DETECTION OF GENERATOR STATOR FAULTS USING NEURO-FUZZY TECHNIQUE

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

ELECTRICAL ENGINEERING

(With Specialization in Measurement and Instrumentation)

By

SAURABH NEMA

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE-247 667 (INDIA)

JUNE, 2004

I.D No.-M.T. 291/HKV/MIM/2004

CANDIDATE'S DECLARATION

I hereby declare that the work presented in this dissertation entitled, **"DETECTION OF GENERATOR STATOR FAULTS USING NEURO-FUZZY TECHNIQUE"** submitted in partial fulfillment of the requirement for the award of degree of **MASTER OF TECHNOLOGY** with specialization in **MEASUREMENT AND INSTRUMENTATION** in the department of **Electrical Engineering, Indian Institute of Technology Roorkee, Roorkee-247667** is an authentic record of my own work under the guidance of **Dr.H.K.Verma,** Professor, Department of Electrical Engineering and **Dr.R.P.Maheshwari,** Assistant Professor, Department of Electrical Engineering, Indian Institute of Technology Roorkee.

I have not submitted the matter embodied in this dissertation for the award of any other degree.

Dated: 29 JUNE 2004

Place: Roorkee

(Saurabh Nema)

This is to certify that the above statement made by the candidate is correct to the best of our knowledge and belief.

29/6/04

(Dr. H.K.Verma)
Professor,
Deptt. of Electrical Engg.
I.I.T Roorkee
Roorkee-247667

(Dr. R.P. Maheshwari)
Assistant Professor,
Deptt. of Electrical Engg.
I.I.T Roorkee
Roorkee-247667

ACKNOWLEDGEMENT

I express my sincere gratitude towards my guides **Dr. H.K.Verma,** Professor, Department of Electrical Engineering and **Dr. R.P. Maheshwari**, Assistant Professor Department of Electrical Engineering, I.I.T. Roorkee, for their guidance, advice, useful criticism, support and encouragement during the work.

My heartfelt gratitude and indebtedness goes to all the teachers of **M&I** group who, with their encouraging and caring words, constructive criticism and suggestions, have contributed directly or indirectly in a significant way towards completion of this dissertation work.

I convey my deep sense of gratitude to the Head of Electrical Engineering department, I.I.T. Roorkee for providing the facilities of the department.

I appreciate and thank the entire laboratory and official staff of Department of Electrical Engineering, who directly or indirectly helped me during the work.

It is difficult for me to express my gratitude to my parents for their affection and encouragement. Special and sincere thanks go to my friends whose support and encouragement have been a constant source of strength and inspection to me.

Saurabh Nema

ABSTRACT

In this work, Neuro-Fuzzy Technique has been used for developing an algorithm for protection and monitoring of synchronous generator. The developed scheme consists of two parts; these are (1) Simulation of various operating states of synchronous generator and (2) Fault detection using neuro-fuzzy technique. In first part various operating states, namely, normal operating state, internal fault and external fault state of synchronous generator have been simulated. Modelling of generator has been done in terms of phase quantities. The fault detection part uses current samples from the line-side and neutral-end in addition to the samples from field current. Neural Network is used for detecting operating state and Fuzzy logic is for final decision making to issue a trip signal.

Using this developed software application, various operating states of synchronous generator connected to infinite bus can be simulated and a trip signal can be issued in case of short circuit faults in stator winding.

CONTENTS

NOMENCLATURE

General

X	= state variable,
p	= d/dt (derivative operator).

For Synchronous Machine

m	= stator phase,
i_m	= instantaneous currents in phase winding m,
e_m	= instantaneous voltages of phase winding m,
ψ_m	= instantaneous flux linkage in phase winding m,
R_m	= resistance of phase winding m,
L_m	= self-inductance of phase winding m,
M_{mn}	= mutual-inductances between stator windings of phase m and n,
M_{mf}	= mutual inductances between m and d-axis field windings,
M_{mkd}	= mutual inductances between m and d-axis damper windings,
M_{mkq}	= mutual inductances between m and q-axis damper windings,
L_f	= self-inductance of field winding,
L_{kd} and L_{kq}	= self-inductances of amortisseur windings,
L_d	= direct axis synchronous inductance,
L_q	= quadrature axis synchronous inductance,
L'_d	= direct axis transient inductance,
L'_q	= quadrature axis transient inductance,
L''_d	= direct axis sub-transient inductance,
L''_q	= quadrature axis sub-transient inductance,
T'_{do}	= direct axis transient open circuit time constant,
T'_{qo}	= quadrature axis transient open circuit time constant,
T''_{do}	= direct axis sub-transient open circuit time constant,
T''_{qo}	= quadrature axis sub-transient open circuit time constant,
T_{elect}	= electrical torque,
T_{mech}	= mechanical torque,
ω_{base}	= base speed,
ω_s	= synchronous speed,
f_s	= frequency,
H	= inertia constant,
K_D	= damping constant.

A = number of parallel path per phase,

Transmission Line

R_{line} = transmission line resistance,

L_{line} = transmission line inductance,

X_{line} = transmission line reactance.

Subscripts

a,b,c = phase variables,

p,m,n,z,r,s = parts of faulty phases,

f = field winding variables,

kd and kq = damper winding variables.

Chapter-1

INTRODUCTION

The generator being the core of an electrical power system, its protection assumes great significance. A fault on, or abnormal operation of, a large generator may seriously affect the operation of the power system to which it is connected in addition to damaging itself. A large variety of faults can occur on the generator, which calls for diverse means of protection. In general, the amount and type of protection to be used for any power system element is governed by economics and importance of that element to the power system. From both considerations, the best protective means, in terms of the speed, sensitivity and selectivity, should be chosen for large generators.

Some deficiencies and problems have been experienced by the protection engineers with the protective relays. Use of digital computers seems to have a great potential in improving the performance of protective system in addition to overcoming many of the identified deficiencies and problems.

1.1 STATEMENT OF PROBLEM

The main objective of this work is to explore use of Artificial Neural Network and Fuzzy Logic for improvement of protection and monitoring of generator. The protective function selected for this purpose is the differential protection, which protects generator stator winding on short circuits, which may be considered as the severest type of fault.

Presence of dc and harmonics in relaying signals, specially during faults, adversely affects the sensitivity and selectivity of protective relays. The use of computers to implement a relaying function can help to overcome this problem. In this work a relay algorithm based on artificial neural network and fuzzy logic has been presented to detect different operating states of synchronous generator.

1.2 OVERVIEW OF PRESENT WORK

Differential protection, using electromechanical and solid state relays, is the most common method used for stator winding protection. However, the rapid advances in digital technology enabled researchers and designers to make significant progress in developing computer based protection algorithms. In this dissertation work, an algorithm based on Neuro-Fuzzy Technique has been developed for protection of stator or armature winding of synchronous generator. Protective function selected for this purpose is the differential protection, which protects generator stator winding on short circuits, which may be considered as the severest type of fault. The developed scheme consists of two parts; these are:

(1) Detection of internal fault using neuro-fuzzy technique, and

(2) Simulation of various operating states of synchronous generator

1.2.1 Fault Detection using Neuro-Fuzzy Technique

Feed Forward Neural Network (FNN) and Fuzzy Logic based this part is used to discriminate between three generator states, namely the normal operating state, internal fault state, and external fault state. In the event of internal fault a trip signal is issued.

Inputs to this part are the current samples from the line side and neutral end. In addition to the samples of phase currents, samples of field winding current are also given as input. The presence of second harmonic in the field current, during a fault, is the indication of existence of an abnormality. And thus, samples of field current help in differentiating between the three operating states. Current patterns used to train the FNN are obtained by simulating normal operating state at different loading conditions and different types of internal and external faults. The performance of the protection scheme is tested using a set of independent test patterns.

Training algorithm used to train the FNN is the Back Propagation algorithm with momentum rate and adaptive learning rate. Weight modification is based on Steepest Descent method. FNN is used to differentiate between the three operating states of generator and final decision to issue trip signal is made by a method based on Fuzzy Logic.

1.2.2 Simulation of Various Operating States

In this section, the current patterns required to train the feed forward neural network as illustrated in previous section are obtained by simulating various operating states of generators; these are:

(1) Normal operating state

(2) Internal fault state

(3) External fault state

The model of synchronous generator considered for simulation consists of a multi parallel path synchronous generator connected to infinite bus through a short transmission line and both the generator and infinite bus neutrals are grounded through resistances as shown in Fig. 1.2.1.

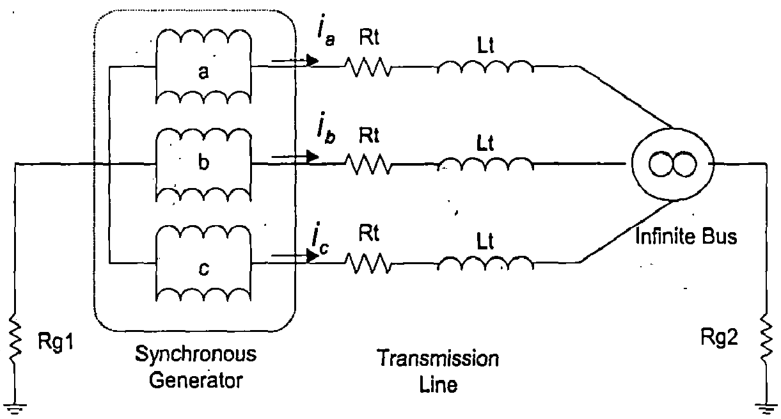


Fig. 1.2.1 System Representation of the Simulated Model

Using this model normal operating state of generator has been simulated at different power levels and at different power factors.

An internal fault in the armature winding of synchronous generator occurs due to the breakdown of winding insulation. Same model has been used to simulate internal short circuit faults in the armature winding at different locations along the winding and at different power levels. Internal faults considered in this work are LG, LLG, LL type short circuits. External faults along the transmission line have also been simulated with the help of same model.

1.3 LITERATURE REVIEW

There is a wealth of literature available in the field of synchronous generator protection using differential protection scheme. Differential protection, using electromechanical and solid state relays, is the most common method used for stator winding protection.

Present literature survey covers two aspects; one for protection of synchronous generator and other for the modelling of generators under various operating states.

1.3.1 Protection of Generator

The paper [1] by M. S. Sachdev and D. Wind presents a real time hybrid, analog-digital, computer technique for differential protection of generators. The fault/no fault decisions are based on the amplitude ratio of the fault and average through currents from a selected generator phase. Typical examples of internal and external faults in three phase generator have been presented.

In the paper [2] by G.S. Hope, P.K. Dash and O.P. Malik an online digital computer technique, based on differential protection of synchronous generator, for fault detection and tripping well within half a cycle and for discriminating between internal and external faults has been presented.

A method which uses field winding current to detect fault is described in the paper [3] presented by P.K. Dash, O.P. Malik, and G.S. Hope.

Paper [4] by A.I. Megahed, and O.P. Malik presents a method which uses ANN technique for the protection of synchronous generator stator winding. Currents from line side and neutral end of generator along with the field currents are used for fault detection.

Use of an ANN based single layer perception and two layer feed forward based detection schemes to detect loss of transient stability, loss of excitation and fault type has been described in paper [5] by A.M. Sharaf, T.T. Lie.

A digital technique that uses voltages and currents at the generator terminals to differentiate between internal and external fault is given in [6] by T. S. Sidhu, B. Sunga, M. S. Sachdev.

In paper [7] by T. S .Sidhu et al a FNN based scheme for fault direction discrimination in case of transmission lines has been proposed.

The paper [8] by Andrzej Wisznieski and Bogdan Kasztenny presents a multi-criteria algorithm based on fuzzy sets for decision making to design a digital relay scheme for primary protection of transformers.

1.3.2 Modelling of Generator

Paper [10] by A.I. Megahed, and O.P. Malik presents a method for for simulating internal faults in synchronous generators using direct phase quantities. Method for calculating inductances of faulty winding of generator has also been described.

The reference [12] by P. Kundur describes the development of detailed mathematical model of synchronous machine and briefly reviews its steady state and transient performance characteristics. It defines the derived parameters of synchronous machine that are directly related to observed behaviour under suitable test conditions and develops their relationships to the fundamental parameters. The simplifications required for the representation of the synchronous machine in stability studies are also discussed.

In reference [13] by P. M. Anderson and A. A. Fouad, a mathematical model for a synchronous machine has been developed for stability studies. Two models have been developed, one using the currents as state variables and another using the flux linkages. Simplified models, which are often used for stability studies have also been discussed. It also covers some practical considerations in the use of the mathematical model of synchronous machines in stability studies. Among these considerations are the determination of initial conditions, determination of the parameters of the machine from available data and construction of simulation models for the machine.

1.4 DISSERTATION LAYOUT

This thesis is organized in six chapters and the work included in each chapter has been briefly outlined here as follows:

The present chapter-1 introduces the concept used in this work for protection of generator and model used for simulating various operating conditions of generator. Brief literature survey on the modelling concept of various operating conditions of generator and application of artificial neural network and fuzzy logic is also presented.

Chapter-2 deals with the block diagrams, circuit model, and/or mathematical equations for simulating normal operating state of generator, internal faults, and external faults.

The chapter-3 describes the structure of artificial neural network and use of fuzzy logic for detecting faulty operation and decision making for issuing trip signal.

The chapter-4 briefly describes the algorithm developed for fault simulation and fault detection.

The chapter-5 includes the results obtained and discussions on results.

Chapter-6 concludes the work with limitations and scope for future work.

Chapter-2

MODELLING OF GENERATOR

In this chapter, the modelling of synchronous generator and necessary equations representing its behaviour during different operating conditions have been presented.

2.1 NORMAL OPERATION

Synchronous generators form the principal source of electrical energy in power systems. Power system stability problem is largely one of keeping interconnected synchronous machines in synchronism.

The magnetic circuits and all rotor windings are symmetrical with respect to both polar and inter-polar axis. Therefore, for the purpose of identifying synchronous machine characteristics, two axes are defined: -

1. The direct (**d**) axis, centred magnetically in the centre of the North Pole,
2. The quadrature (**q**) axis, 90° (electrical) ahead of the **d**-axis.

The position of the rotor relative to the stator is measured by the angle θ between the **d**-axis and the magnetic axis of the phase **a** winding.

In developing the equations of a synchronous machine, the following assumptions are made:-

a. The stator windings are sinusoidally distributed along the air-gap as far as the mutual effects with the rotor are concerned,

b. The stator slots cause no appreciable variation in the rotor inductances with rotor position,

c. Magnetic hysteresis is negligible,

d. Magnetic saturation effects are negligible.

Fig. 2.1.1 shows the circuits involved in the analysis of a synchronous machine. The stator circuits consist of 3-ϕ armature windings carrying alternating currents. The rotor circuits comprise field and amortisseur windings. The field winding is connected to a source of direct current. For the purpose of analysis, the currents in the amortisseur may be assumed to flow in two sets of closed circuits. One whose flux is in line with that of the field winding, along the **d**-axis, and the other whose flux is at right angle to the field axis or along the **q**-axis. In fig. 2.1.1, for simplicity only one amortisseur circuit is assumed in each axis.

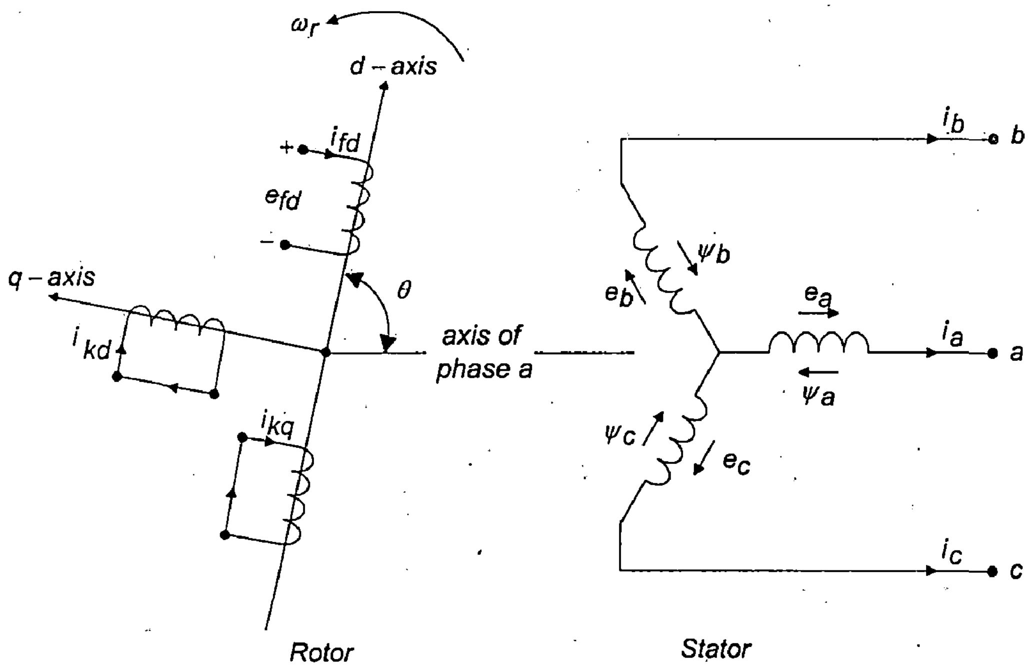


Fig. 2.1.1 Stator and Rotor Circuits of a Synchronous Machine

In fig. 2.1.1, θ is defined as the angle by which the **d**-axis leads the axis of phase a winding in the direction of rotation. Since the rotor is rotating with respect to the stator, angle θ is continuously increasing and is related to the rotor angular velocity, ω_r and time, t as follows,

$\theta = \omega_r t$

Writing equations of the coupled circuits identified in fig. 2.1.1 can develop the electrical performance equations of a synchronous machine. Here we use the generator convention for polarities so that the positive direction of a stator winding current is assumed to be out of the machine. The positive direction of field and amortisseur currents is assumed to be into the machine.

The voltage equations of stator and rotor circuits are:

$$\begin{bmatrix} e_a \\ e_b \\ e_c \\ e_{fd} \\ 0 \\ 0 \end{bmatrix} = p\begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \\ \psi_{fd} \\ \psi_{kd} \\ \psi_{kq} \end{bmatrix} + \begin{bmatrix} -R_a & 0 & 0 & 0 & 0 & 0 \\ 0 & -R_a & 0 & 0 & 0 & 0 \\ 0 & 0 & -R_a & 0 & 0 & 0 \\ 0 & 0 & 0 & R_{fd} & 0 & 0 \\ 0 & 0 & 0 & 0 & R_{kd} & 0 \\ 0 & 0 & 0 & 0 & 0 & R_{kq} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_{fd} \\ i_{kd} \\ i_{kq} \end{bmatrix} \tag{2.1.1}$$

The flux-linkages with stator and rotor windings at any instant *t* are given by:-

$$\begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \\ \psi_{fd} \\ \psi_{kd} \\ \psi_{kq} \end{bmatrix} = \begin{bmatrix} L_a & M_{ab} & M_{ac} & M_{afd} & M_{akd} & M_{akq} \\ M_{ba} & L_b & M_{bc} & M_{bfd} & M_{bkd} & M_{bkq} \\ M_{ca} & M_{cb} & L_c & M_{cfd} & M_{ckd} & M_{ckq} \\ M_{fda} & M_{fdb} & M_{fdc} & L_f & M_{fkd} & 0 \\ M_{kda} & M_{kdb} & M_{kdc} & M_{kfd} & L_{kd} & 0 \\ M_{kqa} & M_{kqb} & M_{kqc} & 0 & 0 & L_{kq} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_{fd} \\ i_{kd} \\ i_{kq} \end{bmatrix} \tag{2.1.2}$$

All inductances are functions of the rotor position, θ and thus time varying.

(A) Stator self-inductances

The stator self-inductance is directly proportional to the permeance, which has a second harmonic variation. The self-inductance, L_a of phase **a** including leakage flux is given by:

$$L_a = L_{ao} + L_{ga2}\cos 2\theta$$

where,

$L_{ao} + L_{ga2}$ = Maximum self-inductance of stator windings,

$L_{ao} - L_{ga2}$ = Minimum self-inductance of stator windings.

