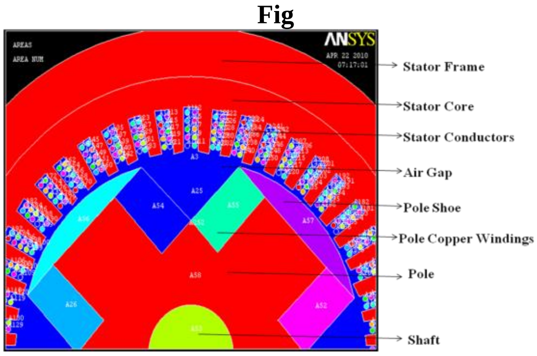


4.3 Model created from the given data.

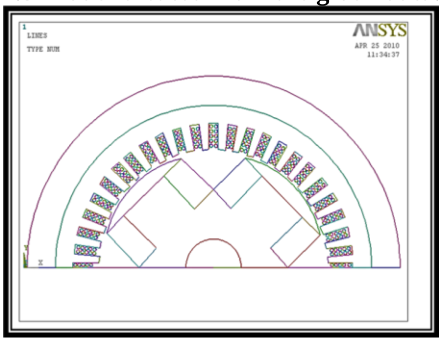


Fig 4.4 Creating Areas

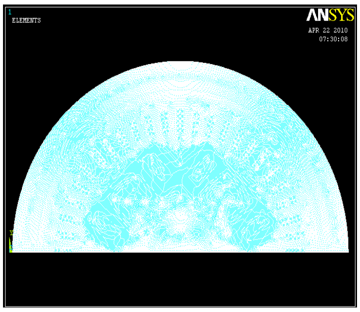
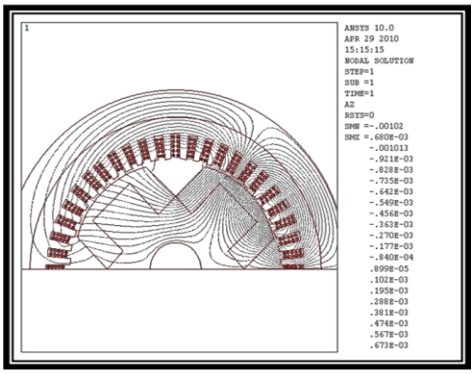


Fig 4.5 Finite Element Mesh

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.4-4 is presented the distribution of the field flux per pole



4.6 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.

ANSYS and Magnetic Analysis-

The ANSYS program uses Maxwell's equations as the basis for magnetic field analysis. The primary unknowns (degrees of freedom) that the finite element solution calculates are either magnetic potentials or flux. Other magnetic field quantities are derived from these degrees of freedom. Depending on the element type and element option you chose the degrees of freedom might be scalar magnetic potentials, vector magnetic potentials, or edge flux.

Types of Static, Harmonic, and Transient Magnetic Analysis

We can do the following types of static, harmonic, and transient magnetic analysis: 2-D static magnetic analysis- analyzing magnetic fields caused by direct current (DC) or permanent magnets. Two-dimensional static analyses use the vector potential formulation.

2-D harmonic magnetic analysis- analyzing magnetic fields caused by low frequency alternating current (AC) or voltage. This type of analysis uses the vector potential formulation.

2-D transient magnetic analysis- analyzing magnetic fields caused by arbitrary electric current or external field that varies over time. Permanent magnet effects also can be included. This analysis type uses the vector potential formation

3-D static magnetic analysis- analyzing magnetic fields caused by direct current (DC) or permanent magnets using a scalar potential approach.

3-D static magnetic analysis- analyzing magnetic fields caused by direct current (DC) or permanent magnets using an edge-based approach.

3-D harmonic magnetic analysis- analyzing magnetic fields caused by low frequency alternating current (AC), using an edge-based approach. The edge formulation is recommended for most harmonic magnetic applications.

