THE APPLICATION OF ARTIFICIAL NEURAL NETWORKS TO TRANSFORMER PROTECTION

by

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Abstract

A new method of using Artificial Neural Networks to identify the magnetizing inrush currents that may occur in transformers is developed in this thesis. It is based on the fact that the magnetizing inrush current has large harmonic components. A feed-forward neural network (FFNN) has been trained using the back-propagation algorithm, to discriminate between transformer magnetizing inrush and fault currents. The proposed ANN-based inrush detector uses magnitudes of fundamental and up to the fifth harmonic components as the inputs and provides inrush or no-inrush indication to the differential relay. Some important issues such as the neural network's and the simulated sample power network's structures; simulation, selection and pre-process of the sample data are discussed. The ANN is trained and tested by using simulated data from the EMTP program. The trained network was verified using field test data from a laboratory transformer. The simulation and field test results are included in this thesis and indicate that the ANN-based inrush detector is fairly efficient with good performance and reliability.

The work reported here is a description of an experimental demonstration that a feed-forward neural network could be used as an alternative method to correctly discriminate between magnetizing inrush and internal fault currents in power transformers. The network and its training process were adapted to the goal of implementing the algorithm in a digital differential protective relay.

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CHAPTER 1

INTRODUCTION

§1.1 Power System Protection

Power system plant has to be protected against faults, abnormal system conditions and other undesirable situations. Protective gear relays and systems are provided for this purpose.

The protective systems include devices that recognize the existence of a fault, indicate its location and type, detect some other abnormal operating conditions, and initiate opening of circuit breakers for disconnecting the faulty equipment.

For purposes of protection, the power system is divided into zones [1] by circuit breakers as indicated in Figure 1.1. The circuit breakers are located at the end of each zone. In order to reduce service interruption, a protective system should only open the minimum number of circuit breakers to isolate the faulted zone from the remaining system. Internal faults are defined as occurring between the zone circuit breakers. Thus a fault which is internal to one zone is external to another. Each zone covers one or more components of the system and adjacent protective zones overlap so that no part of the system is left unprotected.

Each zone is usually protected by a system of relays, circuit breakers and associated equipment. During abnormal conditions, the relays identify the condition and send trip signals to appropriate circuit breakers which open to isolate the faulted zone. The remaining system continues to provide energy to customers.