Since the windings of phases **b** and **c** are identical to that of phase **a** and are displaced from it by 120° and 240° respectively, so,

$$L_b = L_{ao} + L_{ga2}\cos 2\left(\theta - \frac{2\pi}{3}\right) \quad L_c = L_{ao} + L_{ga2}\cos 2\left(\theta + \frac{2\pi}{3}\right) \tag{2.1.3}$$

(B) Stator mutual inductances

The mutual inductance between any two-stator windings also exhibits a second harmonic variation because of the rotor shape. There is a very small amount of mutual flux around the ends of the windings, which does not cross the air-gap. With this flux included, the mutual inductance between phases **a** and **b** can be written as: -

$$M_{ab} = M_{ba} = M_{abo} + L_{ga2}\cos\left(2\theta - \frac{2\pi}{3}\right)$$

where,

$M_{abo} + L_{ga2}$ = Maximum mutual inductance between stator windings,

$M_{abo} - L_{ga2}$ = Minimum mutual inductance between stator windings.

Similarly,

$$M_{bc} = M_{cb} = M_{abo} + L_{ga2}\cos(2\theta)$$

$$M_{ca} = M_{ac} = M_{abo} + L_{ga2}\cos\left(2\theta + \frac{2\pi}{3}\right) \quad (2.1.4)$$

(C) Mutual Inductance between stator and rotor windings

With the variations in air-gap due to stator slots neglected, rotor circuits see a constant permeance. So, the variation in mutual inductance is due to relative motion between the windings themselves. With a sinusoidal distribution of mmf and flux waves, mutual inductance between stator phase **a** winding and rotor windings can be given as:-

$$M_{af} = M_{fa} = M_{af}\cos\theta$$

$$M_{akd} = M_{kda} = M_{af}\cos\theta$$

$$M_{akq} = M_{kqa} = -M_{aq}\sin\theta \quad (2.1.5)$$

For considering the mutual inductance between phases **b** and **c** and the rotor circuits, θ is replaced by $\theta - \frac{2\pi}{3}$ and $\theta + \frac{2\pi}{3}$ respectively.

(D) Self and Mutual Inductances for rotor windings

The rotor circuits see constant permeance because of the cylindrical structure of the stator. Therefore, the self-inductances of rotor circuits and mutual inductances between each other do not vary with rotor position.

2.2 INTERNAL FAULTS

Along with the development of electrical power industry, the protection of synchronous generator with several parallel paths becomes more important. The internal short circuit current for the generator may be several times larger than its terminal short circuit current. This strong current could cause severe heating and mechanical damage. Hence an accurate method for calculating the internal fault currents is required for adequate generator protection. A simulation model of system has been shown in Fig. 2.2.0 for this purpose.

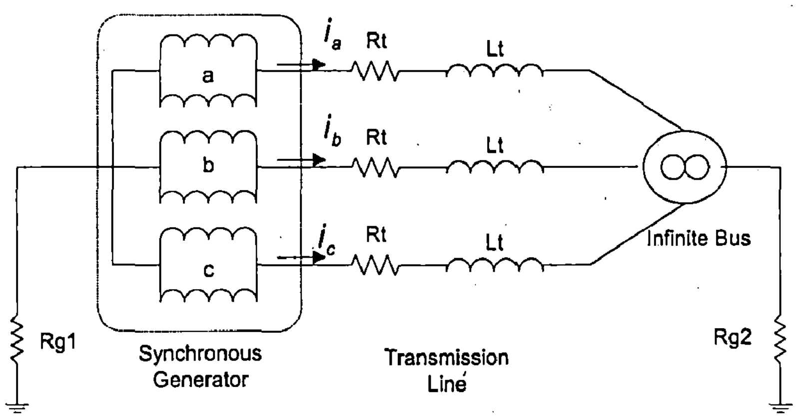


Fig. 2.2.0 Simulation Model

This model consists of a multi-parallel path synchronous generator connected to infinite bus through a short transmission line. Both the generator and infinite bus neutrals are grounded through resistances R_{g1} and R_{g2} respectively.

2.2.1 Simulation of LG Fault

A schematic representation of synchronous machine with two damper coils (one along **d**-axis and other along **q**-axis) during an internal single phase to ground fault in phase **a**, is shown in Fig. 2.2.1. It is assumed that the armature winding of synchronous machine consisting of 'A' number of parallel paths per phase and it is tapped at a certain point on one of the parallel paths of phase **a**. The tapped parallel path is divided in two parts; one path is adjacent to neutral point (**m** winding) and other adjacent to machine terminal (**n** winding). The remaining 'A-1' parallel paths are lumped into one equivalent winding (**p** winding) [10].

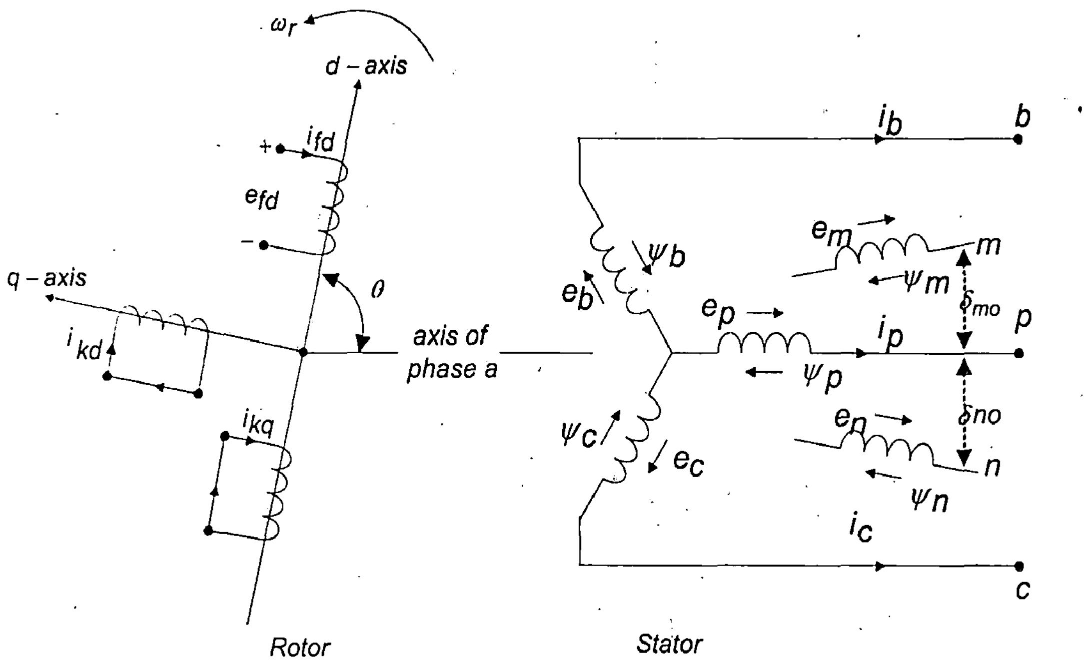


Fig. 2.2.1 Schematic Representation of Synchronous Machine during LG Fault

(1) Modelling of Generator during LG Fault

In direct phase quantities, the performance of synchronous generator, during an internal single phase to ground fault, connected to an infinite busbar through a short transmission line, as in Fig. 2.2.2, can be described by the following equations [11], [13]:

$$\begin{bmatrix} e_p \\ e_m \\ e_n \\ e_b \\ e_c \\ e_f \\ e_{kd} \\ e_{kq} \end{bmatrix} = p \begin{bmatrix} \psi_p \\ \psi_m \\ \psi_n \\ \psi_b \\ \psi_c \\ \psi_f \\ \psi_{kd} \\ \psi_{kq} \end{bmatrix} + \begin{bmatrix} -R_p & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -R_m & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -R_n & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -R_b & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -R_c & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & R_f & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & R_{kd} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_{kq} \end{bmatrix} \begin{bmatrix} i_p \\ i_m \\ i_n \\ i_b \\ i_c \\ i_f \\ i_{kd} \\ i_{kq} \end{bmatrix} \tag{2.2.1}$$

And the flux linkage relationships during the fault are given as:

$$\begin{bmatrix} \psi_p \\ \psi_m \\ \psi_n \\ \psi_b \\ \psi_c \\ \psi_f \\ \psi_{kd} \\ \psi_{kq} \end{bmatrix} = \begin{bmatrix} L_p & M_{pm} & M_{pn} & M_{pb} & M_{pc} & M_{pf} & M_{pkd} & M_{pkq} \\ M_{mp} & L_m & M_{mn} & M_{mb} & M_{mc} & M_{mf} & M_{mkd} & M_{mkq} \\ M_{np} & M_{nm} & L_n & M_{nb} & M_{nc} & M_{nf} & M_{nkd} & M_{nkq} \\ M_{bp} & M_{bm} & M_{bn} & L_b & M_{bc} & M_{bf} & M_{bkd} & M_{bkq} \\ M_{cp} & M_{cm} & M_{cn} & M_{cb} & L_c & M_{cf} & M_{ckd} & M_{ckq} \\ M_{fp} & M_{fm} & M_{fn} & M_{fb} & M_{fc} & L_f & M_{fkd} & 0 \\ M_{kdp} & M_{kdm} & M_{kdn} & M_{kdb} & M_{kdc} & M_{kdf} & L_{kd} & 0 \\ M_{kqp} & M_{kqm} & M_{kqn} & M_{kqb} & M_{kqc} & 0 & 0 & L_{kq} \end{bmatrix} \begin{bmatrix} i_p \\ i_m \\ i_n \\ i_b \\ i_c \\ i_f \\ i_{kd} \\ i_{kq} \end{bmatrix}$$

(2.2.2)

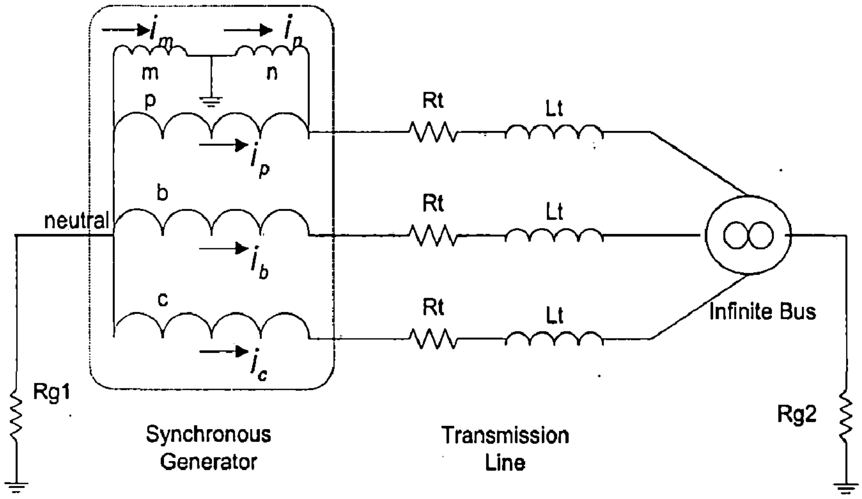


Fig. 2.2.2 System Representation during LG Fault

During an internal phase to ground fault, the machine terminal voltages can be written from Fig. 2.2.2

$$e_p = E_{bus}\sin(\omega t) + R_t(i_p + i_n) + L_t\left(\frac{di_p}{dt} + \frac{di_n}{dt}\right) + R_{g1}\left(i_p + i_m + i_b + i_c\right) + R_{g2}\left(i_p + i_n + i_b + i_c\right)$$

$$e_m = R_{g1}\left(i_p + i_m + i_b + i_c\right)$$

$$e_n = e_p$$

$$e_b = E_{bus}\sin\left(\omega t - \frac{2\pi}{3}\right) + R_t(i_b) + L_t\left(\frac{di_b}{dt}\right) + R_{g1}\left(i_p + i_m + i_b + i_c\right) + R_{g2}\left(i_p + i_n + i_b + i_c\right)$$

$$e_c = E_{bus}\sin\left(\omega t + \frac{2\pi}{3}\right) + R_t(i_c) + L_t\left(\frac{di_c}{dt}\right) + R_{g1}\left(i_p + i_m + i_b + i_c\right) + R_{g2}\left(i_p + i_n + i_b + i_c\right)$$

(2.2.3)

(2) Inductance of Faulty Phase

The inductance matrix of equation (2.2.2) can be viewed as having two parts, a healthy part and a faulty part. The healthy part is associated with the self and mutual inductances of the healthy phases (i.e. **b**, **c**, **f**, **kd**, **kq**). The fault part is associated with the self and mutual inductances of different parts of faulty phase **a** (i.e. **p**, **m**, **n**). The inductances of faulty part need some modification from the normal values [10], [11].

The fault current in a short circuited part of the armature winding produces a magnetic flux with relatively stronger harmonics. Consequently, the differential leakage is relatively high for a small part of one parallel path of armature winding. Therefore, the ratio of leakage inductance of one part to the whole winding is not proportional to the ratio between the squared effective numbers of turns of the corresponding windings. However, the main inductance is proportional to effective number of turns of corresponding winding.

$$\frac{L_{gm}}{L_{ga}} = \left(\frac{N_m}{N}\right)^2 \qquad (2.2.4)$$

Where, L_{gm} and L_{ga} are the main inductances of **m** and **a** winding respectively, and N_m and N are the number of turns of **m** and **a** winding respectively. Hence self inductance of **m** winding is:

$$L_m = L_{lm} + L_{gm} \qquad (2.2.5)$$

Where,

$$L_{gm} = L_{gm0} + L_{gm2}\cos(2\theta_m) \qquad (2.2.6)$$

Same method can be used to calculate self inductance of **n** winding. Due to the distributed nature of the winding of synchronous machine, the faulted parts of the winding, **m**, n, have rotor displacement angles different from that of the **p** winding, Fig. 2.2.1. The displacement angles of windings **m** and **n** can be calculated as follows:

$$\begin{aligned}\theta_m &= \theta + \delta_{mo} \\ \theta_n &= \theta + \delta_{no}\end{aligned} \qquad (2.2.7)$$

Mutual inductance between any two faulty winding parts can be calculated as:

$$M_{pm} = M_{mp} = \left(\frac{N}{N_m}\right) L_{gm} \qquad (2.2.8)$$

As internal fault does not affect the main inductance of faulted phase, hence the portion of the flux linking a healthy phase due to the faulted phase, should be the same as before fault occurrence. Hence

$$i_a M_{ab} = i_p M_{pb} + i_m M_{mb} + i_n M_{nb}$$

$$\Rightarrow i_a M_{ab} = \left(\frac{A-1}{A}\right) i_a M_{ab} + \frac{i_a}{A} \frac{N_m M_{ab}}{N} + \frac{i_a}{A} \frac{N_n M_{ab}}{N}$$

This gives

$$\begin{aligned}M_{pb} &= M_{bp} = M_{ab} = M_{ba} \\ M_{mb} &= M_{bm} = \left(\frac{N_m}{N}\right) M_{ab} \\ M_{nb} &= M_{bn} = \left(\frac{N_n}{N}\right) M_{ab}\end{aligned} \qquad (2.2.9)$$

Similarly, the self inductance of winding **p** can be calculated.

$$i_a L_a = i_p L_p + i_m M_{pm} + i_n M_{pn}$$

$$\Rightarrow i_a L_a = \left(\frac{A-1}{A}\right) i_a L_p + \frac{i_a}{A} \frac{N L_{gm}}{N_m} + \frac{i_a}{A} \frac{N L_{gn}}{Nn}$$

Substituting values of L_{gm} and L_{gn} from equation (2.2.6) and rearranging the above expression results in:

$$L_p = L_a + \frac{L_{la}}{A-1} \qquad (2.2.10)$$

Finally, the inductances of all phases can be listed as:

$$L_p = L_{ao} + L_{ga2}\cos 2\theta + \frac{L_{la}}{A-1}$$

$$M_{pm} = M_{mp} = \frac{N}{N_m}\left[L_{gm0} + L_{gm2}\cos(2\theta_m)\right]$$

$$M_{pn} = M_{np} = \frac{N}{Nn}\left[L_{gn0} + L_{gn2}\cos(2\theta_n)\right]$$

$$M_{pb} = M_{bp} = M_{abo} + L_{ga2}\cos\left(2\theta - \frac{2\pi}{3}\right) \tag{2.2.11}$$

$$M_{pc} = M_{cp} = M_{abo} + L_{ga2}\cos\left(2\theta + \frac{2\pi}{3}\right)$$

$$M_{pf} = M_{fp} = M_{af}\cos\theta$$

$$M_{pkd} = M_{kdp} = M_{af}\cos\theta$$

$$M_{pkq} = M_{kqp} = -M_{aq}\sin\theta$$

$$L_m = L_{mo} + L_{gm2}\cos(2\theta_m)$$

$$M_{mn} = M_{nm} = \frac{N_n}{N_m}\left[L_{gm0} + L_{gm2}\cos(2\theta_{mn})\right]$$

$$M_{mb} = M_{bm} = \frac{N_m}{N}\left[M_{abo} + L_{ga2}\cos\left(2\theta - \frac{2\pi}{3}\right)\right]$$

$$M_{mc} = M_{cm} = \frac{N_m}{N}\left[M_{abo} + L_{ga2}\cos\left(2\theta + \frac{2\pi}{3}\right)\right] \tag{2.2.12}$$

$$M_{mf} = M_{fm} = \frac{N_m}{N}\left[M_{af}\cos\theta_m\right]$$

$$M_{mkd} = M_{kdm} = \frac{N_m}{N}\left[M_{af}\cos\theta_m\right]$$

$$M_{mkq} = M_{kqm} = \frac{N_m}{N}\left[-M_{aq}\sin\theta_m\right]$$

Similarly, the inductances of winding **n** can be calculated.

Inductances of windings **b**, **c**, **f**, **kd**, and **kq** will be same as described in section 2.1. In the above equations, L_{ao}, L_{ga2} and M_{abo} are the inductance coefficients of healthy armature winding and

$$\theta_{mn} = \theta + \frac{\delta_{mo} - \delta_{no}}{2} \tag{2.2.13}$$

(3) Swing Equation

The rotor swing equation can be given by [12]:

$$\frac{d\delta}{dt} = \omega_{base}\Delta\omega$$
$$\frac{d\Delta\omega}{dt} = \frac{T_{mech} - T_{elect} - K_D\Delta\omega}{2H} \tag{2.2.14}$$

The formula used for T_{elect} is

$$T_{elect} = -\frac{1}{3}\left(\frac{1}{2}i_{11}\frac{dL_{11}}{d\theta}i_{11}^t + i_{11}\frac{dL_{12}}{d\theta}i_{12}^t\right) \tag{2.2.15}$$

Where

$$i_{11} = \begin{bmatrix} i_p & i_m & i_n & i_b & i_c \end{bmatrix}$$
$$i_{12} = \begin{bmatrix} i_f & i_{kd} & i_{kq} \end{bmatrix} \tag{2.2.16}$$

And

$$L_{11} = \begin{bmatrix} L_p & M_{pm} & M_{pn} & M_{pb} & M_{pc} \\ M_{mp} & L_m & M_{mn} & M_{mb} & M_{mc} \\ M_{np} & M_{nm} & L_n & M_{nb} & M_{nc} \\ M_{bp} & M_{bm} & M_{bn} & L_b & M_{bc} \\ M_{cp} & M_{cm} & M_{cn} & M_{cb} & L_c \end{bmatrix}$$
$$L_{12} = \begin{bmatrix} M_{pf} & M_{pkd} & M_{pkq} \\ M_{mf} & M_{mkd} & M_{mkq} \\ M_{nf} & M_{nkd} & M_{nkq} \\ M_{bf} & M_{bkd} & M_{bkq} \\ M_{cf} & M_{ckd} & M_{ckq} \end{bmatrix} \tag{2.2.17}$$

The formula given in equation (2.2.15) is based on the fact that an electrical torque is produced in a machine when a change occurs in the energy stored in its coupling field W_{fld} [11] i.e.

$$T_{elect} = \frac{-dW_{fld}}{d\theta}$$

Equations (2.2.1) to (2.2.3) and (2.2.14) form the complete model of synchronous machine during LG fault.