3-D transient magnetic analysis- analyzing magnetic fields caused by arbitrarily electric current or external field that varies over time, using an edge-based approach. The edge formulation is recommended for most transient magnetic applications.

3-D static magnetic analysis nodal-based. This analysis type uses a vector potential formulation.

3-D harmonic magnetic analysis nodal-based. This type of analysis uses only the vector potential formulation.

3-D transient magnetic analysis nodal-based. This type of analysis uses only the vector potential formulation.

Steps in 2D Harmonic Magnetic Analysis:

The procedure for doing a static magnetic analysis consists of five main steps:

- Create the physics environment.
- Build and mesh the model and assign physics attributes to each region within the model.

Apply boundary conditions and loads (excitation)

- Obtain the solution.

Basically there are two ways provided in the package (ANSYS), viz. Graphical User Interface (GUI) method and Command method.

Create physics environment- In defining the physics environment for an analysis a mathematical simulation model of the physical problem is established on entering the ANSYS preprocessor (PREP7). To do so, the steps listed below are followed.

- Set GUI Preferences.
- Define the analysis title.
- Define element types and options (KEYOPT settings).
- Define element coordinate systems.
- Set real constants and define a system of units.
- Define material properties.

Building and meshing the Model and Assigning Region Attributes- To build the model, we use the procedures discussed in the ANSYS Modeling and Meshing Guide. Then, attributes to each region in the model are assigned. (Attributes are the element types and options, element coordinate systems, real constants, and material properties you defined in creating the Physics Environment).

After assigning all regional attributes, we mesh the model using the procedures explained in the ANSYS Modeling and Meshing Guide.

Boundary conditions and loads (excitation)

It is possible to apply boundary conditions and loads to a 2-D Harmonic magnetic analysis either on the solid model (key-points, lines, and areas) or on the finite element model (nodes and elements). The ANSYS program automatically transfers loads applied to the solid model to the mesh during solution.

Table 1 The boundary conditions and loads choose for 2-D Harmonic analyses are as follows

Boundary	Excitation	Flag	Other
Vector Potential	Current Density	Comp. Force	Current Segment
On Key-points	On Key-points	Infinite Surf	On Key-points
On Nodes	On Nodes	On Lines	On Nodes
-Flux Parallel-	On Elements	On Areas	Maxwell Surf
On Lines	Voltage Drop	On Nodes	On Lines
On Nodes			On Areas
-Flux Normal-			On Nodes
On Lines			Virtual Displacement
On Nodes			On Key-points
Periodic Boundary Conditions			On Nodes

All loading operations are accessed through a series of cascading menus. The ANSYS program lists available boundary conditions and three load categories. The appropriate category and the appropriate boundary condition or loads are then chosen according to the table 1.

Solving the Analysis

This section describes the tasks performed to solve a 2-D static magnetic analysis problem. Defining Analysis Options-

It is specified by any of the following:

- Frontal solver (default)
- Jacobi Conjugate Gradient (JCG) solver
- JCG out-of-memory solver
- Incomplete Cholesky Conjugate Gradient (ICCG) solver
- Preconditioned Conjugate Gradient solver (PCG)
- PCG out-of-memory solver.

The frontal solver is recommended for 2-D models. However, the JCG or PCG solvers may be more useful for extremely large models. Models that are voltage-fed or that include velocity effects produce unsymmetrical matrices and can use only the frontal solver, the JCG solver, or the ICCG solver. Circuit-fed models can use only the frontal solver.

Saving a Backup Copy of the Database- SAVE_DB button on the ANSYS Toolbar saves a backup copy of the ANSYS database. This enables us to retrieve the model even if the computer fails while analysis is in progress.

Starting the Solution- In this step, we specify magnetic solution options and initiate the solution. For a nonlinear analysis, two-step solution sequence is used. Ramp the loads over three to five sub-steps, each with one equilibrium iteration.