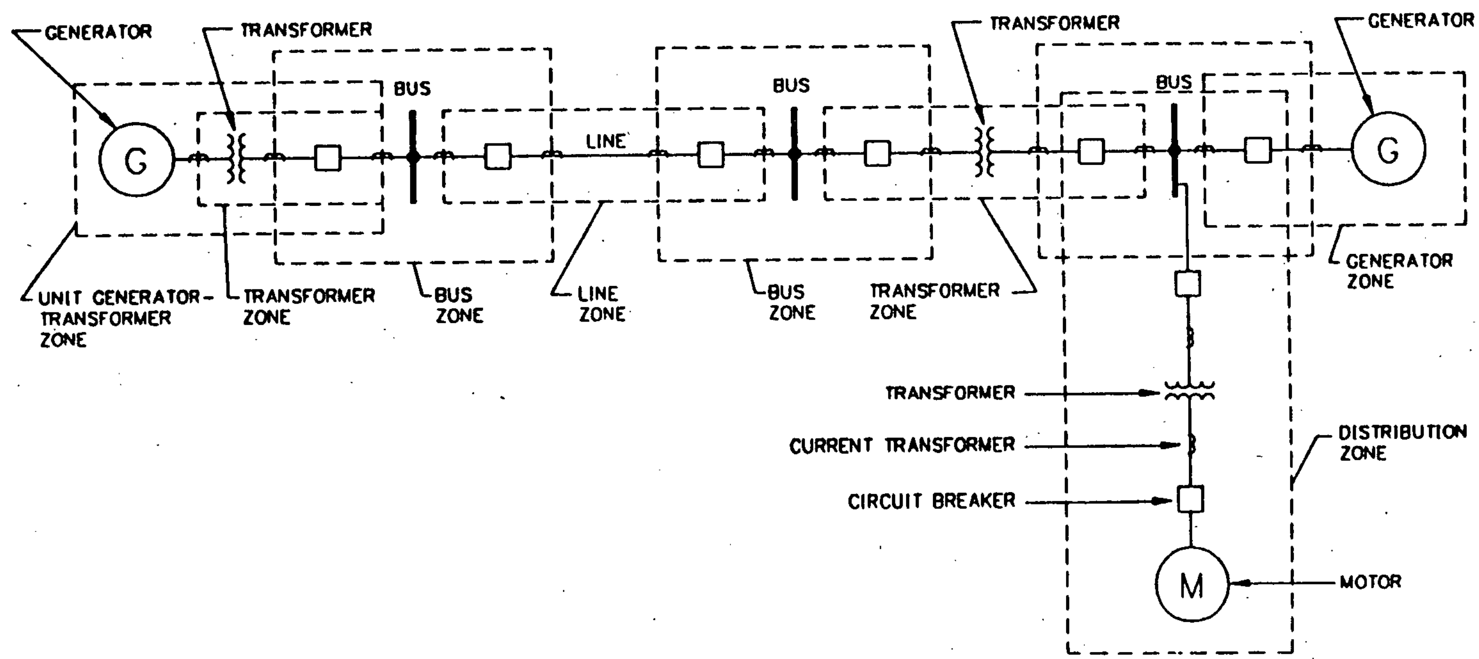


Figure 1.1: Typical relay protection zones in a power system.

Each zone is generally protected by two sets of relays, primary relays and back-up relays [2]. Primary protection should only operate for internal faults (inside the zone) and initiate control actions for isolating the faulted zone as quickly as possible. Back-up protection will trip for internal and external faults. The purpose is to take care of primary protection failure and circuit breaker failure. The back-up relay is to provide primary protection when the primary relay fails to operate. Back-up protection is subject to time delays in order not to interfere with primary protection operation.

Many types of protective relays are used, separately or collectively, depending on the type of fault and the equipment to be protected. The basic electrical parameters which may change in the transition from healthy to abnormal condition are currents, voltages, direction, power factor, phase angle and frequency, etc.[2]. These parameters provide information on the nature of a disturbance, the equipment that is experiencing a fault and the location of the fault. In a protection scheme, each relay performs an assigned function and responds in a specific manner to the changes in these parameters. The relays are generally known by their connections, the actuating quantities and the disturbances to which they respond.

§1.2 Changing Trends in Power System Protection

Earlier relays were automatic electromechanical devices for isolating a fault in a electrical system, and were later replaced by solid-state analogue relays. The complexity of modern power systems requires that the protective relays be more reliable, faster and of greater accuracy [3].

Recent developments in the field of digital electronics have made it possible to build microprocessor-based relays which provide a viable alternative to the presently used electro-mechanical and solid-state devices. Microprocessor-based relays use software [4] for interpreting signals and implementing logic. Memory storage capabilities of these relays are used to save useful information concerning pre- and post-fault currents and voltages. This information can be examined and analyzed later for developing improved operating practices and relay designs. With the advent of microprocessors, various digital algorithms have been developed and successfully used for power system protection.

§1.3 Differential Relays in Transformer Protection

Large transformers are usually protected from internal faults by percentage current differential relays. When an internal fault occurs, the balance current of the differential relay will be disturbed, and the relay will trip the circuit breaker. However, this method may result in unnecessary service interruptions when a transformer is switched on to the power system.

During energization of a transformer, abnormal currents may flow in the winding that is being energized. These are known as magnetizing inrush currents, caused by the saturation of the transformer core. This is exactly the condition obtained when there is an internal fault in the transformer. The relay may detect this unbalance of currents and cause the differential relay to mis-operate and disconnect the transformer. Two classic methods used [5] to avoid undesired operation due to inrush currents are:

1) implementation of delays in the relay, and

2) restraining or blocking the relay operation according to the harmonic content of the measured current.