Various inductances, as listed in equations (2.2.11) and (2.2.12) are dependent on rotor position, which varies with time. Hence the performance equations are differential equations with variable coefficients. As the speed of generator varies under transient operating conditions, the performance equations are nonlinear.

Equations (2.2.1) to (2.2.3) can be simplified in the form of simultaneous equations as:

$$[A]\left[\frac{di}{dt}\right]+[B][i]+[C]=0$$

This can further be simplified as:

$$\left[\frac{di}{dt}\right]=inv[A](-[B][i]-[C]) \qquad (2.2.18)$$

As there are total 8 current derivative terms, and two more from equation (2.2.14) i.e. rotor swing equation, all these 10 equations can be solved with the help of Runge-Kutta method.

2.2.2 Simulation of LLG Fault

Fig. 2.2.3 shows a synchronous generator having an internal two phase to ground fault in phases **a** and **b**. The faulty path of phase **b** is divided in two parts; one path is adjacent to neutral point (**r** winding) and other adjacent to machine terminal (**s** winding). The remaining A-1 parallel paths of phase **b** are lumped into one equivalent winding (**z** winding).

(1) Modelling of Generator during LLG Fault

In direct phase quantities, the performance of synchronous generator, during an internal double line to ground fault, connected to an infinite busbar through a short transmission line, as in Fig. 2.2.3, can be described by the following equations:

$$\begin{bmatrix} e_p \\ e_m \\ e_n \\ e_z \\ e_r \\ e_s \\ e_c \\ e_f \\ e_{kd} \\ e_{kq} \end{bmatrix} = p \begin{bmatrix} \psi_p \\ \psi_m \\ \psi_n \\ \psi_z \\ \psi_r \\ \psi_s \\ \psi_c \\ \psi_f \\ \psi_{kd} \\ \psi_{kq} \end{bmatrix} + \begin{bmatrix} -R_p & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -R_m & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -R_n & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -R_z & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -R_r & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -R_s & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -R_c & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_f & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_{kd} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_{kq} \end{bmatrix} \begin{bmatrix} i_p \\ i_m \\ i_n \\ i_z \\ i_r \\ i_s \\ i_c \\ i_f \\ i_{kd} \\ i_{kq} \end{bmatrix} \quad (2.2.19)$$

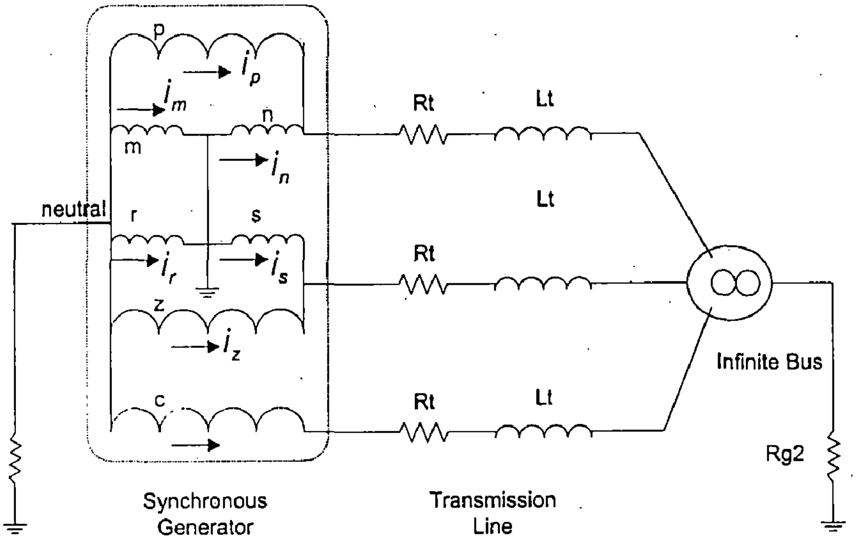


Fig. 2.2.3 System Representation during LLG Fault

And the flux linkage relationships during the fault are given as:

$$\begin{bmatrix} \psi_p \\ \psi_m \\ \psi_n \\ \psi_z \\ \psi_r \\ \psi_s \\ \psi_c \\ \psi_f \\ \psi_{kd} \\ \psi_{kq} \end{bmatrix} = \begin{bmatrix} L_p & M_{pm} & M_{pn} & M_{pz} & M_{pr} & M_{ps} & M_{pc} & M_{pf} & M_{pkd} & M_{pkq} \\ M_{mp} & L_m & M_{mn} & M_{mz} & M_{mr} & M_{ms} & M_{mc} & M_{mf} & M_{mkd} & M_{mkq} \\ M_{np} & M_{nm} & L_n & M_{nz} & M_{nr} & M_{ns} & M_{nc} & M_{nf} & M_{nkd} & M_{nkq} \\ M_{zp} & M_{zm} & M_{zn} & L_z & M_{zr} & M_{zs} & M_{zc} & M_{zf} & M_{zkd} & M_{zkq} \\ M_{rp} & M_{rm} & M_{rn} & M_{rz} & L_r & M_{rs} & M_{rc} & M_{rf} & M_{rkd} & M_{rkq} \\ M_{sp} & M_{sm} & M_{sn} & M_{sz} & M_{sr} & L_s & M_{sc} & M_{sf} & M_{skd} & M_{skq} \\ M_{cp} & M_{cm} & M_{cn} & M_{cz} & M_{cr} & M_{cs} & L_c & M_{cf} & M_{ckd} & M_{ckq} \\ M_{fp} & M_{fm} & M_{fn} & M_{fz} & M_{fr} & M_{fs} & M_{fc} & L_f & M_{fkd} & 0 \\ M_{kdp} & M_{kdm} & M_{kdn} & M_{kdz} & M_{kdr} & M_{kds} & M_{kdc} & M_{kdf} & L_{kd} & 0 \\ M_{kqp} & M_{kqm} & M_{kqn} & M_{kqz} & M_{kqr} & M_{kqs} & M_{kqc} & 0 & 0 & L_{kq} \end{bmatrix} \begin{bmatrix} i_p \\ i_m \\ i_n \\ i_z \\ i_r \\ i_s \\ i_c \\ i_f \\ i_{kd} \\ i_{kq} \end{bmatrix} \tag{2.2.20}$$

During an internal two phase to ground fault, the machine terminal voltages can be written from Fig. 2.2.3

$$\begin{aligned} e_p &= E_{bus}\sin(\omega t) + R_t(i_p + i_n) + L_t\left(\frac{di_p}{dt} + \frac{di_n}{dt}\right) + R_{g1}\left(i_p + i_m + i_z + i_r + i_c\right) + R_{g2}\left(i_p + i_n + i_z + i_s + i_c\right) \\ e_m &= R_{g1}\left(i_p + i_m + i_z + i_r + i_c\right) \\ e_n &= e_p \\ e_z &= E_{bus}\sin\left(\omega t - \frac{2\pi}{3}\right) + R_t(i_z + i_s) + L_t\left(\frac{di_z}{dt} + \frac{di_s}{dt}\right) + R_{g1}\left(i_p + i_m + i_z + i_r + i_c\right) + R_{g2}\left(i_p + i_n + i_z + i_s + i_c\right) \\ e_r &= R_{g1}\left(i_p + i_m + i_z + i_r + i_c\right) \\ e_s &= e_z \\ e_c &= E_{bus}\sin\left(\omega t + \frac{2\pi}{3}\right) + R_t(i_c) + L_t\left(\frac{di_c}{dt}\right) + R_{g1}\left(i_p + i_m + i_b + i_c\right) + R_{g2}\left(i_p + i_n + i_b + i_c\right) \end{aligned} \tag{2.2.21}$$

(2) Inductance of Faulty Phase

Most of the inductances in this part are same as described in previous section of LG fault simulation. However, inductances whose calculations are different are listed here.

$$\begin{aligned} M_{mr} = M_{rm} &= \frac{N_m N_r}{N^2}\left[M_{ab0} + L_{ga2}\cos\left(2\theta_{mr} - \frac{2\pi}{3}\right)\right] \\ M_{ms} = M_{sm} &= \frac{N_m N_s}{N^2}\left[M_{ab0} + L_{ga2}\cos\left(2\theta_{ms} - \frac{2\pi}{3}\right)\right] \end{aligned} \tag{2.2.22}$$

Where,

$$\theta_{mr} = \theta_m + \delta_{ro}$$
$$\theta_{ms} = \theta_m + \delta_{so} \qquad (2.2.23)$$

The rotor swing equation will be same as described for simulation of LG fault. Electrical torque can also be calculated by the same method as described before.

Equations (2.2.21), to (2.2.23) along with the rotor swing equation form the complete model of synchronous machine during an internal two phase to ground fault. These equations can be solved with the help of Runge-Kutta method.

2.2.3 Simulation of LL Fault

Fig. 2.2.4 shows a synchronous generator having an internal line to line fault in phases **a** and **b**.

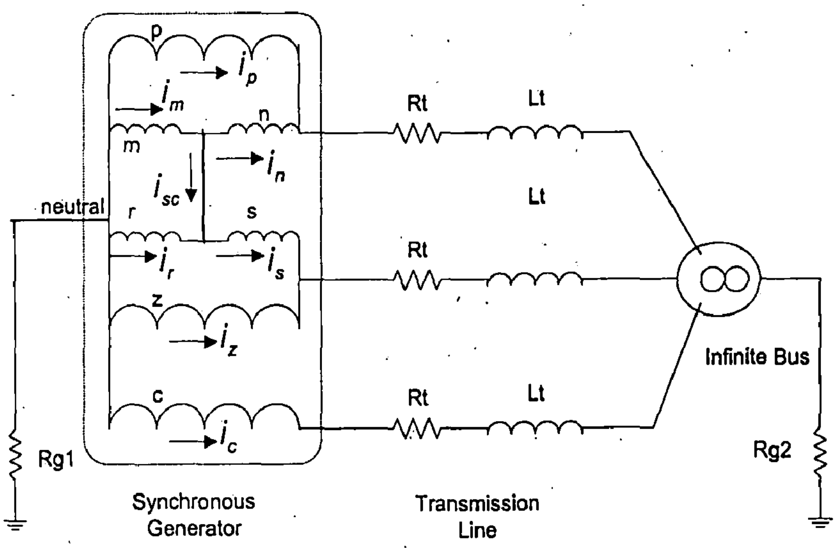


Fig. 2.2.4 System Representation during LL Fault

In direct phase quantities, the performance of synchronous generator, during an internal phase to phase fault, connected to an infinite busbar through a short transmission line, as in Fig. 2.2.4, can be described by the following equations:

$$\begin{bmatrix} e_p \\ e_m \\ e_n \\ e_z \\ e_r \\ e_s \\ e_c \\ e_f \\ e_{kd} \\ e_{kq} \end{bmatrix} = p \begin{bmatrix} \psi_p \\ \psi_m \\ \psi_n \\ \psi_z \\ \psi_r \\ \psi_s \\ \psi_c \\ \psi_f \\ \psi_{kd} \\ \psi_{kq} \end{bmatrix} + \begin{bmatrix} -R_p & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -R_m & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -R_n & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -R_z & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -R_r & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -R_s & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -R_c & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_f & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_{kd} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_{kq} \end{bmatrix} \begin{bmatrix} i_p \\ i_m \\ i_n \\ i_z \\ i_r \\ i_s \\ i_c \\ i_f \\ i_{kd} \\ i_{kq} \end{bmatrix}$$

(2.2.24)

And the flux linkage relationships during the fault are given as:

$$\begin{bmatrix} \psi_p \\ \psi_m \\ \psi_n \\ \psi_z \\ \psi_r \\ \psi_s \\ \psi_c \\ \psi_f \\ \psi_{kd} \\ \psi_{kq} \end{bmatrix} = \begin{bmatrix} L_p & M_{pm} & M_{pn} & M_{pz} & M_{pr} & M_{ps} & M_{pc} & M_{pf} & M_{pkd} & M_{pkq} \\ M_{mp} & L_m & M_{mn} & M_{mz} & M_{mr} & M_{ms} & M_{mc} & M_{mf} & M_{mkd} & M_{mkq} \\ M_{np} & M_{nm} & L_n & M_{nz} & M_{nr} & M_{ns} & M_{nc} & M_{nf} & M_{nkd} & M_{nkq} \\ M_{zp} & M_{zm} & M_{zn} & L_z & M_{zr} & M_{zs} & M_{zc} & M_{zf} & M_{zkd} & M_{zkq} \\ M_{rp} & M_{rm} & M_{rn} & M_{rz} & L_r & M_{rs} & M_{rc} & M_{rf} & M_{rkd} & M_{rkq} \\ M_{sp} & M_{sm} & M_{sn} & M_{sz} & M_{sr} & L_s & M_{sc} & M_{sf} & M_{skd} & M_{skq} \\ M_{cp} & M_{cm} & M_{cn} & M_{cz} & M_{cr} & M_{cs} & L_c & M_{cf} & M_{ckd} & M_{ckq} \\ M_{fp} & M_{fm} & M_{fn} & M_{fz} & M_{fr} & M_{fs} & M_{fc} & L_f & M_{fkd} & 0 \\ M_{kdp} & M_{kdm} & M_{kdn} & M_{kdz} & M_{kdr} & M_{kds} & M_{kdc} & M_{kdf} & L_{kd} & 0 \\ M_{kqp} & M_{kqm} & M_{kqn} & M_{kqz} & M_{kqr} & M_{kqs} & M_{kqc} & 0 & 0 & L_{kq} \end{bmatrix} \begin{bmatrix} i_p \\ i_m \\ i_n \\ i_z \\ i_r \\ i_s \\ i_c \\ i_f \\ i_{kd} \\ i_{kq} \end{bmatrix}$$

(2.2.25)

During an internal phase to phase fault, the machine terminal voltages can be written from Fig. 2.2.4

$$e_p = E_{bus}\sin(\omega t) + R_t(i_p + i_n) + L_t\left(\frac{di_p}{dt} + \frac{di_n}{dt}\right) + R_{g1}\left(i_p + i_m + i_z + i_r + i_c\right) + R_{g2}\left(i_p + i_n + i_z + i_s + i_c\right)$$

$$e_z = E_{bus}\sin\left(\omega t - \frac{2\pi}{3}\right) + R_t(i_z + i_s) + L_t\left(\frac{di_z}{dt} + \frac{di_s}{dt}\right) + R_{g1}\left(i_p + i_m + i_z + i_r + i_c\right) + R_{g2}\left(i_p + i_n + i_z + i_s + i_c\right)$$

$$e_c = E_{bus}\sin\left(\omega t + \frac{2\pi}{3}\right) + R_t(i_c) + L_t\left(\frac{di_c}{dt}\right) + R_{g1}\left(i_p + i_m + i_b + i_c\right) + R_{g2}\left(i_p + i_n + i_b + i_c\right)$$

(2.2.26)

$$e_m = \left(\frac{N_m}{N}\right)e_p$$
$$e_n = \left(\frac{N_n}{N}\right)e_p \qquad (2.2.27)$$

$$e_r = \left(\frac{N_r}{N}\right)e_z$$
$$e_s = \left(\frac{N_s}{N}\right)e_z \qquad (2.2.28)$$

$$i_{sc} = i_m + i_n$$
$$i_m = -i_r \qquad (2.2.29)$$
$$i_n = -i_s$$

Inductances in this part are same as used for simulation of LLG fault. The rotor swing equation will be same as described for simulation of LG fault and electrical torque can also be calculated by the same method as described before.

Equations (2.2.24), to (2.2.29) along with the rotor swing equation form the complete model of synchronous machine during an internal phase to phase fault. These equations can be solved with the help of Runge-Kutta method.

2.3 EXTERNAL FAULTS

2.3.1 Simulation of External LG Fault

Model of synchronous machine used for simulation of external single line to ground fault in phase a along the transmission line is as shown in Fig. 2.3.1.

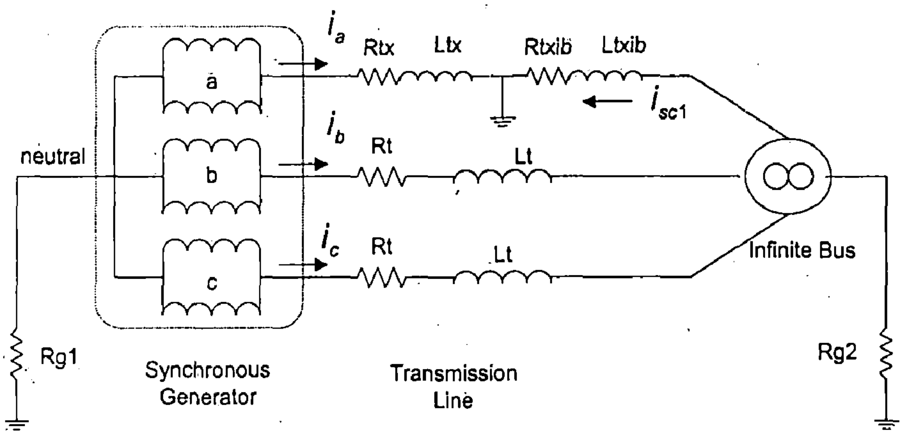


Fig. 2.3.1 System Representation during External LG Fault

In direct phase quantities, the performance of synchronous generator, during an external single phase to ground fault, can be described by the following equations:
The voltage equations of stator and rotor circuits are:

$$\begin{bmatrix} e_a \\ e_b \\ e_c \\ e_{fd} \\ 0 \\ 0 \end{bmatrix} = p \begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \\ \psi_{fd} \\ \psi_{kd} \\ \psi_{kq} \end{bmatrix} + \begin{bmatrix} -R_a & 0 & 0 & 0 & 0 & 0 \\ 0 & -R_a & 0 & 0 & 0 & 0 \\ 0 & 0 & -R_a & 0 & 0 & 0 \\ 0 & 0 & 0 & R_{fd} & 0 & 0 \\ 0 & 0 & 0 & 0 & R_{kd} & 0 \\ 0 & 0 & 0 & 0 & 0 & R_{kq} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_{fd} \\ i_{kd} \\ i_{kq} \end{bmatrix} \quad (2.3.1)$$

The flux-linkages with stator and rotor windings at any instant *t* are given by:

$$\begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \\ \psi_{fd} \\ \psi_{kd} \\ \psi_{kq} \end{bmatrix} = \begin{bmatrix} L_a & M_{ab} & M_{ac} & M_{afd} & M_{akd} & M_{akq} \\ M_{ba} & L_b & M_{bc} & M_{bfd} & M_{bkd} & M_{bkq} \\ M_{ca} & M_{cb} & L_c & M_{cfd} & M_{ckd} & M_{ckq} \\ M_{fda} & M_{fdb} & M_{fdc} & L_f & M_{fkd} & 0 \\ M_{kda} & M_{kdb} & M_{kdc} & M_{kfd} & L_{kd} & 0 \\ M_{kqa} & M_{kqb} & M_{kqc} & 0 & 0 & L_{kq} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_{fd} \\ i_{kd} \\ i_{kq} \end{bmatrix} \quad (2.3.2)$$

All inductances are functions of the rotor position, θ and thus time varying.
During an external single phase to ground fault, the machine terminal voltages can be written from Fig. 2.3.1.

$$e_a = R_{tx}(i_a) + L_{tx}\left(\frac{di_a}{dt}\right) + R_{g1}(i_a + i_b + i_c)$$

$$e_b = E_{bus}\sin\left(wt - \frac{2\pi}{3}\right) + R_t(i_b) + L_t\left(\frac{di_b}{dt}\right) + R_{g1}(i_a + i_b + i_c) + R_{g2}(i_{sc1} + i_b + i_c)$$

$$e_c = E_{bus}\sin\left(wt + \frac{2\pi}{3}\right) + R_t(i_c) + L_t\left(\frac{di_c}{dt}\right) + R_{g1}(i_a + i_b + i_c) + R_{g2}(i_{sc1} + i_b + i_c)$$

(2.3.3)

Assuming that current from infinite bus to fault point is i_{sc1}, the voltage equation of the path of current i_{sc1} can be written as [14]:

$$0 = E_{bus}\sin(\omega t) - R_{txib}(i_{sc1}) - L_{txib}\left(\frac{di_{sc1}}{dt}\right) - R_{g2}(i_{sc1} + i_b + i_c) \quad (2.3.4)$$

Where,

R_{tx} = Resistance of transmission line up to the fault point, and

L_{tx} = Inductance of transmission line up to the fault point

R_{txib} = Resistance of transmission line from the fault point to infinite bus, and

L_{txib} = Inductance of transmission line from the fault point to infinite bus

Inductances of synchronous machine used here are same as described in section 2.1, simulation of normal operation. Rotor swing equations are same as given in section 2.2.1 and electrical torque can be calculated with same method as mentioned in that section. Equations (2.3.1) to (2.3.4) along with the rotor swing equation form the complete model of synchronous machine during an external single phase to ground fault. These equations can be solved with the help of Runge-Kutta method.