Calculate the final solution over one sub-step, with five to 10 equilibrium iterations. If we like, we can step manually through the two-step solution sequence. See alternative Analysis Options and Solution Methods for the procedure to follow for manual solution.

Finishing the Solution- To leave the solution processor, either of the following is used.
Command(s): FINISH
GUI: Main Menu>Finish
Command(s): /POST1
GUI: Main Menu>General postproc>Plot results.

III. 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 analyses 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
Amps /phase	-	36.084991
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
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.4.2 and creation of areas and meshing is shown in the fig.4.3.The following figures show the generator model based on above data and fig 5.1 shows the solution after the load is applied.

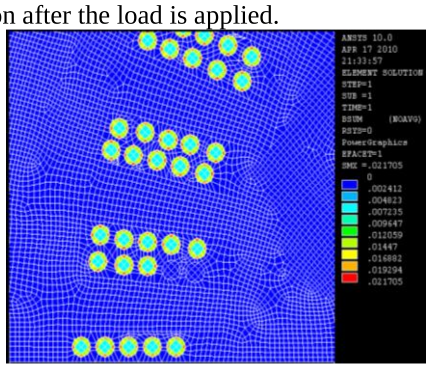


Fig 5.1 Ten Conductors per Slot Solution after the load is applied.

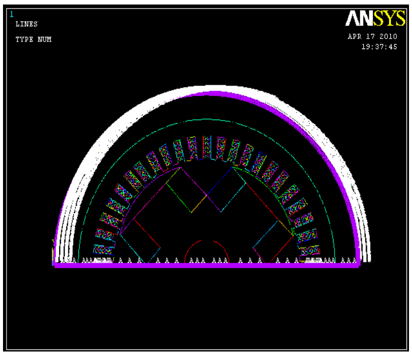


Fig 5.2 Excited conductors of 3-Phase Synchronous Generator at normal condition.

When the generator is subjected to excitation the flux produced in normal condition is shown in following fig 5.3 & the flux produced in faulty condition when two conductors are short circuited is shown in following fig 5.4.

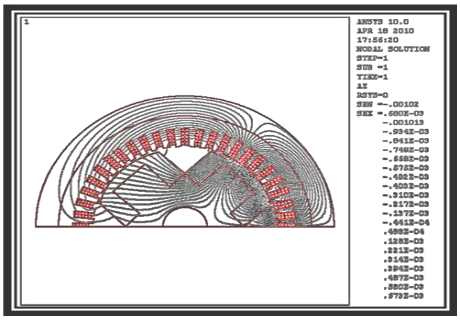


Fig 5.3 Ten Conductor Flux Excitation Output in faulty condition

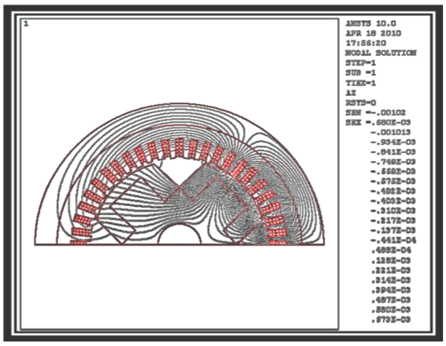


Fig 5.4 Ten Conductor Flux Excitation Output in faulty condition

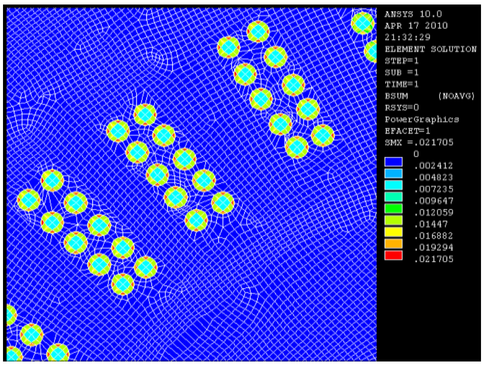


Fig 5.5 Short circuited conductors of 3-Phase Synchronous Generator at faulty condition.