The first method is undesirable because of the potential danger of delaying the tripping time during a real internal fault. The second method, which utilizes harmonic components of the differential currents to inhibit the relay operation during magnetizing inrush conditions is most commonly used. Magnetizing inrush current are rich in harmonic contents whereas internal faults mainly contain fundamental frequency content [6].

Different blocking schemes, such as second harmonic or total harmonic are used. However each harmonic restraint relay requires a setting [7] to compare the relative level of the harmonic component with reference to the fundamental frequency component. When the relative level of harmonic component is greater than the setting, an inrush condition is identified and the operation of the relay is restrained. This setting is generally decided by the relay application engineer based on his experience and established rules-of-thumb. An incorrect setting can cause either false tripping during switching conditions or no tripping during some internal faults, especially when the transformer is connected to the receiving end of a long transmission line.

§1.4 Neural Networks in Power System Protection

A great deal of research has been done in the development of neural networks over the past few years. Neural network computing was developed as a method of using a large number of simple parallel processors to recognize preprogrammed, or " learned ", patterns. This approach can be adapted to recognizing learned patterns of behavior in electrical networks where exact functional relationships are not easily defined [8,9]. As far as power system are concerned, some applications have been made in several problems: In the paper [10], the ANN was used for directional comparison protection of transmission lines. Sonia Ebron and David L.Lubkeman in [11] proposed a method for the detection of incipient faults on power distribution feeders. The back propagation (BP) algorithm was utilized [9] for monitoring and identification of the harmonic source. And in another paper [12], the ANN was used for real-time estimation of basic waveforms of voltages and currents.

A recent paper [5] reported attempts to use neural networks to identify magnetizing inrush currents. It was based on recognizing its wave shape, more precisely, using raw data samples of currents as inputs to the ANN, in differentiating magnetizing inrush wave shape from the fault wave shapes.

In this thesis, an attempt is made to develop an artificial neural network (ANN)-based inrush detector suitable for use in a transformer differential relay. It is based on the fact that the magnetizing inrush current has large harmonic components. The proposed inrush detector uses the magnitudes of fundamental and up to the fifth harmonic components as the inputs and provides inrush or no-inrush indication to the differential relay. The main advantage of this detector is that it requires no relay settings.

§1.5 Object of the Thesis

The object of this thesis is to describe the use of artificial neural networks for the inrush current detection in transformer protection. A feedforward neural network (FFNN) has been trained using the back-propagation algorithm, to discriminate between transformer magnetizing inrush and no-inrush currents. The proposed ANN-based inrush detector is trained and tested by using simulated data from the EMTP program. The ability of the trained network to respond to generalized conditions was tested using currents obtained from a laboratory transformer.

§1.6 Outline of the Thesis

The thesis is divided into seven chapters and four appendices.

Chapter 1 introduces the subject of power system protection and the used artificial neural networks.

In chapter 2, the principle of transformer internal fault protection, problems associated with differential relays and methods to overcome them are outlined. The effects of the magnetizing inrush current and how to distinguish between magnetizing inrush and fault currents is also reviewed.

Chapter 3 provides a brief introduction of digital relays and their benefits.

In chapter 4, the basic concepts of the ANN such as neuron (PE), layers and structure are introduced. The emphasis is on the description of the operation of the FFNN and the back-propagation algorithm.

A new proposed ANN-based detector is presented in Chapter 5. The focus of the work reported in this chapter is on the training and testing process of the ANN-based inrush detector.

Test results using data recorded from the laboratory transformer are reported in chapter 6. The results presented show that the proposed ANN-based detector performed correctly and reliably.