2.3.2 Simulation of External LLG Fault

Model of synchronous machine used for simulation of external two phase to ground fault in phase **a** and phase **b** along the transmission line is as shown in Fig. 2.3.2.

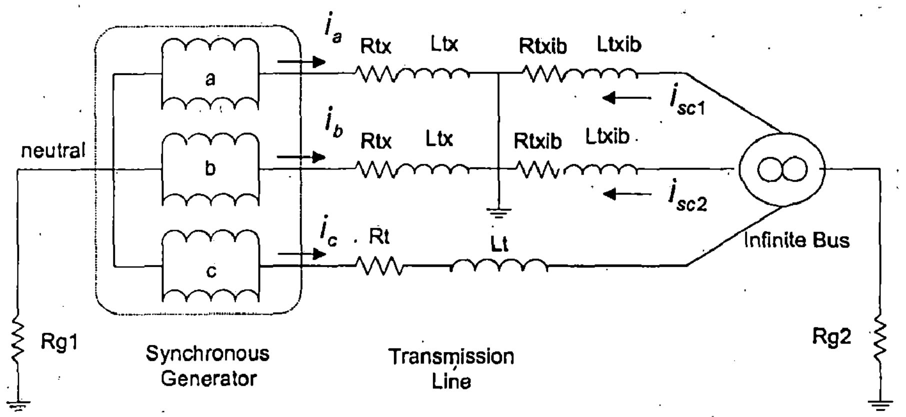


Fig. 2.3.2 System Representation during External LLG Fault

During an external two phase to ground fault along the transmission line voltage and flux linkage relationship of synchronous machine will remain same as given in section 2.3.1. Only terminal voltage equations will change. These equations can be written from Fig. 2.3.2.

$$e_a = R_{tx}(i_a) + L_{tx}\left(\frac{di_a}{dt}\right) + R_{g1}(i_a + i_b + i_c)$$

$$e_b = R_{tx}(i_b) + L_{tx}\left(\frac{di_b}{dt}\right) + R_{g1}(i_a + i_b + i_c)$$

$$e_c = E_{bus}\sin\left(wt + \frac{2\pi}{3}\right) + R_t(i_c) + L_t\left(\frac{di_c}{dt}\right) + R_{g1}(i_a + i_b + i_c) + R_{g2}(i_{sc1} + i_{sc2} + i_c)$$

(2.3.5)

The voltage equation of the path of current i_{sc1} and i_{sc2} can be written as:

$$0 = E_{bus}\sin(\omega t) - R_{txib}(i_{sc1}) - L_{txib}\left(\frac{di_{sc1}}{dt}\right) - R_{g2}(i_{sc1} + i_{sc2} + i_c)$$

$$0 = E_{bus}\sin\left(\omega t - \frac{2\pi}{3}\right) - R_{txib}(i_{sc2}) - L_{txib}\left(\frac{di_{sc2}}{dt}\right) - R_{g2}(i_{sc1} + i_{sc2} + i_c)$$

(2.3.6)

Equations (2.3.1) to (2.3.2) and equation (2.3.5) to (2.3.6) along with the rotor swing equation form the complete model of synchronous machine during an external two phase to ground fault. These equations can be solved with the help of Runge-Kutta method.

2.3.3 Simulation of External LL Fault

Model of synchronous machine used for simulation of external phase to phase fault in phase **a** and phase **b** along the transmission line is as shown in Fig. 2.3.3.

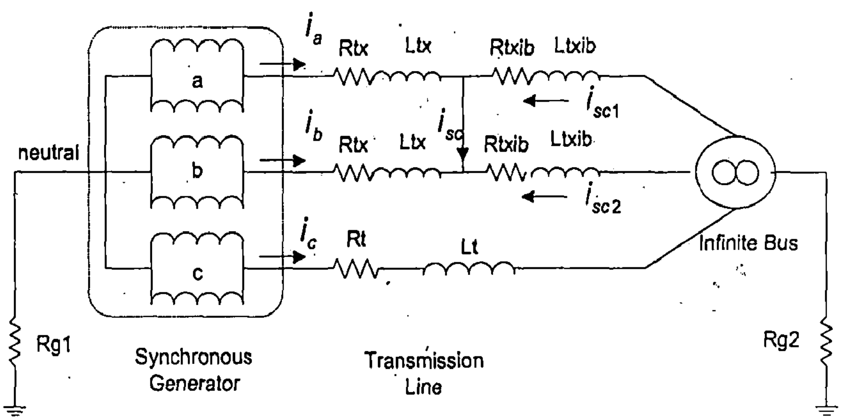


Fig. 2.3.3 System Representation during External LL Fault

During an external phase to phase fault along the transmission line voltage and flux linkage relationship of synchronous machine will remain same as given in section 2.3.1.

Only terminal voltage equations will change. These equations can be written from Fig. 2.3.3.

$$e_a = R_{tx}(i_a) + L_{tx}\left(\frac{di_a}{dt}\right) + R_{g1}(i_a + i_b + i_c)$$

$$e_b = R_{tx}(i_b) + L_{tx}\left(\frac{di_b}{dt}\right) + R_{g1}(i_a + i_b + i_c) \qquad (2.3.7)$$

$$e_c = E_{bus}\sin\left(wt + \frac{2\pi}{3}\right) + R_t(i_c) + L_t\left(\frac{di_c}{dt}\right) + R_{g1}(i_a + i_b + i_c) + R_{g2}(i_c)$$

$$i_a = -i_b$$

$$i_{sc1} = -i_{sc2} \qquad (2.3.8)$$

The voltage equation of the path of current i_{sc1} and i_{sc2} can be written as:

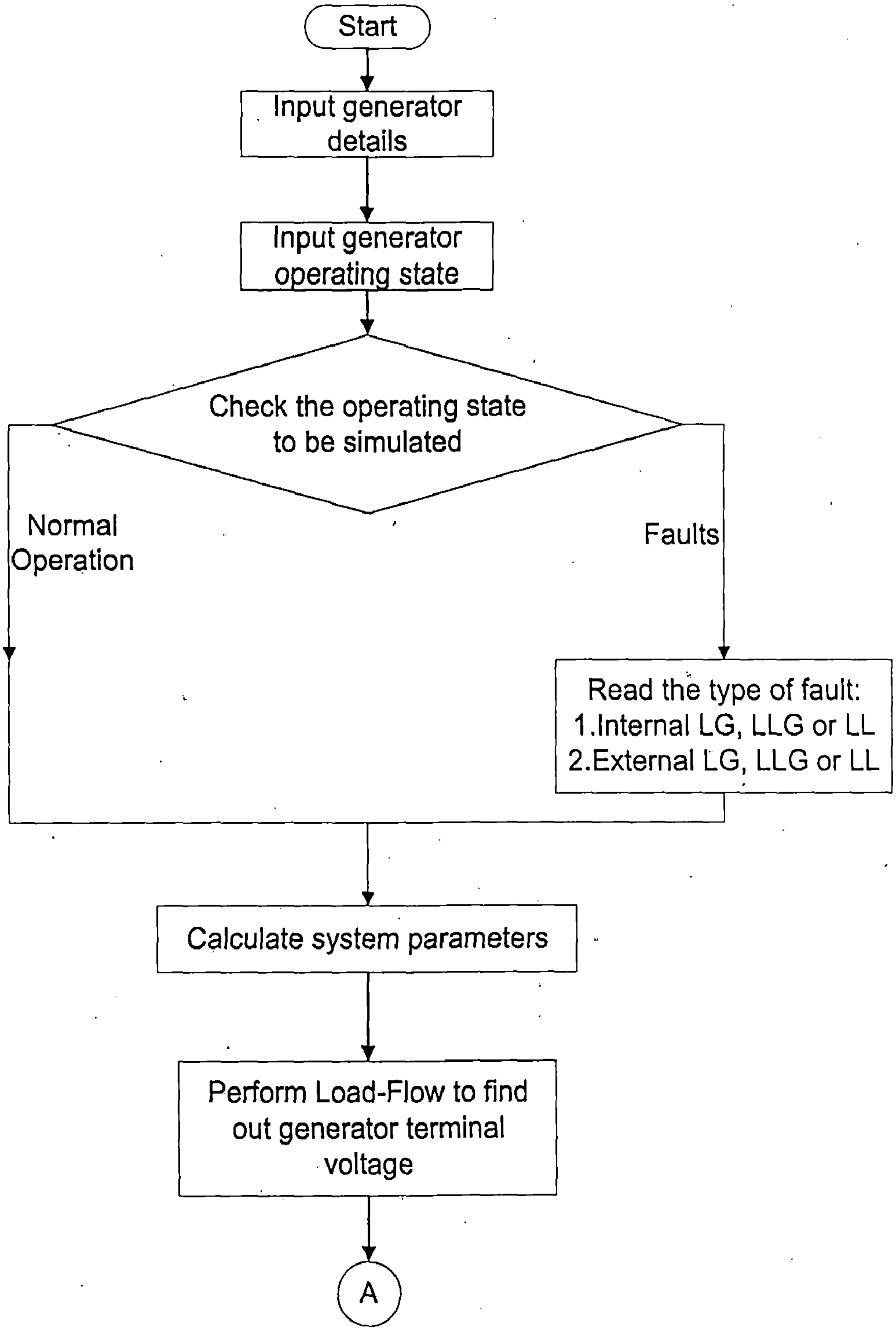
$$0 = E_{bus}\sin(wt) - R_{txib}(i_{sc1}) - L_{txib}\left(\frac{di_{sc1}}{dt}\right) - R_{g2}(i_c)$$

$$0 = E_{bus}\sin\left(wt - \frac{2\pi}{3}\right) - R_{txib}(i_{sc2}) - L_{txib}\left(\frac{di_{sc2}}{dt}\right) - R_{g2}(i_c) \qquad (2.3.9)$$

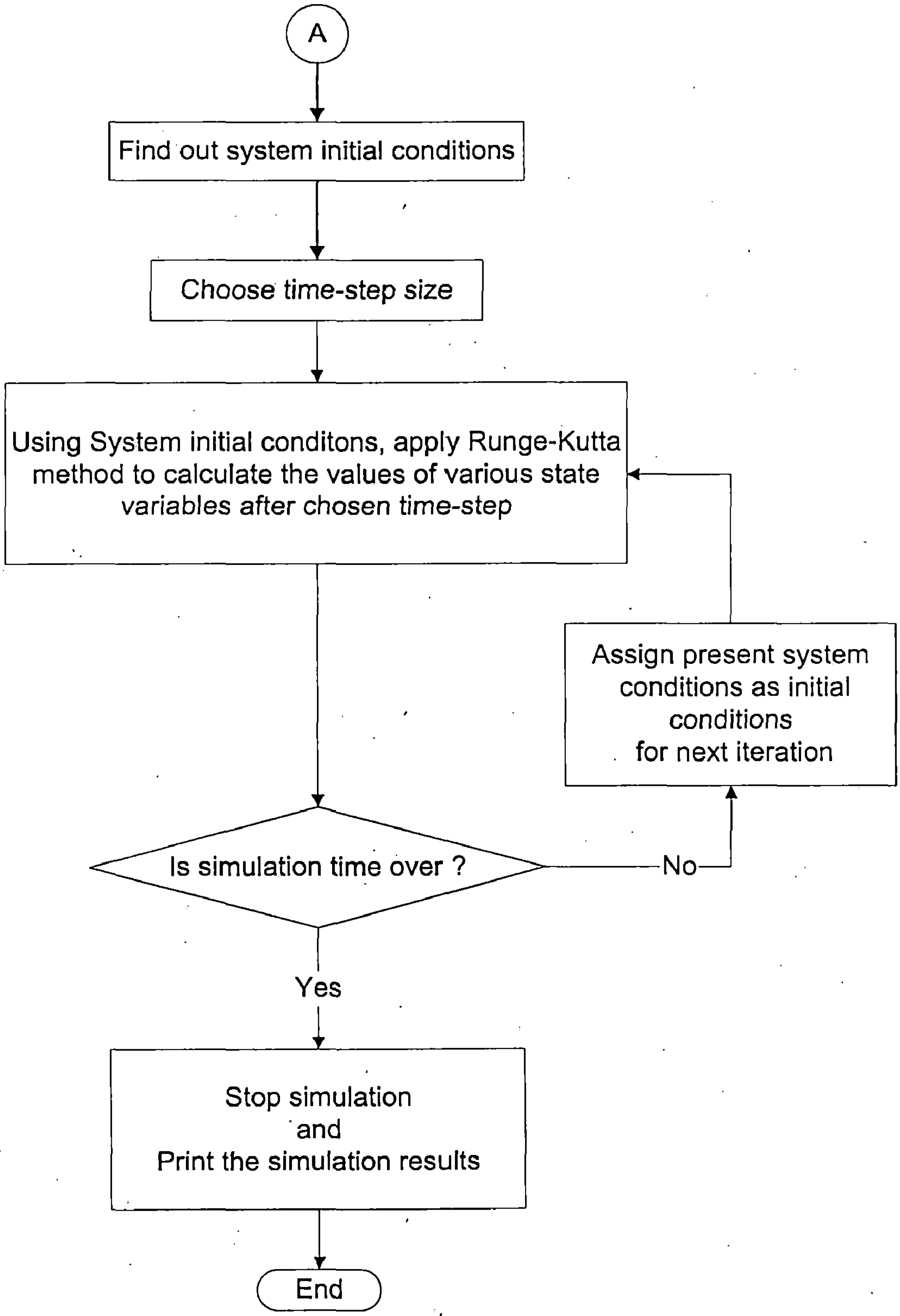
Equations (2.3.1) to (2.3.2) and equation (2.3.7) to (2.3.9) along with the rotor swing equation form the complete model of synchronous machine during an external phase to phase fault. These equations can be solved with the help of Runge-Kutta method.

2.4 SIMULATION ALGORITHM

In this part a flow chart representing algorithm for modelling synchronous generator under various operating states has been presented. For modelling any generator details of generator, for example, rating of generator, power supplying by it, voltage rating, grounding resistance, values of inductances etc (Appendix-A) are required. If fault simulation has to be done user must input the type of fault to be simulated. As generator is connected to infinite bus through a short transmission line load flow is performed to calculate generator terminal voltage and system initial conditions. Runge Kutta method has been applied to calculate values of state variables after each preset time interval. As simulation time is over results, three phase currents at the line-end and at the neutral-end and values of field winding currents are stored in a file for further use in fault detection part.



Start
Input generator details
Input generator operating state
Check the operating state to be simulated
Normal Operation
Faults
Read the type of fault:
1.Internal LG, LLG or LL
2.External LG, LLG or LL
Calculate system parameters
Perform Load-Flow to find out generator terminal voltage
A


A
Find out system initial conditions
Choose time-step size
Using System initial conditons, apply Runge-Kutta method to calculate the values of various state variables after chosen time-step
Assign present system conditions as initial conditions for next iteration
Is simulation time over ?
No
Yes
Stop simulation and Print the simulation results
End

Chapter-3

NEURO-FUZZY TECHNIQUE

In this chapter use of Artificial Neural Network and Fuzzy Logic for protection and monitoring of generator has been described. The method of protection selected for this purpose is the differential protection, which protects generator stator winding on short circuits..

3.1 NEURAL NETWORK

3.1.1 The Artificial Neural Network (ANN)

An Artificial Neural Network (ANN) is an information-processing paradigm that is inspired by the way biological nervous systems, such as the brain, process information. The key element of this paradigm is the novel structure of the information processing system. It is composed of a large number of highly interconnected processing elements (neurons) working in unison to solve specific problems. ANNs cannot be programmed to perform a specific task, they learn by example. An ANN is configured for a specific application, such as pattern recognition or data classification, through a learning process. Neural Networks, with their remarkable ability to derive meaning from complicated or imprecise data, can be used to extract patterns that are too complex to be noticed by either humans or other computer techniques. A trained neural network can be an expert in the category of information it has been given to analyze.

3.1.2 Advantages of ANN

Neural Networks have self-adapting and super-fast computing features that have made them well suited for handling nonlinearities, uncertainties and parameter variations. Some of the advantages of ANN include:

1. Adaptive learning: An ability to learn how to do tasks based on the data given for training or initial experience.

2. Self-Organization: An ANN can create its own organization or representation of the information it receives during learning time.

3. Real Time Operation: ANN computations may be carried out in parallel, and special hardware devices are being designed and manufactured which take advantage of this capability.

4. Fault Tolerance via Redundant Information Coding: Partial destruction of a network leads to the corresponding degradation of performance. However, some network capabilities may be retained even with major network damage.

3.1.3 ANN Topology

ANNs generally consist of a number of interconnected processing elements or neurons. The arrangements and strengths of the inter-neuron connections determine the overall behaviour of an ANN. A general neuron symbol is shown in Fig. 3.1.1. The neuron output is given by the sigmoid function [16], i.e.

$$out = f(net) = \frac{1}{1 + \exp(-\lambda \cdot net)} \tag{3.1.1}$$

This varies between 0 and 1.

In equation (3.1.1), $\lambda > 0$ controls the steepness of the rise of the function from 0 to 1, and

$$net = w \cdot \Sigma x$$

Where w is the weight vector defined as:

$$w = [w_1 \ w_2 \ \cdots \ w_n] \tag{3.1.2}$$

x is the input vector defined as:

$$x = [x_1 \ x_2 \ \cdots \ x_n] \tag{3.1.3}$$

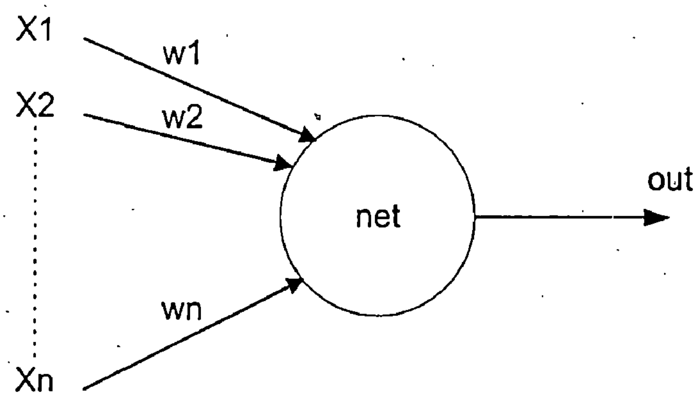


Fig. 3.1.1 General Neuron Symbol

Architecture of ANNs consists of two structures: feedforward and recurrent. Feedforward type ANN is popular network and is extensively used in pattern recognition. It has three layers, the input layer, hidden layer and the output layer. Each layer is connected by feedforward combination branches with weight, from input layer to hidden layer and hidden layer to output layer. Generally recurrent type ANN also has three layers and feedforward connections. In addition to these connections, recurrent ANN has feedback connection from hidden layer to input layer, output layer to input layer and so on. Feedback networks are dynamic; their state is changing continuously until they reach an equilibrium point.

Information is stored in the weight matrix w of a neural network. Learning is the determination of the weights. In adaptive networks, the ANN is trained by changing the weights w. Adaptive networks have two learning methods: supervised learning and unsupervised learning. Supervised learning incorporates an external media, so that each output unit is told what its desired response to input signals ought to be. Unsupervised learning uses no external media and is based upon local information only. Paradigms of supervised learning include error-correction learning, reinforcement learning and stochastic learning. Important issue concerning supervised learning is the problem of error convergence, i.e., the minimizations of error between the desired and computed unit values. The aim is to determine a set of weights that minimises the error. One well-known method, which is common to many learning paradigms, is the least mean square (LMS) convergence. Therefore supervised learning method is commonly used where we have to minimize the error between desired output and actual output.