The fig5.1 shows the generator model based on above given data after applying the load across the boundary vector potential with flux parallel and then applying magnetic current density on the areas of the conductors.

After that the fig 5.2 shows the excited conductor of 3-phase synchronous generator at normal condition and fig 5.3 shows the flux pattern with normal condition fig 5.4 shows the flux pattern in abnormal condition and fig.5.5 shows the short circuit condition after excitation by comparison of stored energy .In fig5.3, 5.4 we can see the changes in the values and deviation of the flux lines. By this we can conclude that there is a short circuit or flux in the stator conductors.

Calculation of Reactance

Current (I),

$$I = \frac{KVA}{\sqrt{3} * V_L}$$

Current density (J),

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

As,

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

Table 2 Calculation of short circuit currents for various conditions of faults

Number of conductors short circuited	Total energy stored(J)	Inductance(H)	Reactance(Ω)	Short circuit current(Isc mA)
0	0.877862	1.348027677*10-3	0.42349538 47	1.103153924
2	0.875076	1.34374955*10-3	0.422115137 15	1.099652933
3	0.874250	1.342481161*10-3	0.421752895 3	1.098614
5	0.870160	1.336200637*10-3	0.419779810 5	1.093475305
8	0.865915	1.329682098*10-3	0.417731951 1	1.088140881 4

The above Table 2 shows the summary of calculation of short circuit currents for various conditions of faults in a obtained values of inductance, short circuit current can be used to develop an off-line condition monitoring method using artificial intelligence tools like Neural Networks or Fuzzy logic, where the above values can be used to train NN/FL. If these samples are given as inputs to the neural network it can provide an accurate approximation for input /output mapping functions between interturn fault parameters and output voltage and terminal currents. Thus in the future such system is expected to develop for offline or online condition monitoring.

IV. CONCLUSION

A inter turn fault in the stator winding of a generator causes a large circulating current to flow in the shorted turns. If left undetected, turn faults can propagate, leading to phase-ground or phase-phase faults. Incipient detection of turn's faults is essential to avoid hazardous operating conditions and reduce down time. The knowledge of synchronous generator reactances is very important when analyzing both the steady state and transient performance characteristics, at various loading and operating conditions. Machine reactances are calculated via Finite Element Analysis (FEA). After, they are determined analytically. The final evaluation of SG reactances is done experimentally. At present the synchronous generators are protected against almost all kind of faults using differential methods of protection. All kind of faults develops into inter winding fault by damaging inter winding insulation. So it is necessary to protect the synchronous generator from inter winding faults which represents the protection against all kind of faults. For in this 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.

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

FUTURE SCOPE

At present the synchronous generators are protected against almost all kind of faults using differential methods of protection. Synchronous generators reliability and proper functioning are crucial in maintaining an uninterrupted power supply to the customers. The causes may be due to insulation degradation in the windings as well as environmental influence such as moisture or oil in combination with dirt settles on the coil surfaces outside the stator slots. This often leads to electrical tracking discharges in the end winding which eventually punctures the ground wall. Stator's winding fault must be avoided since the amount of time wasted and the cost for repairing a generator is enormous. Protection schemes in current use can readily detect most of the serious or major faults. All kind of faults develops into inter winding fault by damaging inter winding insulation. So it is necessary to protect the synchronous generator from inter winding faults which represents the protection against all kind of faults There are different method based techniques for analyzing generator incipient/inter turn faults on stator side. They are circuit based, field based, wavelet based, artificial intelligence based, fuzzy based, artificial neural networks based. Machine performance characteristics that could be monitored to diagnose the stator inter-turn fault in generator include line current, terminal voltage, torque pulsations, temperature rise due to excessive losses, shaft vibrations, air-gap flux and speed ripples.

So in this 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.

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