In chapter 7, conclusions and some recommendations for future studies are given. The main conclusion is that the proposed ANN-based inrush detector applying the back-propagation algorithm can be successfully used to discriminate between magnetizing inrush and no-inrush currents.

A list of references follow in the chapter 7. Appendix A lists the parameters of the sample power network used to simulate the single-phase transformer using the EMTP program. Appendix B gives the training file and the results of the learning the ANN. Appendix C gives the results of the testing which demonstrate the performance of the proposed ANN-based inrush detector. Appendix D provides the current waveforms that were recorded on a laboratory transformer.

Chapter 2

TRANSFORMER PROTECTION

§2.1 Introduction

Transformers are an integral part of modern power systems. All items of plant in a power system must be protected against faults, including transformers. However, there are problems which are peculiar to transformers, which are not encountered in other items of power system plant.

One of these problems is the large magnetizing inrush current which is caused by the non-linear flux-current characteristic [13]. At the moment when a transformer is connected to the power system, a large current may flow into the magnetizing shunt branch during the transient period. The large magnetizing inrush current may reach magnitudes as high as the internal fault current. It may cause the circuit breaker to operate and to disconnect the circuit. The main difference between the magnetizing inrush current and the internal fault is that the inrush current has high harmonic components of which the second is the largest whereas internal faults have virtually no harmonic components.

Transformers are difficult to protect because of the inrush problem. Thus the problems of transformers and traditional methods to protect them should be reviewed before a new method to protect them is developed.

In this chapter, different types of faults affecting the performance of power transformers are briefly reviewed first. The nature of the transformer and methods used for detecting faults and isolating the affected transformers from the system are discussed. The emphasis is on differential relays that are presently used by electric power utilities for transformer protection. The nature of magnetizing inrush current and how to discriminate between magnetizing inrush and internal fault currents are also explained.

§2.2 Definition of Through Faults and Internal Faults

Faults are unacceptable power system operating conditions and must be removed as quickly as possible. Excessive currents due to short-circuits and partial short circuits cause damage by overheating and also may lead to voltage reductions and frequency changes.

Faults are removed by strategically placing circuit breakers in the power system. In the case of most important items of plant (generators, transformers, transmission lines, etc.), there is a circuit breaker at each node which connects the item to the power system. Thus there is usually a circuit breaker at each end of a line, and for each winding of a transformer (2 or 3) depending on the existence of a tertiary winding.

With reference to the following diagram:

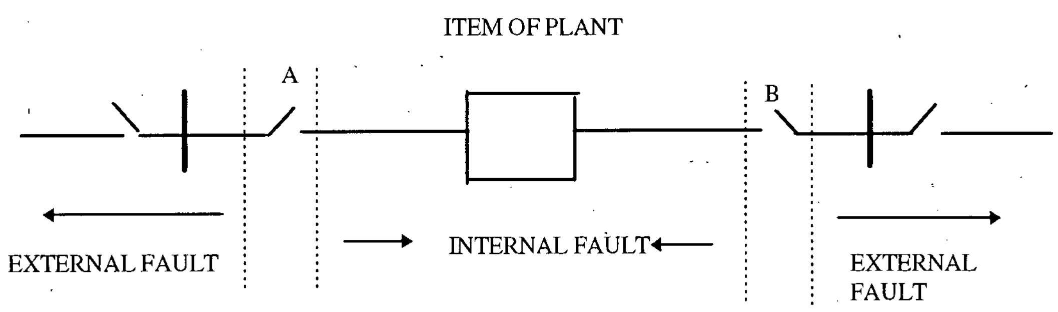


Figure 2.1: Definition of Through Faults and Internal Faults

A fault which occurs on the item of plant can be removed by opening breaker A and B and is called internal fault. Other faults require the opening of other breakers and are called external faults [1].

It should be evident that an external fault to one item of plant is an internal fault for another. The protection design requires that internal faults be removed in the shortest period of time, while under no circumstances disconnecting items of plant facing external faults.