Training of ANN is most important part of ANN control. The most commonly used supervised learning algorithm is back propagation algorithm for training ANN.

3.1.4 Back Propagation Algorithm

In order to train a neural network to perform some task, we must adjust the weights of each unit in such a way that the error between the desired output and the actual output is reduced. This process requires that the neural network compute the error derivative of the weights. In other words, it must calculate how the error changes as each weight is increased or decreased slightly. The back propagation algorithm is the most widely used method for determining the error derivative of the weights.

When input vector x is submitted, an output vector *out* is calculated. The error vector is then determined as the difference between the desired output vector and the computed output vector. The so-called weight matrix adjustment is then found by back propagating the error vector through the current weight matrices. New weight matrices are found by adding the weight matrix adjustment to the current weight matrices. After a weight matrix adjustment, another input vector is submitted, and another weight adjustment is obtained. This recursive learning procedure stops when the final error value, determined using the LMS function, is less than an arbitrarily chosen bound.

3.2 STRUCTURE OF ANN FOR FAULT DETECTION

Structure of ANN used for fault detection is as shown in Fig. 3.2.1. Its function is to differentiate between three generator states, namely the normal operating state, internal fault state, and external fault state.

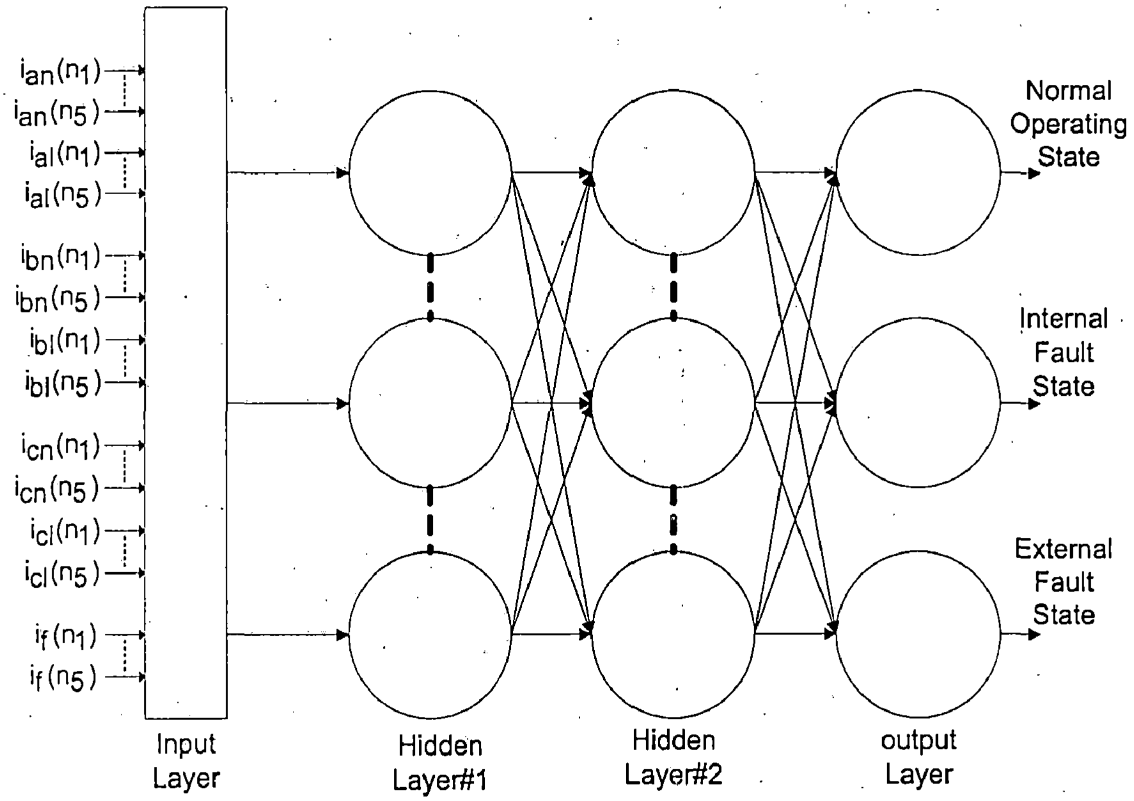


Fig. 3.2.1 Structure of ANN for Fault Detection

One of the characteristic features of ANNs is the ability to learn by training any required input/output mapping, and subsequently respond to new input in the most appropriate manner. The model of ANN is determined according to network architecture, transfer function and learning rule. One layer FNNs are used for simple cases of pattern classification, two layer FNNs can be used to classify inside, convex and open or closed fields, but three layer FNNs can generate arbitrary complex decision regions.

In this work three layer FNN has been used. The structure of this is FNN as shown in Fig. 3.2.1. The inputs to the FNN are 7 currents, each current is being represented by five consecutive samples, 3 phase currents from the line side, 3 from the neutral end of generator, and one is the field winding current. Thus there are total 35 (7*5) inputs. The index n in Fig. 3.2.1 is used to indicate the most recent sample of each current. The FNN has three layers, with 18 tan-sigmoid neurons in first hidden layer, 10 tan-sigmoid neurons in second hidden layer and 3 log-sigmoid neurons in the output layer. Each neuron in output layer is responsible for one operating state of generator. Therefore, depending on the state of the generator being simulated one output is mapped to a value greater than 0.8 while the others are less than 0.2 [4].

The training algorithm used is the back propagation algorithm with momentum and adaptive learning rate. Training set consists of patterns representing different cases of the three generator states. Normal operation state is represented by three phase balanced operation of generator at different loads and power factors. The internal faults training data consists of various types of faults, namely LG, LLG, and LL at different percentages of stator winding. Patterns from different types of external faults (LL, LLG, and LL) at various locations along the transmission line are also used for training purpose. Procedure for simulating various operating conditions of generator to produce different data set has been described in previous chapter. Training is stopped after the normalized average squared error drops to 0.019 so that the ANN is able to adequately generalize. This training algorithm has been described in detail with the help of a flow chart in the following chapter.

3.3 TRIP LOGIC

The trip logic is designed to make decisions regarding the operation of relay to issue a trip signal only when it confirms that internal fault in generator stator winding has occurred.

Artificial neural networks are difficult to account for and explain their results. If the outputs of ANN, as described in preceding section, are in narrow range it is difficult to make confident decision regarding any particular generator operation. To overcome this difficulty and to prevent maloperation of relay, in case of normal operating condition and in case of occurrence of external faults, Fuzzy Logic has been used in addition to ANN technique.

3.3.1 Fuzzy Variables

For developing trip logic outputs of ANN have been used as criteria signals. Thus there are three criteria signals, (as there are three output nodes in ANN structure) each representing one operating state of generator, are available. In order to use these criteria for fault detection, three outputs of ANN are converted into fuzzy variables with the help of method described in Appendix-B. Five consecutive samples of each output neuron are considered for designing corresponding fuzzy membership functions.

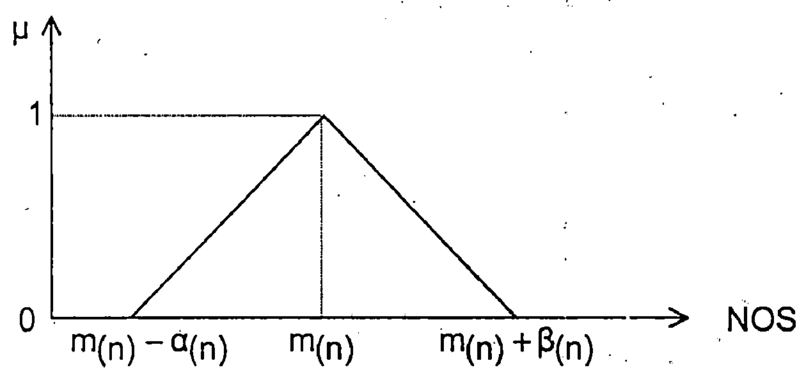


Fig. 3.3.1 Fuzzy Membership function for NOS

In Fig. 3.3.1 fuzzy membership function for normal operating state (NOS) output has been shown. Similarly fuzzy membership functions for other two outputs internal fault state (IFS) and external fault state (EFS) can be designed.

3.3.2 Fault Detection Criteria

The protective relay may make decisions: 'to trip' or 'to block' and this is to based on some fault detecting criteria. A protection criterion may be considered as a pair of signal settings [8]. In present case fault detection criteria or fuzzy setting can be designed as follows:

Based on the observations of values of output nodes of ANN during its training for different operating states it can be said that any particular operation of generator can be assured if value of output node corresponding to that output is greater than 0.7 and at the same time other two outputs are less than 0.4 [4]. Thus, for three different operations fuzzy settings are

(1) Generator would be working under normal operating condition **if** value of membership function for NOS is **greater than** 0.7 **and** values of membership functions of IFS and EFS are **less than** 0.4.

(2) Generator would be subjected to internal faults **if** value of membership function for IFS is **greater than 0.7 and** values of membership functions of NOS and EFS are **less than** 0.4.

(3) Generator would be subjected to external faults **if** value of membership function for EFS is **greater than** 0.7 **and** values of membership functions of NOS and IFS are **less than** 0.4.

3.3.3 Decision Making

For making decision regarding operating state of generator fuzzy variables (relay signals) are compared with their fuzzy settings (relay settings). An appropriate comparison algorithm is necessary when fuzzy relaying signals and settings are used. The level of presumption that a fuzzy signal reaches its fuzzy setting is represented by the shaded area (F') in Fig. 3.3.2 and may be defined as the ratio of shaded area to total area under the membership function of the fuzzy relaying signal [8].

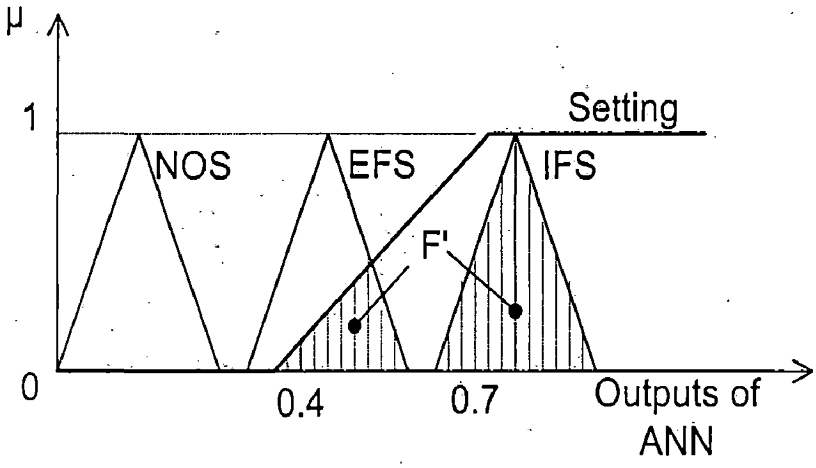


Fig. 3.3.2 Decision Making With Fuzzy Logic

$$v = \frac{F'}{F} \qquad (3.3.1)$$

Where F is the total area under the membership function of the fuzzy relaying signal and F' is the area of shaded part in Fig. 3.3.2.

$v = 0$ when output of ANN is less than 0.4,

$v = 1$ when output of ANN is greater than 0.7.

Thus, if output for any state is larger than 0.7 then that particular state of generator operation can be considered with large confidence.

And if output for any state is smaller than 0.4 then it is certain that generator is not operating under that particular state.

If output is between 0.4 and 0.7, it is a doubtful case: it may be a fault case. In this case value of v determines the level of certainty for a given output.

Chapter-4

FAULT DETECTION ALGORITHM

In this chapter the algorithm developed for fault detection has been described. Flow charts describing back propagation algorithm for training of artificial neural network and fuzzy logic based decision making algorithm for issuing trip signal in case of internal faults have been presented.

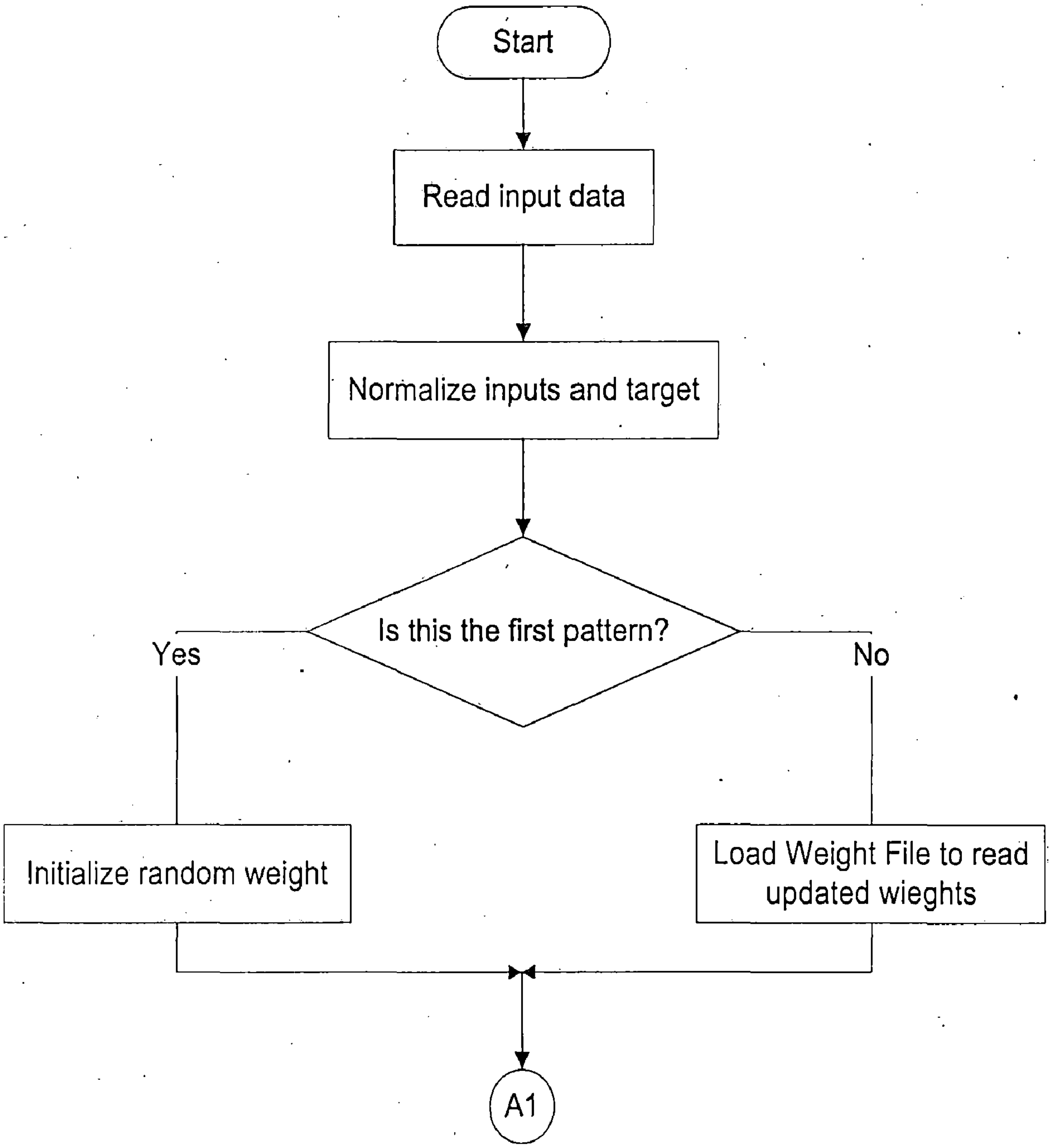
4.1 DESIGN AND IMPLEMENTATION

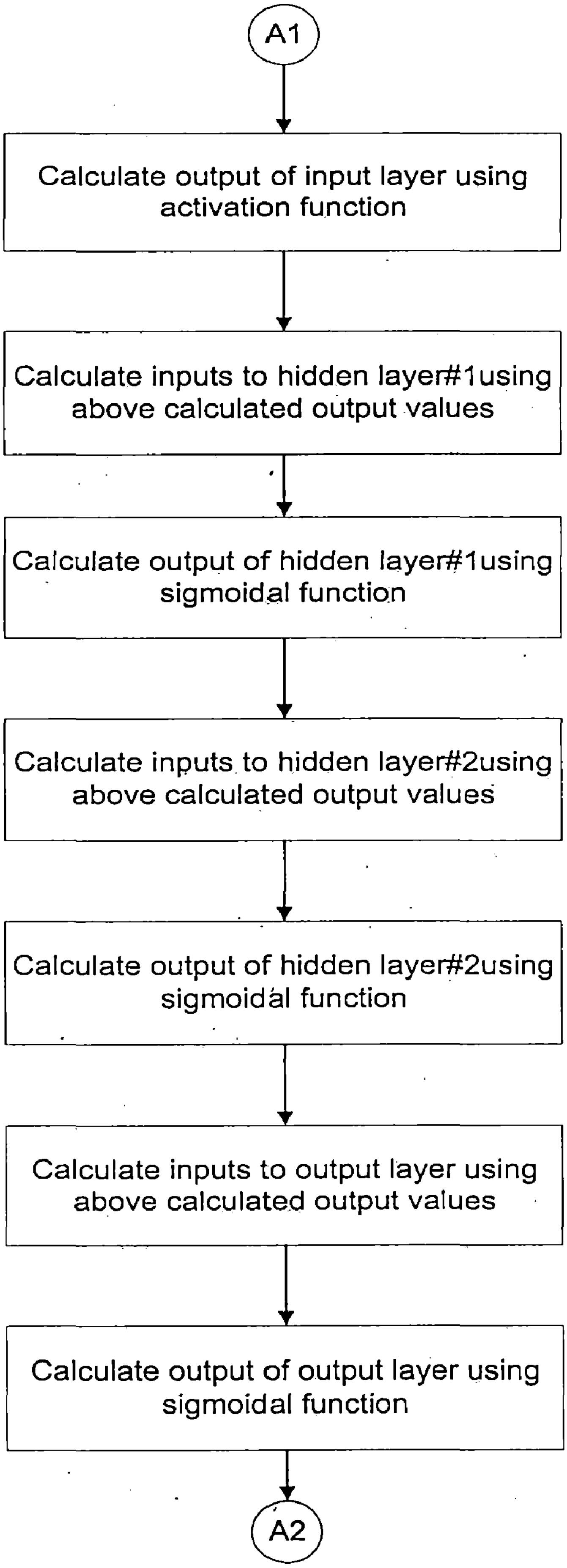
Design of algorithm consists of two parts; first is training of ANN with the given patterns and the other is fault detection part in which fuzzy logic has been used to make decision about issuing the trip signal in case of stator winding short circuits.