§2.3 The Nature of a Transformer

A transformer is a static device and consists of two or more windings coupled by a mutual magnetic field [14]. Transformers are widely used and their primary function is to change voltage levels to satisfy different needs.

§2.3.1 Basic Transformer Principles

When a voltage is applied to the terminals of the primary winding, an alternating current will flow in that winding and create an alternating flux. It will induce a voltage in the coil which is nearly equal to this applied voltage. The induced voltage determines the magnitude of the core flux (ϕ) and the flux density (B).

With no burden (load) connected to the secondary terminals, the current flowing in the primary winding is the excitation or magnetizing current. With a load connected to the secondary terminals, current will flow in the secondary winding, its value depending on the impedance of the load, and additional current will flow in the primary winding determined by the turns-ratio of the transformer. The current of the primary winding is the sum of the load current corrected for turns ratio and the magnetizing current.

The relationships for an ideal transformer are (disregarding magnetizing current and other losses):

$$V_1/V_2 = N_1/N_2$$

$$I_1/I_2 = N_2/N_1$$

§2.3.2 Practical Transformer

For a practical Transformer [7,14], the windings have resistance. Besides the mutual flux ϕ_m, there is a small amount of flux known as leakage flux ϕ_l that links only one winding and does not link with the others. So the resistances R_1, R_2 and the leakage reactances $X_{l1}=2\pi fL_1$, $X_{l2} = 2\pi fL_2$ can be represented in series with the winding terminals.

In a practical magnetic core having finite permeability, a magnetizing current I_m is required to establish a flux in the core. This effect can be represented by a magnetizing inductance L_m. Also, the core loss in the magnetic material can be represented by a resistance R_c. If these imperfections are also accounted for, a practical transformer is therefore equivalent to an ideal transformer plus external impedances to represent the imperfections of an actual transformer.

The schematic of a practical transformer is shown in Fig. 2.2.

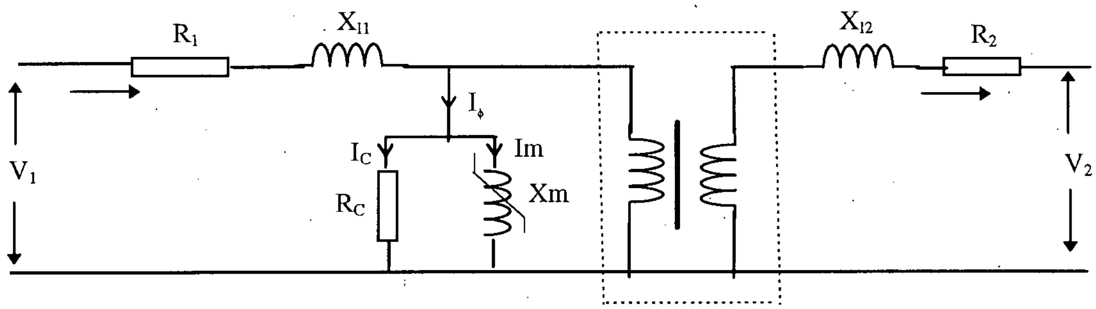


Figure 2.2. Practical Transformer Equivalent Circuit

Where:

$X_{l1}=2\pi f L_{l1}$

$X_{l2}=2\pi f L_{l2}$

$X_m=2\pi f L_m$

$L_{l1} = \frac{N_1 \phi_{l1}}{i_1}$ = leakage inductance of winding 1

$L_{l2} = \frac{N_2 \varphi_{l2}}{i_2}$ = leakage inductance of winding 2

L_m = magnetizing inductance in the core

§2.4 MAGNETIZING INRUSH CURRENT IN A POWER TRANSFORMER

Under normal steady-state operation the exciting current of a transformer is very low, usually less than 5 percent of rated current. However, at the moment when a transformer is connected to the power system, a large inrush current may flow in the transformer for a short transient period. This is due to the non-linear magnetizing characteristic and consequential flux saturation. This current may be as high as 20 to 30 times the rated current [15]. Knowledge of the nature of this large inrush current is very important in the design of transformer protection. The phenomenon of magnetizing inrush will be discussed in this section.

The magnitude of the inrush current depends on the residual flux trapped in the core when the transformer was previously switched-off and the instantaneous magnitude of the voltage when it is switched on [4, 13].

Consider a transformer whose core is initially unmagnetized. The transformer primary winding is now connected to a supply voltage at time t_0:

$$v(t) = V_m \cdot \sin(\omega t) \qquad (-\pi<\omega t<\pi)$$

where:

V_m: is the amplitude of the voltage,

ω: is the angular frequency of the voltage

When voltage is applied to the primary terminals, currents flow in the primary windings that produce magnetic fluxes in the transformer core. The rate of change of the fluxes in turn induce opposing voltages in the primary windings. The applied voltage expressed as a function of flux in the core and primary current can be rewritten as:

$$v(t) = R \cdot i(t) + N \cdot \frac{d\phi(t)}{dt}$$

where:

i(t): is the current in the primary winding,

ϕ(t): is the flux in the transformer core,

R: is the resistance of the primary winding,

N: is the number turns in the primary winding.

If core losses and resistance R are negligible, then

$$v(t) = N \cdot \frac{d\phi(t)}{dt} \tag{2.1}$$

so

$$V_m \cdot \sin(\omega t) = N \frac{d\phi(t)}{dt}$$

The flux in the transformer core must, therefore, be

$$\varphi(t) = \frac{1}{N} \int_{-\infty}^{t} v(t) \cdot dt \tag{2.2}$$

$$\varphi(t) = \frac{V_m}{N} \cdot \int_{-\infty}^{t} \sin(\omega t) \cdot dt \tag{2.3}$$

Integrating Equation (2.3) provides

$$\varphi(t) = \frac{V_m}{N} \cdot \int_{-\infty}^{t_o} \sin(\omega t) \cdot dt + \frac{V_m}{N} \cdot \int_{t_o}^{t} \sin(\omega t) \cdot dt$$

$$\varphi(t) = \varphi_{residual} + \frac{V_m}{N} \cdot \int_{t_o}^{t} \sin(\omega t) \cdot dt \tag{2.4}$$

$$\varphi(t) = \varphi_{residual} - \frac{V_m}{N\omega} \cdot \cos(\omega t)\Big|_{t_0}^{t} = \varphi_{residual} - \varphi_m \cdot \cos(\omega t)\Big|_{t_0}^{t} \tag{2.5}$$

where: φ_m is the maximum value of the normal flux waveform in the core

$$\phi_m = \frac{V_m}{N\omega} = \frac{\sqrt{2}V}{N\omega}$$

so the equation (2.5) can be rewritten as

$$\varphi(t) = \varphi_{residual} - \phi_m[\cos(\omega t) - \cos(\omega t_0)]$$

That is

$$\varphi(t) = -\phi_m[\cos(\omega t)] + [\varphi_{residual} + \varphi_m \cos(\omega t_o)] \quad (2.6)$$

$$\varphi(t) = -\phi_m[\cos(\omega t)] + (\varphi_{residual} + c) \quad (2.7)$$

In Eqn. (2.7), the second term is the integration constant, $\phi_m\cos(\omega t_o)+\phi_{residual}$ and its value depends on the residual flux in the transformer core and the phase angle of the applied voltage at the instant of applying the voltage to the transformer winding.

Two cases have to be analyzed as follows:

1) The transformer is connected when the voltage is maximum.