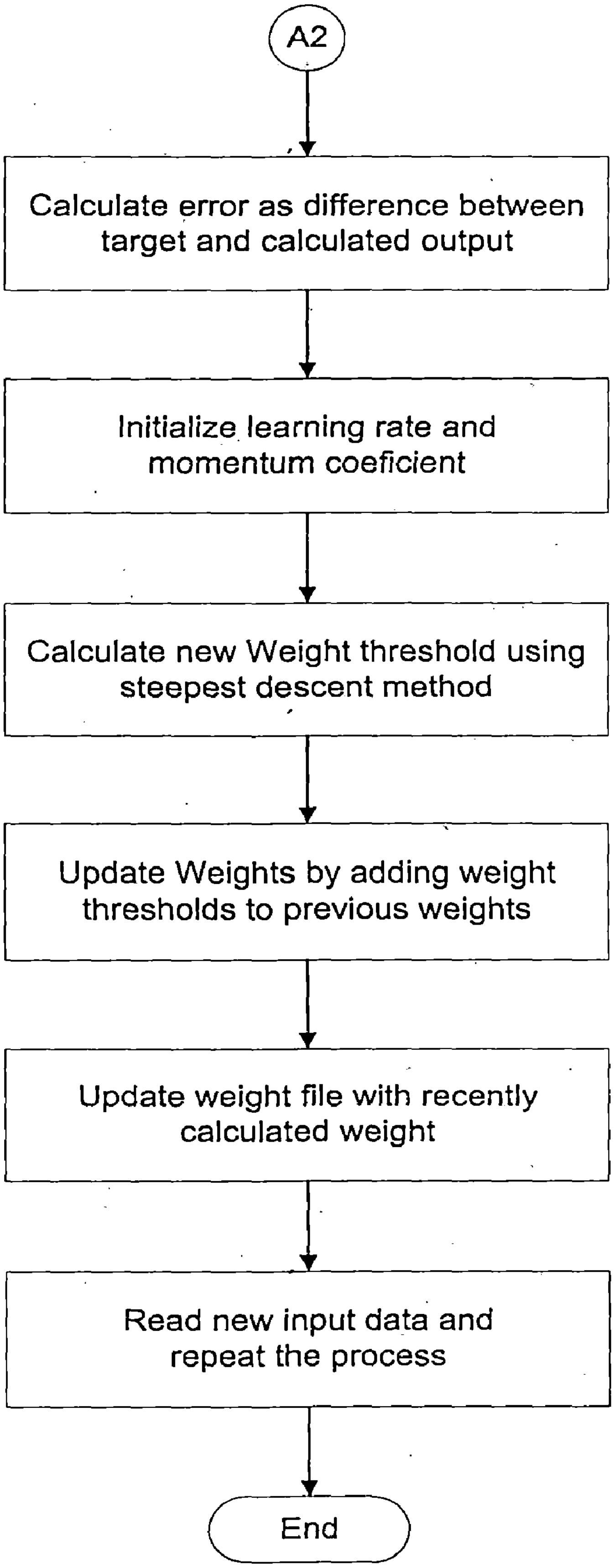
Data required to train the ANN have been generated through simulation process. ANN has been trained for generator working under normal operating condition at different loads and at different power factors, for internal short circuits in generator stator winding and external faults at various locations along transmission line. Internal fault training data consist of faults at different percentages of synchronous generator stator winding. Three different machine parameters have been used to generate the training set to ensure that FNN is able to identify the three states for any generator. These three machines are 500KVA, 30MVA and 500MVA salient pole generators. Data corresponding to these generators are given in Appendix-A.

To test the fault detection algorithm an independent test pattern is given to ANN. The outputs obtained from the outputs node of ANN contain some information regarding the generator operating state, still some uncertainties are there. To be certain about the internal fault in order to operate relay, fuzzy logic has been used. For this purpose ANN outputs are converted in fuzzy numbers by designing fuzzy membership functions (Appendix B). These fuzzy variables are then compared with the corresponding fuzzy settings using the method described in section 3.3. Based on this method a decision can be made regarding operating state of generator and relay can be operated in case of internal fault.

A flow chart representing Back Propagation algorithm for training of ANN has been presented. Input data required for this purpose are the samples of phase currents from line side and neutral end. In addition to this samples of field current are also used as input. Weights are updated depending upon the difference of calculated output and target values.

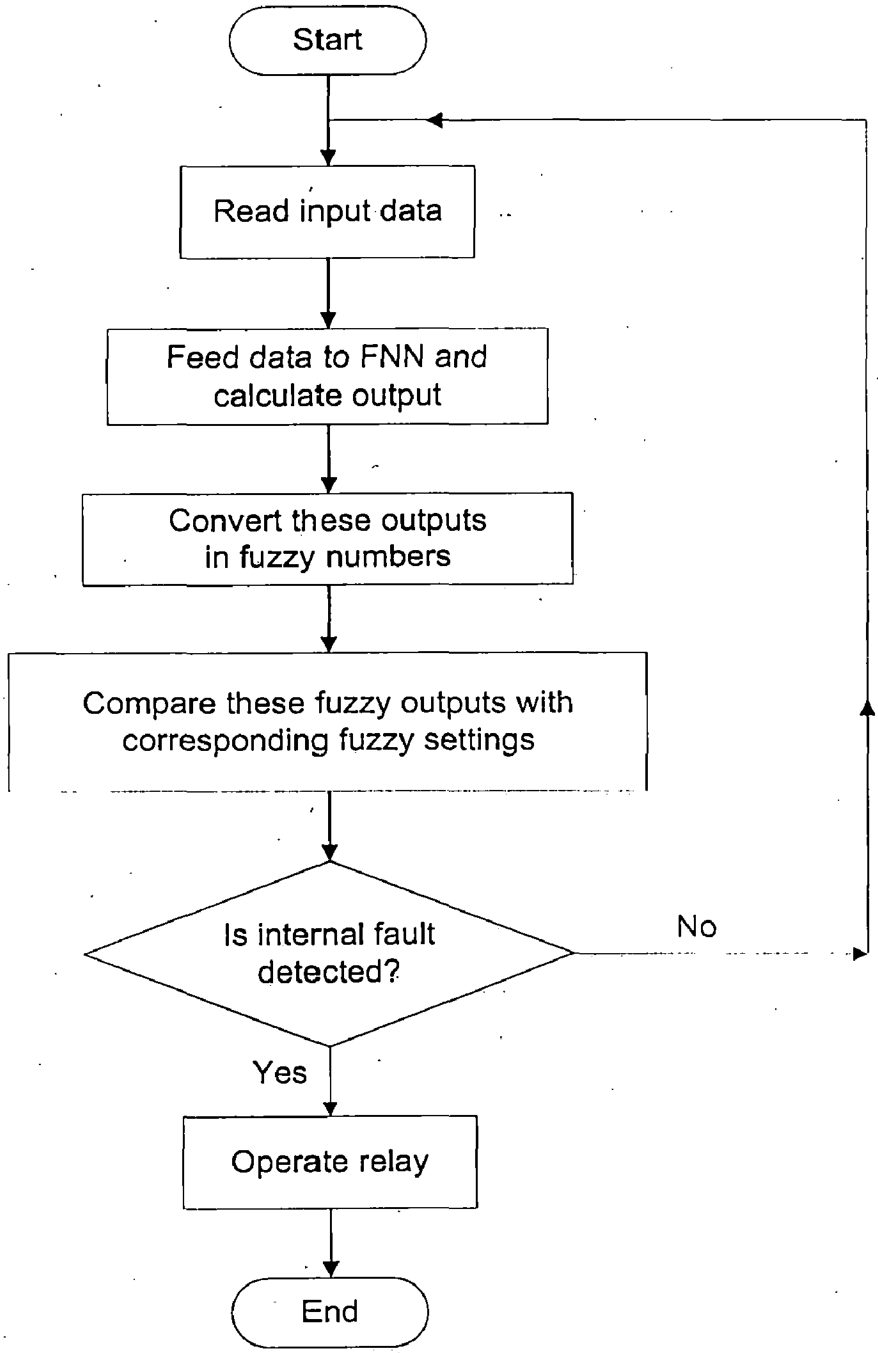



A1
Calculate output of input layer using activation function
Calculate inputs to hidden layer#1using above calculated output values
Calculate output of hidden layer#1using sigmoidal function
Calculate inputs to hidden layer#2using above calculated output values
Calculate output of hidden layer#2using sigmoidal function
Calculate inputs to output layer using above calculated output values
Calculate output of output layer using sigmoidal function
A2


A2
Calculate error as difference between target and calculated output
Initialize learning rate and momentum coeficient
Calculate new Weight threshold using steepest descent method
Update Weights by adding weight thresholds to previous weights
Update weight file with recently calculated weight
Read new input data and repeat the process
End

4.2 TESTING

A flow chart describing the testing algorithm for protection and monitoring of generator has been presented here.



Chapter-5

RESULTS AND DISCUSSION

In this chapter results obtained from developed algorithm for various operating conditions of generator have been discussed.

5.1 NORMAL OPERATION OF GENERATOR

In this case results are shown when generator of rating 160 MVA, 15KV, is working under normal operating condition. Generator supplying active power P=0.8 pu to load at 0.8 power factor lagging.

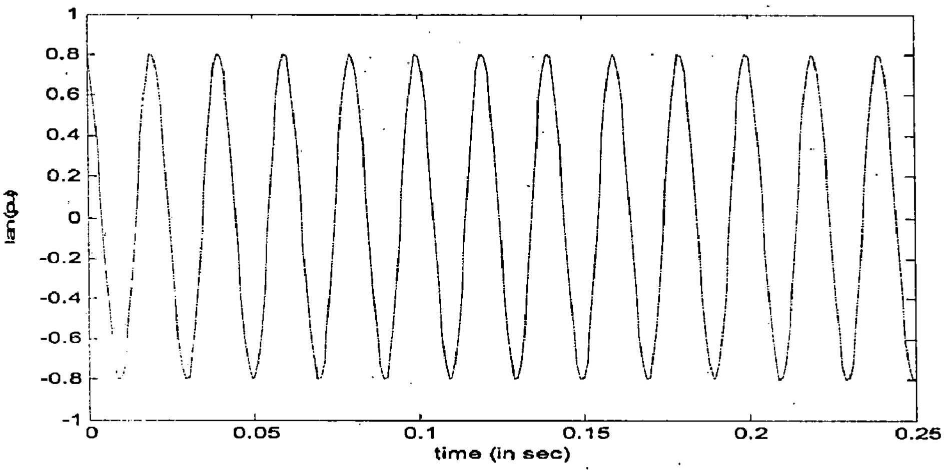


Fig. 5.1.1 Phase a current (pu) at neutral end vs. time (sec)

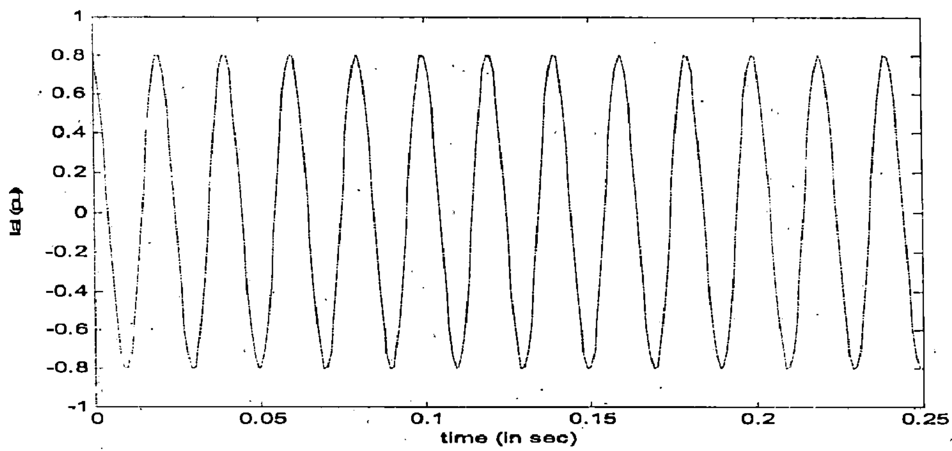


Fig. 5.1.2 Phase a current (pu) at line side vs. time (sec)

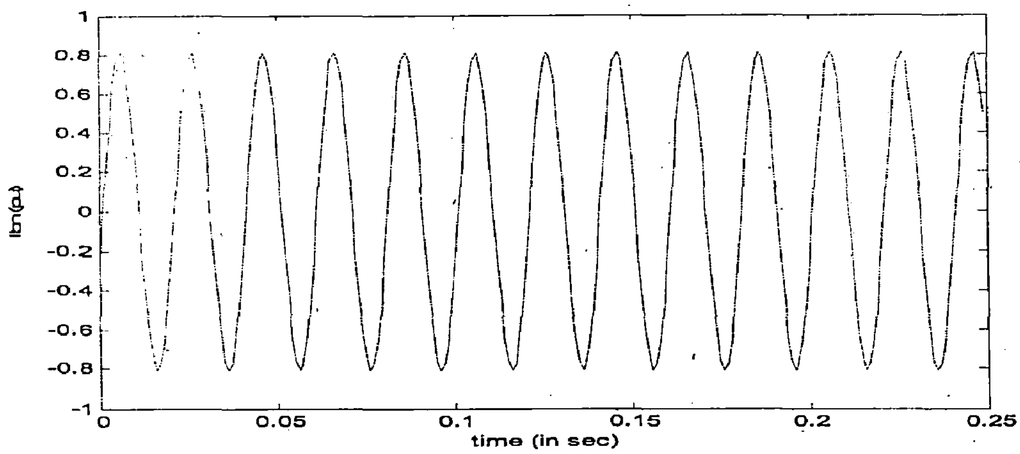


Fig. 5.1.3 Phase b current (pu) at neutral end vs. time (sec)

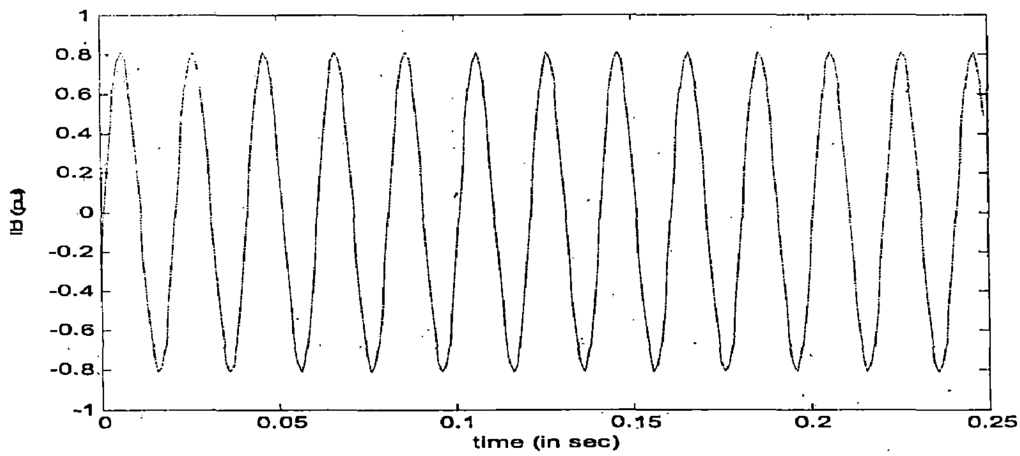


Fig. 5.1.4 Phase b current (pu) at line side vs. time (sec)

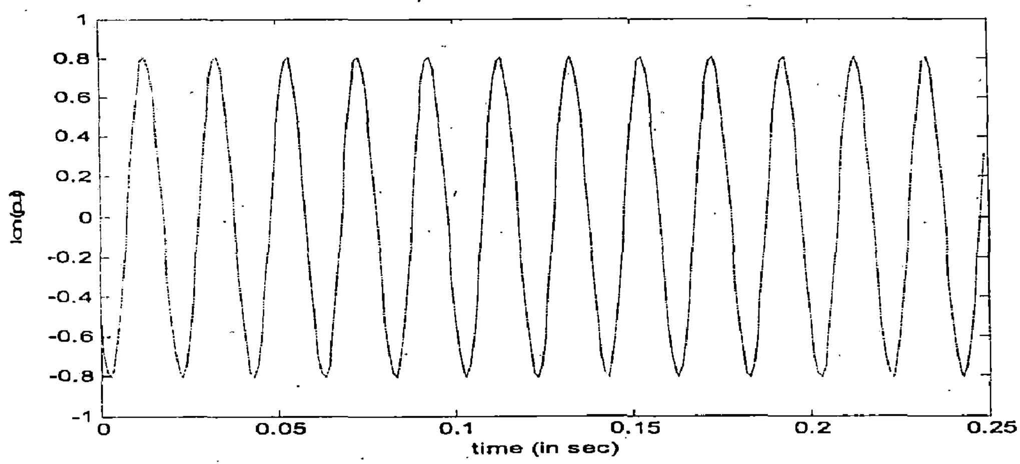


Fig. 5.1.5 Phase c current (pu) at neutral end vs. time (sec)

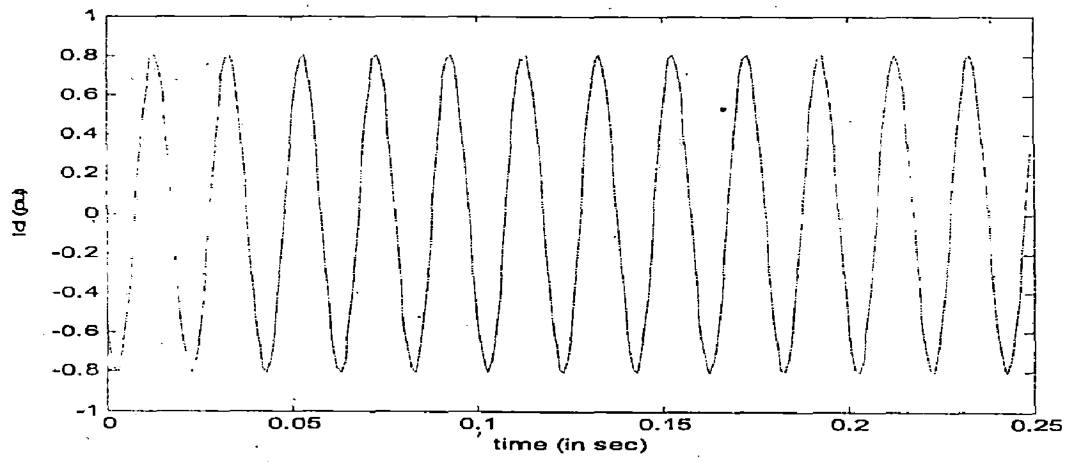


Fig. 5.1.6 Phase c current (pu) at line side vs. time (sec)

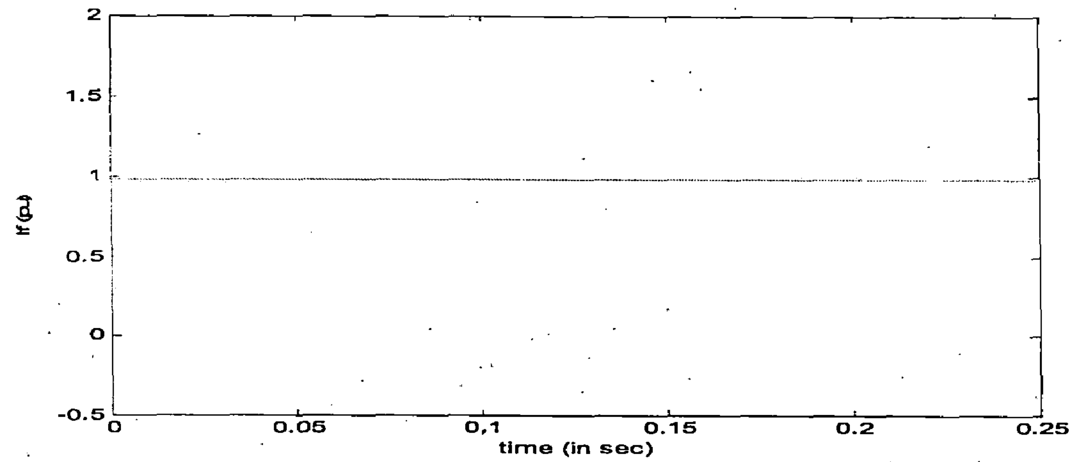


Fig. 5.1.7 Field winding current (pu) vs. time (sec)

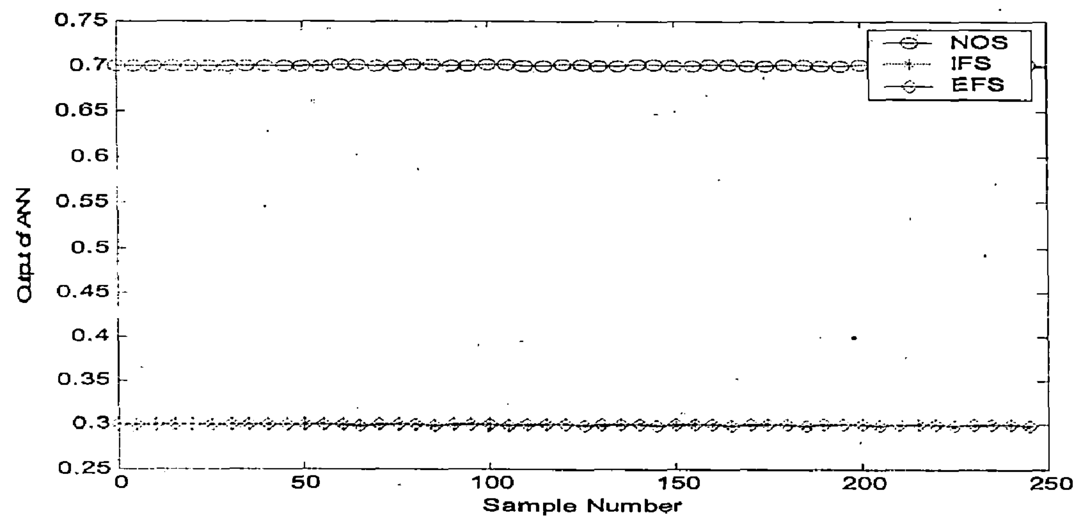


Fig. 5.1.8 Outputs of ANN vs. number of samples

In Fig. 5.1.8, NOS, IFS, and EFS are the three outputs of the ANN. NOS is responsible for normal operating condition, IFS is for internal faults, and EFS for external faults. From this Fig. it can be seen that for generator working under normal operating conditions, the relay remains stable.

5.2 INTERNAL FAULT STATE

In this case results are shown when 160 MVA, 15KV, generator is subjected to internal line to ground fault. Generator was supplying active power P=0.8 pu at 0.8 power factor lagging before occurrence of fault. LG fault at 50% of phase a winding has been simulated in this case. Simulation results are shown in Fig. 5.2.1 to Fig. 5.2.7.

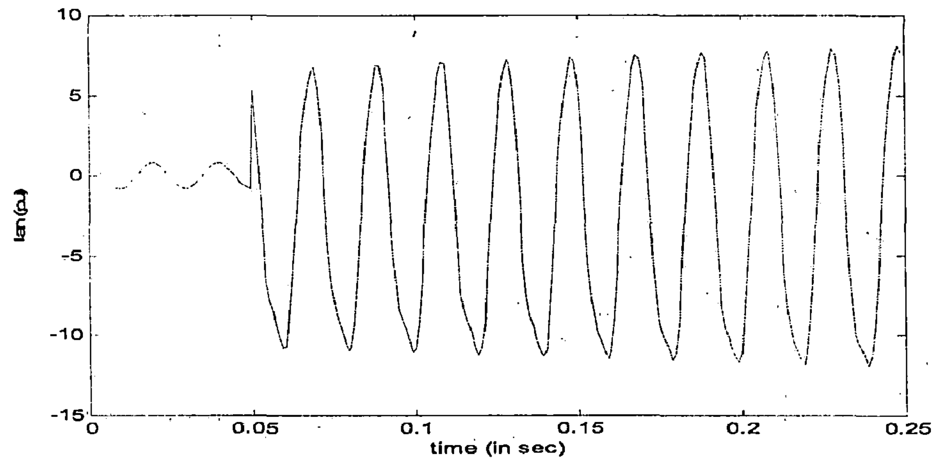


Fig. 5.2.1 Phase a current (pu) at neutral end vs. time (sec)

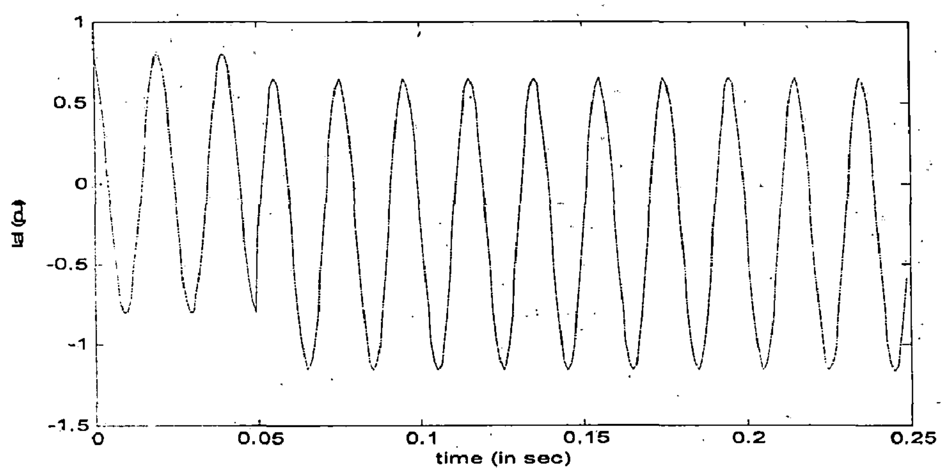


Fig. 5.2.2 Phase a current (pu) at line side vs. time (sec)

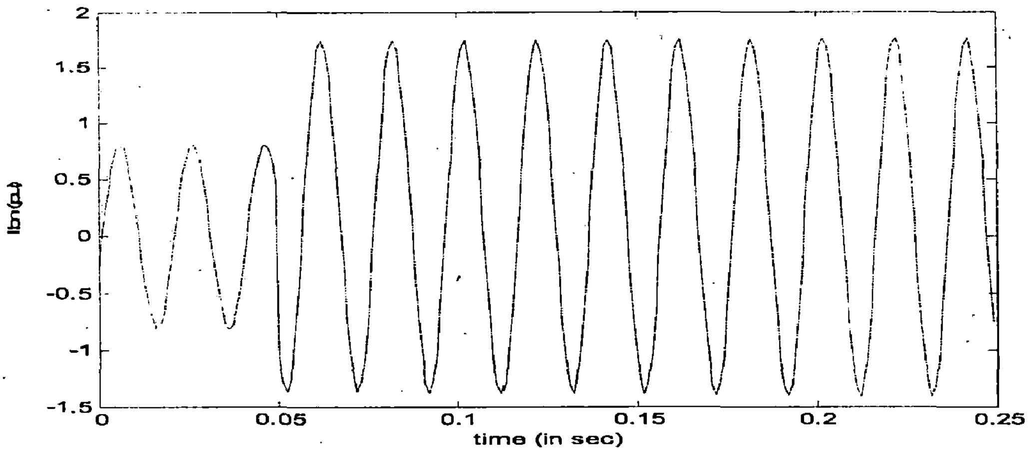


Fig. 5.2.3 Phase b current (pu) at neutral end vs. time (sec)

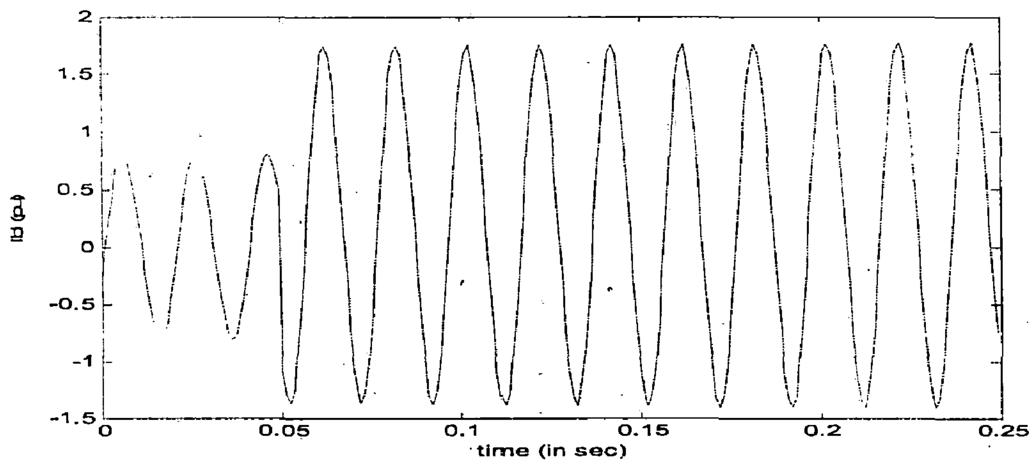


Fig. 5.2.4 Phase b current (pu) at line side vs. time (sec)

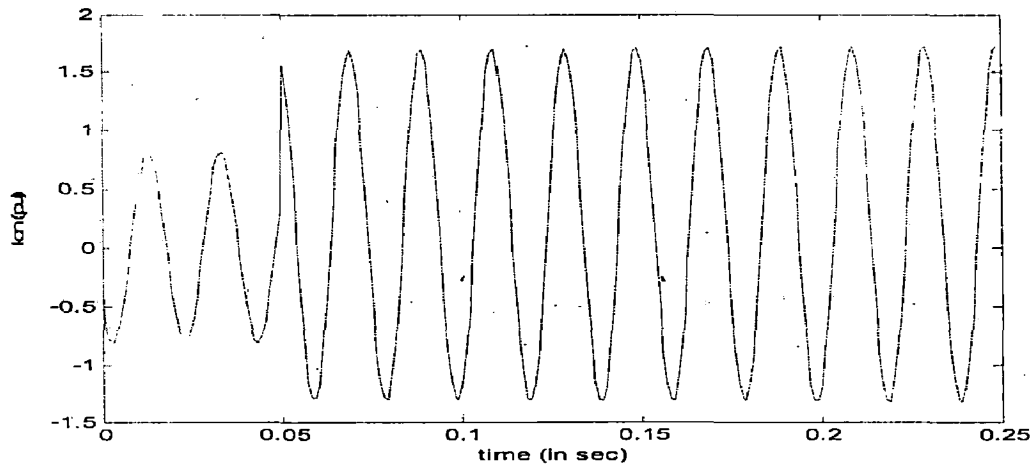


Fig. 5.2.5 Phase c current (pu) at neutral end vs. time (sec)

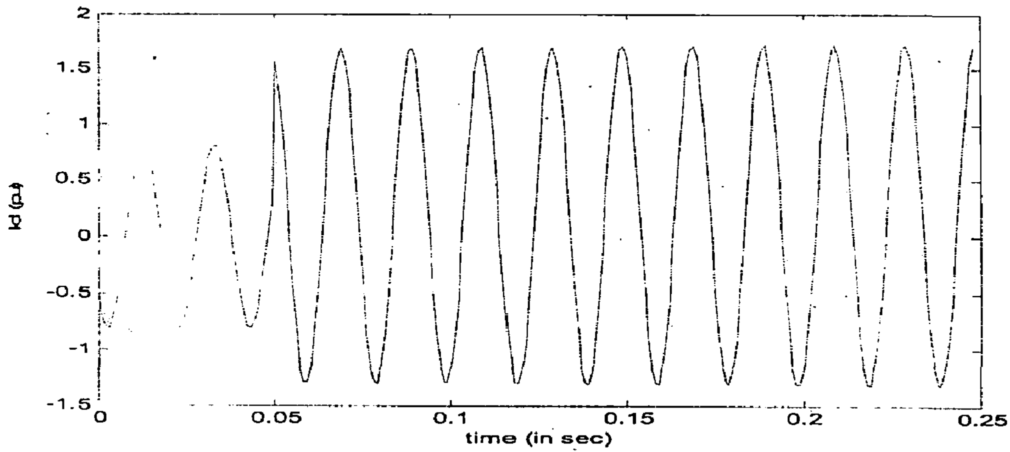


Fig. 5.2.6 Phase c current (pu) at line side vs. time (sec)

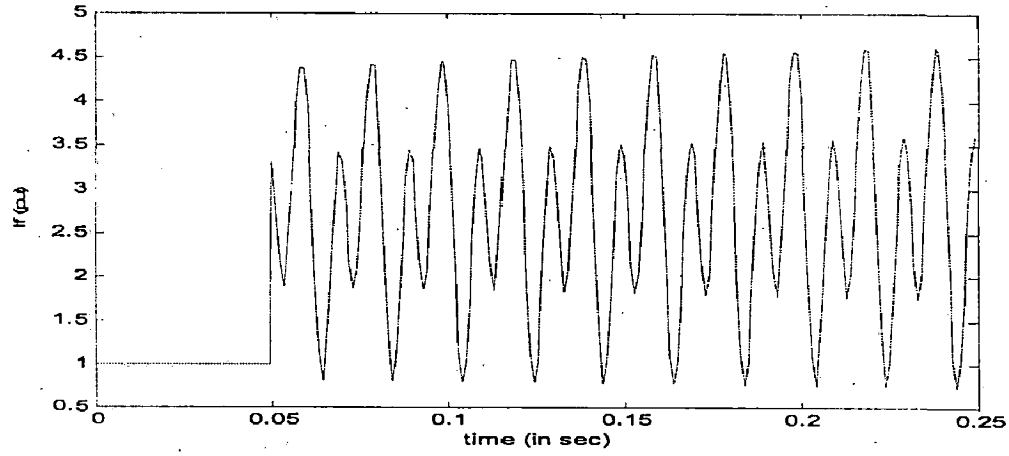


Fig. 5.2.7 Field winding current (pu) vs. time (sec)

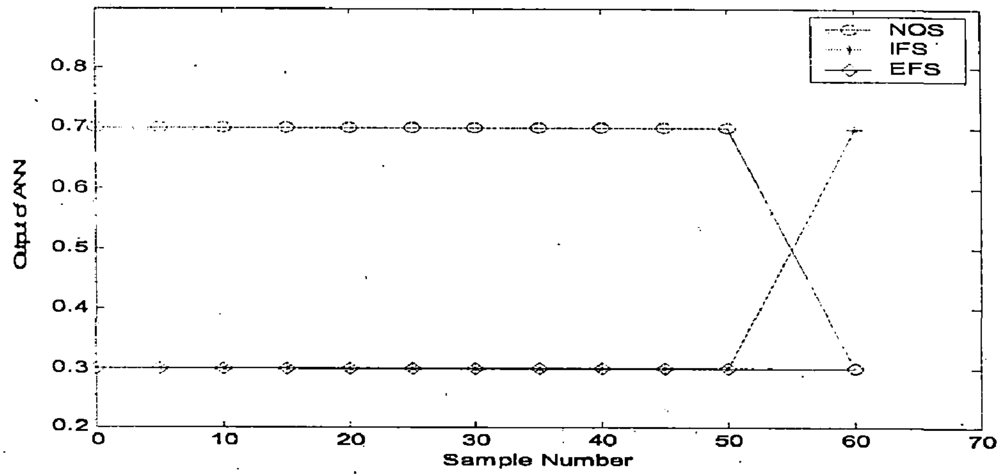


Fig. 5.2.8 Outputs of ANN vs. number of samples

Fig. 5.2.8 shows the output of fault detection algorithm. It can be observed that internal fault has been detected. Fault has been created after 5oth sample and algorithm can issue a trip signal after 5-10 samples of fault occurrence. Thus a very fast (5 to 10 ms) and reliable protection of generator can be ensured.

5.3 EXTERNAL FAULT STATE

In this case results are shown when generator (160 MVA, 15KV) is subjected to single phase to ground fault at 50% of phase a along the transmission line. Generator supplying active power P=0.8 pu at 0.8 power factor lagging. Simulation results are shown in Fig. 5.3.1 to Fig. 5.3.7.

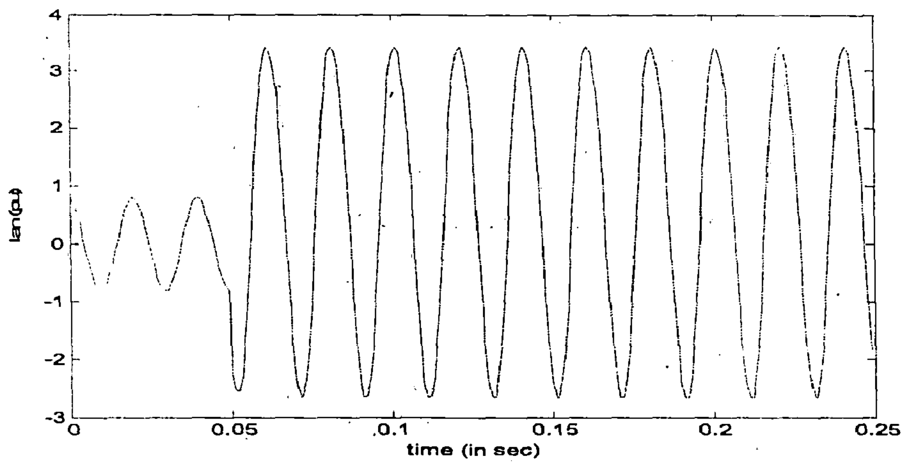


Fig. 5.3.1 Phase a current (pu) at neutral end vs. time (sec)

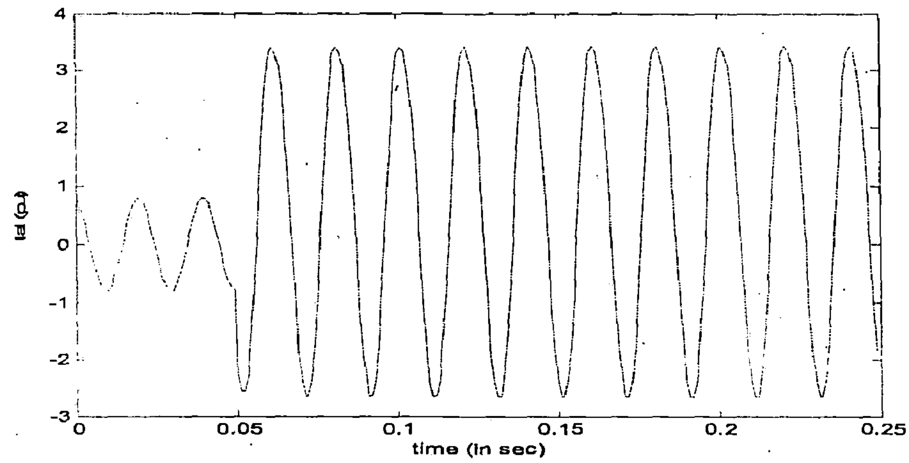


Fig. 5.3.2 Phase a current (pu) at line side vs. time (sec)

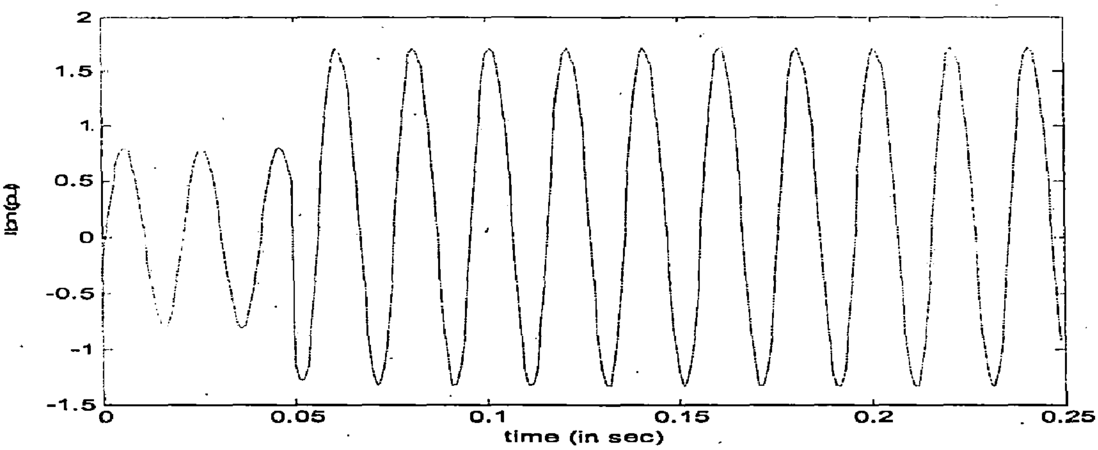


Fig. 5.3.3 Phase b current (pu) at neutral end vs. time (sec)