When the transformer is energized at the instant of voltage is maximum, and neglecting the transformer residual flux, $\phi_{residual} = 0$

that is for sinusoidal voltage source:

$$\omega t_0 = 90^0 = \frac{\pi}{2}$$

with $$t_0 = \frac{\pi}{2\omega},$$

giving:

$$\phi(t) = -\phi_m[\cos(\omega t) - \cos(\omega t_0)]$$

$$= -\phi_m[\cos(\omega t) - \cos(\pi/2)]$$

$$= -\phi_m[\cos(\omega t)]$$

so $$\phi(t) = -\phi_m[\cos(\omega t)] \qquad (2.8)$$

That is the constant c is 0. There is no transient in flux and the time variation of flux is:

$$\phi(t) = \phi_m \sin(\omega t - \frac{\pi}{2}) \qquad (\text{ for } \omega t > \frac{\pi}{2})$$

where: $$\phi_m = \frac{V_m}{N\omega} = \frac{\sqrt{2}V}{N\omega}$$

The magnetizing characteristic of a transformer core is non-linear, as shown in Figure 2.3. The knee point is defined to be when a 10% increase in flux leads to a doubling in magnetizing current [7].

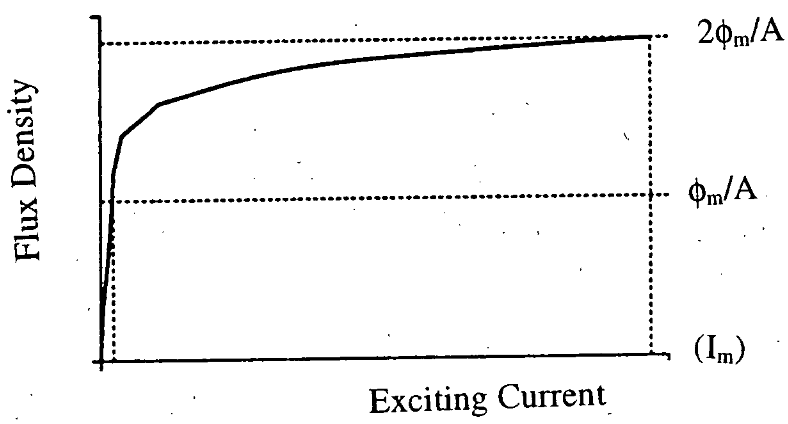


Figure 2.3. A typical Magnetizing Characteristic of the Core Showing relationship between flux density and magnetizing current

The flux will not pass the knee point, there will be little saturation and no magnetizing current inrush and the transformer will be in steady state from the start.

The steady state magnitude of flux is given by

$$\phi_{m\,steady-state} = \frac{V_m}{\omega N} \tag{2.9}$$

The voltage, flux variations and magnetizing current for this situation [13] are shown in Figure 2.4.

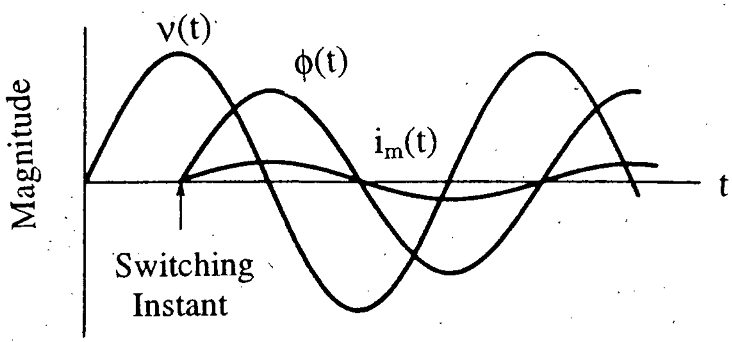


Figure 2.4. Transformer Inrush Current. Transformer Connected to Supply at the Instant of Maximum Voltage

2) The transformer is connected when the voltage is zero.

If the transformer is energized at an instant when the system voltage is zero and the transformer core has no residual flux. the constant c will be

$$\omega t_0 = 0$$

so

$$t_0 = 0$$

From equation (2.6), the flux is given by

$$\phi(t) = -\phi_m[\cos(\omega t)-\cos(0)]$$

$$= -\phi_m[\cos(\omega t)-1]$$

so $$\phi(t)= - \phi_m[\cos(\omega t)]+\phi_m \qquad (2.10)$$

That is the constant c is equal to ϕ_m

This equation shows that the flux builds up to $2\phi_m$ which is double the peak value of the steady state flux maximum in the transformer core under normal operating conditions.