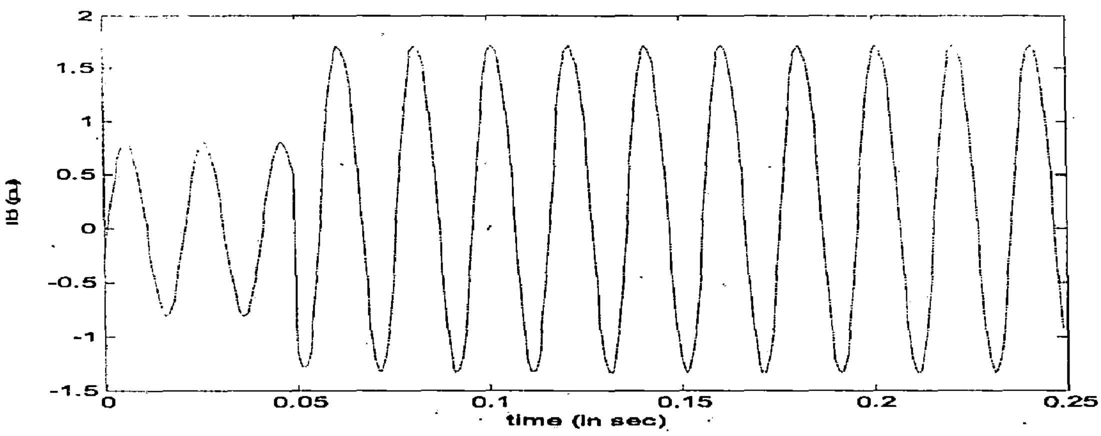


Fig. 5.3.4 Phase b current (pu) at line side vs. time (sec)

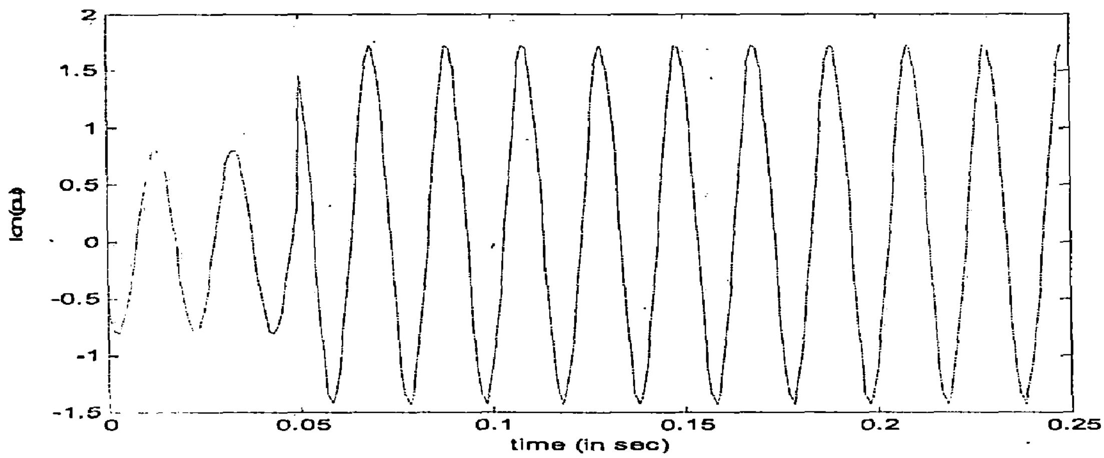


Fig. 5.3.5 Phase c current (pu) at neutral end vs. time (sec)

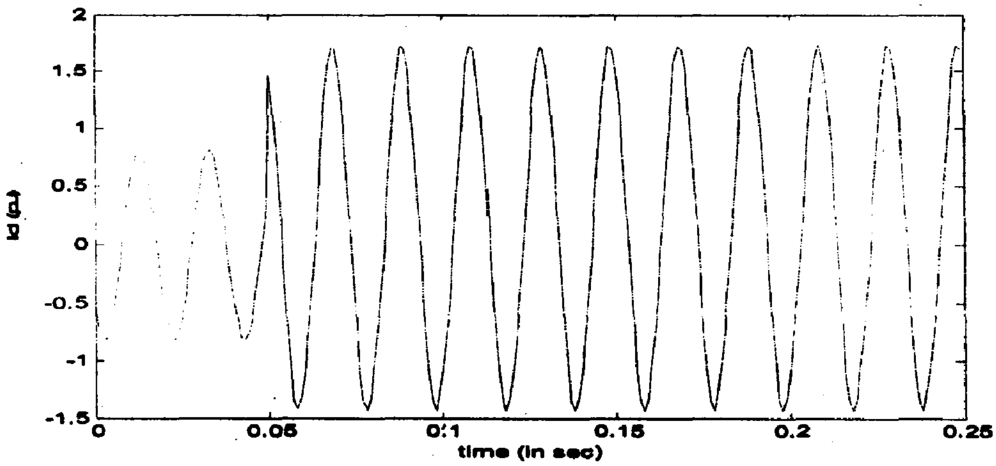


Fig. 5.3.6 Phase c current (pu) at line side vs. time (sec)

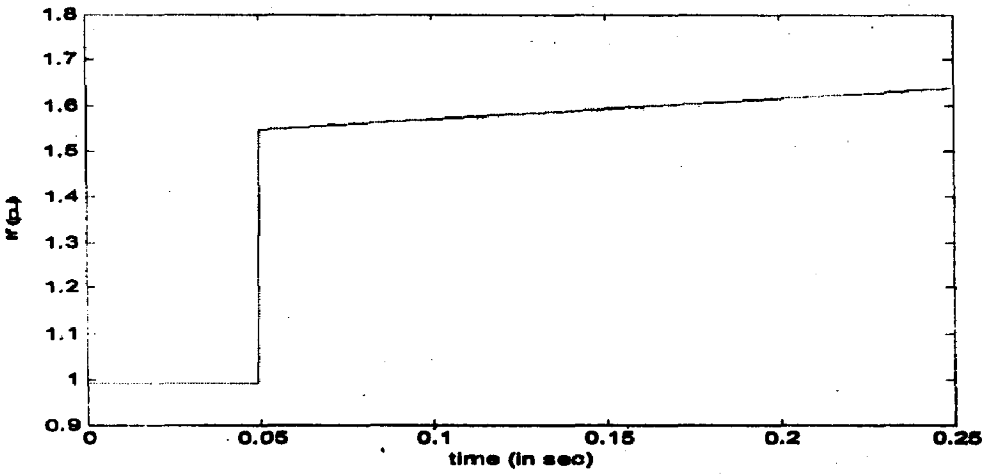


Fig. 5.3.7 Field winding current (pu) vs. time (sec)

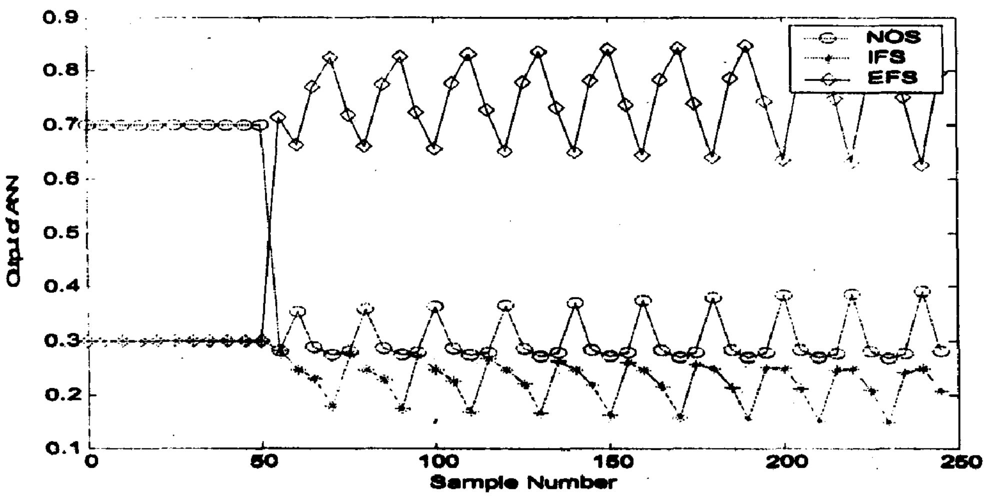


Fig. 5.3.8 Outputs of ANN vs. number of samples

Fig. 5.3.8 shows the output of fault detection algorithm when generator is subjected to external line to ground fault in phase **a** of transmission line. From the Fig. it can be seen that external fault has been identified. As value of output corresponding to internal fault is well within the limit relay is stable and will not operate.

Chapter-6
CONCLUSION

The work was started with an intention to develop an algorithm, based on Neuro-Fuzzy technique, which can be used for protection and monitoring of synchronous generators connected to infinite bus. The work was planned to develop the algorithm which can discriminate between normal operating state, internal fault state and external fault state of synchronous generator and to generate a trip signal in case of short circuits in stator winding of generator.

The work done contains two parts; first one is modelling of generator when working under normal operating condition and when subjected to internal faults at different percentages of stator winding and external faults at various locations along the transmission line, while the second part include design of Neuro-Fuzzy based fault detection algorithm which could be able to differentiate between the three operating conditions and to operate the relay in case of internal short circuits in generator. Results achieved in this work include:

(1) Simulation of normal operating state, internal fault state and external fault state of generator. Simulation results are obtained for generator working at different power level and power factor. Simulation of internal LG, LLG and LL faults at different percentage of stator winding and external LG, LLG and LL faults at different locations of transmission line can be done with the developed model.

(2) The algorithm based on Neuro-Fuzzy technique which can discriminate between three operating states of synchronous generator and operate relay in case of internal faults in stator winding. Fault detection is fast and reliable and the results obtained also indicate that the algorithm can be used to support existing protection algorithms, hence increasing the reliability of the protection operations.

Suggestions for Further Work

As per expectations all results have been achieved. Anyhow some of the aspects, which could not be included in present development, can be taken up in the further work.

(1) In present work unbalanced short circuit faults in stator winding of generator and along the transmission line have been analysed. The work can be extended for three phase short circuits and for loss of excitation in synchronous machines.

(2) Yet more refinement of the presented work can be achieved by taking more options for simulation of system like turbines, governors and excitation systems.

(3) In present work algorithm has been tested for a generator connected to infinite bus through ha short transmission line. Further, work can be extended to more complicated power system network.

REFERENCES

[1] Sachdev M.S., Wind D.W., "Generator Differential Protection Using a Hybrid Computer" IEEE Trans. On PAS, Vol. 92, No. 6, November/December 1973, pp. 2063-2072.

[2] Hope G.S., Dash P.K., Malik O.P., "Digital Differential Protection of a Generating Unit: Scheme and Real-Time Test Results" IEEE Trans. On PAS, Vol. 96, No. 2, March/April 1977, pp. 502-512.

[3] Dash P.K., Malik O.P., and Hope G.S., "Fast Generator Protection against Internal Asymmetrical Faults", IEEE Trans. On PAS, Vol. 96, No. 5, September/October 1977, pp. 1498-1506.

[4] Megahed A.I., Malik O.P., "An Artificial neural Network Based Digital Differential Protection scheme for Synchronous Generator Stator Winding Protection" IEEE Trans. On Power delivery, Vol. 14, No.1, January 1999, pp. 86-93.

[5] Sharaf A.M., Lie T.T., "ANN Based Pattern Classification of Synchronous Generator Stability and Loss of Excitation" IEEE Trans. On Energy Conversion, Vol. 9, No. 4, December 1994, pp. 753-759.

[6] Sidhu T.S., Sunga B., Sachdev M.S., "A Digital Technique for Stator Winding Protection of Synchronous Generators", Electrical Power System Research, Vol. 36, No. 1, pp. 45-55, Jan 1996.

[7] Sidhu T.S, Singh H., Sachdev M.S, "Design, Implementation and Testing of An Artificial Neural Network Based Fault Direction Discriminator for Protecting Transmission Lines" IEEE Trans. On Power Delivery, Vol. 2, No. 10, April 1995, pp. 697-706.

[8] Wisznieski Andrzej and Kasztenny Bogdan, "A Multi-Criteria Differential Transformer Relay based on Fuzzy Logic" IEEE Trans. On Power Delivery, Vol. 10, No. 4, October 1995, pp. 1786-1792.

[9]Tutorial on Fuzzy Logic Applications in Power Systems, IEEE Tutorial Course, Prepared for IEEE Power Engineering Society Winter Meeting in Singapore, January 2000.

[10] Megahed A.I., Malik O.P., "Simulation of Internal Faults in Synchronous Generators" IEEE Trans. On Energy Conversion, Vol. 14, No. 4, December 1999, pp. 1306-1311.

[11] Megahed A.I., Malik O.P., "Synchronous Generator Internal Fault Computation and Experimental Verification" IEE Proceeding on Generation, Transmission, Distribution, Vol. 145, No. 5, September 1998, pp. 604-610.

[12] Kundur P., "Power System Stability and Control", book, McGraw Hill Inc., New York.

[13] Anderson P.M. and Fouad A.A., "Power System Control and Stability", book, Vol. 1, 1st edition, The Iowa state university press, Ames, Iowa, USA.

[14] Nagrath I.J., Kothari D.P., "Power System Engineering", book, Tata McGraw-Hill Publishing Company Limited, New Delhi, 2001.

[15] Krause P.C., "Analysis of Electrical Machinery", book, McGraw-Hill Book Company, 1986.

[16] Rajasekaran S., Vijayalakshmi Pai G.A., "Neural Networks, Fuzzy Logic, and Genetic Algorithms: Synthesis and Applications", book, Prentice-Hall India Private Limited, New Delhi, 2003.

[17] Chapman Stephen J., "MATLAB Programming for Engineers", book, Second Edition, 2000, THOMSONS BROOKS/COLE Publishing Company.

Simulation Data

Three different machine parameters have been used to generate the patterns for training of artificial neural network. Various parameters for modelling of generator are as follows [12], [15]:

(1) 500 MVA, 33 KV Synchronous Generator

L_f	=	1.1479	L_{kd}	=	0.0031
L_{kd}	=	0.0007	L_d	=	0.0033
L_q	=	0.0032	M_{af}	=	0.0460
M_{aq}	=	0.0012	M_{fkd}	=	0.0574
M_{ab0}	=	-0.0134	L_{la}	=	0.0345
L_{ga0}	=	0.0303	L_{ga2}	=	0.0126
R_a	=	0.0009	R_f	=	0.1836
R_{kd}	=	0.0686	R_{kq}	=	0.0686
H	=	4.0 sec	K_D	=	0.0500
R_{g1}	=	1.5000	R_{g2}	=	0.8000

(2) 30 MVA, 11 KV Synchronous Generator

L_f	=	0.6199	L_{kd}	=	0.0017
L_{kd}	=	0.0004	L_d	=	0.0018
L_q	=	0.0018	M_{af}	=	0.0248
M_{aq}	=	0.0012	M_{fkd}	=	0.0310
M_{ab0}	=	-0.0072	L_{la}	=	0.0186
L_{ga0}	=	0.0164	L_{ga2}	=	0.0068
R_a	=	0.0005	R_f	=	0.9914

R_{kd}	=	0.0371	R_{kq}	=	0.0371
H	=	4.0 sec	K_D	=	0.0270
R_{g1}	=	0.8100	R_{g2}	=	0.5000

(3) 500 KVA, 6.6 KV Synchronous Generator

L_f	=	0.0287	L_{kd}	=	0.0003
L_{kd}	=	0.0001	L_d	=	0.0003
L_q	=	0.0002	M_{af}	=	0.0060
M_{aq}	=	0.0002	M_{fkd}	=	0.0074
M_{ab0}	=	-0.0034	L_{la}	=	0.0034
L_{ga0}	=	0.0041	L_{ga2}	=	0.0016
R_a	=	0.0009	R_f	=	0.0736
R_{kd}	=	0.0086	R_{kq}	=	0.0086
H	=	4.0 sec	K_D	=	0.0200
R_{g1}	=	0.8000	R_{g2}	=	0.5000

(4) Transmission Line

R_t	=	0.0091	L_t	=	0.5000

Design of Fuzzy Membership Function

In digital protection schemes, relaying signals are sampled at regular intervals, digitized and processed within a predefined window. With reference to Fig. A.1, the value, $x_{(n)}$, of the nth sample of a signal, $x_{(t)}$, can be considered as a fuzzy number, $X_{(n)}$, having a membership function, $\mu\left(X_{(n)}\right)$, defined by the following parameters [8], [9]:

$$m_{(n)} = \frac{1}{k}\left(x_{(n)} + x_{(n-1)} + \ldots.. + x_{(n-k+1)}\right) \quad \text{(A.1)}$$

$$\alpha_{(n)} = \left(m_{(n)} - \min\left(x_{(n-p)}\right)\right) \quad \text{(A.2)}$$

$$\beta_{(n)} = \left(\max\left(x_{(n-p)}\right) - m_{(n)}\right) \quad \text{(A.3)}$$

Where

p = (n-k+1) to (n)

And

K – the number of samples in a fuzzification window,

$\alpha_{(n)}$ - minimum value of samples,

$\beta_{(n)}$ - maximum value of samples in the window.

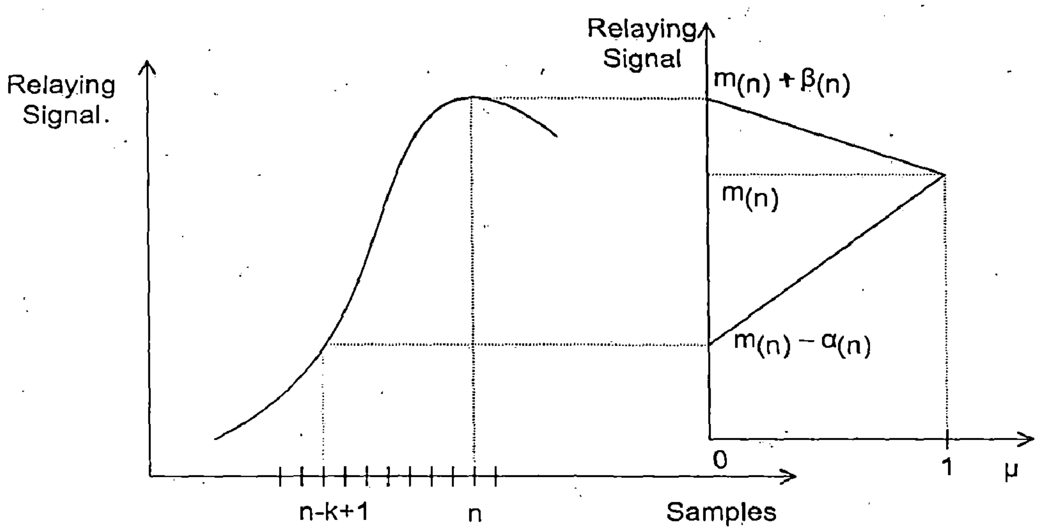


Fig. A.1 Design of fuzzy membership function

While a fuzzy signal represents uncertainty s to the actual value of a relaying signal; a fuzzy setting represents uncertainty related to the level of a setting, i.e. related to the expert knowledge about the boundaries in the universe of criteria signals between the tripping and blocking regions. Fig. A.2 shows a fuzzy setting (S2) in contrast with a fixed setting (S1), both for a current amplitude (i).

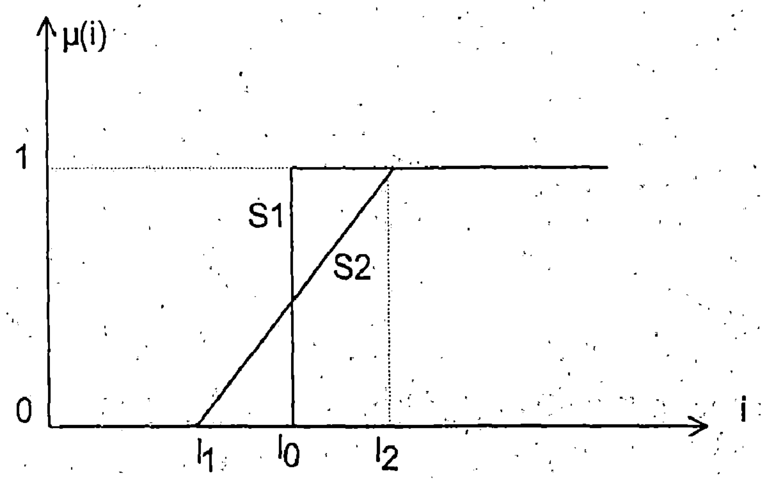


Fig. A.2 Fuzzy Setting

In case of a fixed setting, a measured current is recognized as a fault current, if its magnitude is greater than I_0. When the setting is fuzzy, currents larger than I_2 are recognized as fault currents with larger confidence. Similarly currents below than I_1 are considered as certainly non-fault currents. If the current amplitude is between I_1 and I_2, it is a doubtful case: it may be a fault case and value of μ(i) shows the level of certainty for a fault current.