The transient magnitude of flux is given by

$$\phi_{mtransient} = \phi_{residual} + \frac{2V_m}{\omega N} \qquad (2.11)$$

The above discussion demonstrates that excessive flux can build up in the transformer core depending on the instantaneous magnitude of the applied voltage and the residual flux at the instant of applying the voltage to the transformer.

As shown in Figure 2.3, the exciting current required to provide twice the normal flux in the transformer core is extremely large compared to the magnetizing current required for normal operation. The time variations of voltage, flux and magnetizing current are shown [13] in Fig 2.5. The peak flux has doubled and the corresponding peak magnetizing currents is very large because of core saturation.

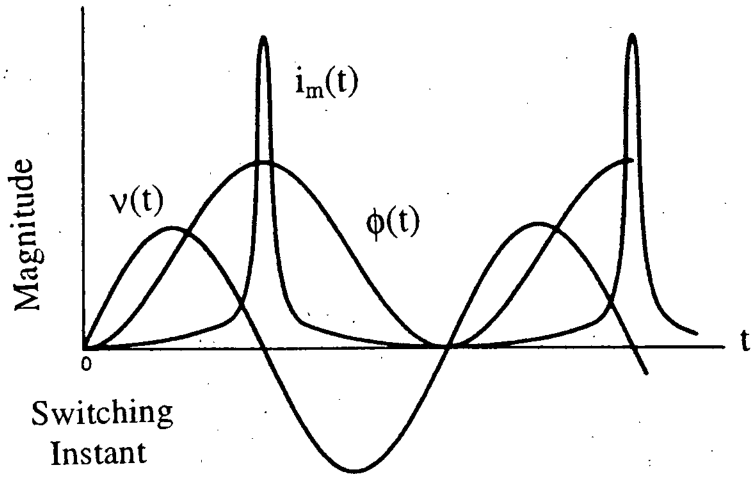


Figure 2.5. Transformer Inrush Current. Transformer Connected to Supply at the Instant of Zero Voltage

The transient exciting currents drawn by transformer are referred to as magnetizing inrush currents. These currents become even larger if residual flux is present and its polarity is such that it causes most severe saturation of the core. The initial magnetizing inrush can be 20 to 30 times the full-load current and can last for about 5 to 15 seconds in large transformers [4].

In practice, the presence of load and winding resistance will slightly reduce magnetizing inrush current and increase its rate of decay but still last several seconds as shown in Figure 2.6.

Since transformer switching is a random phenomenon, the magnetizing inrush is also random. However, The fact remains that during energisation, large magnitudes of currents can flow into the primary windings of a transformer while no currents flow out of the secondary windings. This is similar to the conditions occurring during internal faults.

The differential relay may as a consequence incorrectly trip the circuit breaker. Therefore, it is necessary to distinguish between an internal fault and a magnetizing inrush condition.

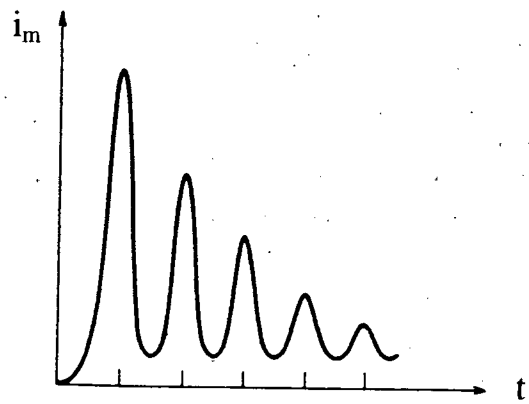


Figure 2.6. Effect of Winding Resistance on Transformer Inrush Current

§2.5. Differential Transformer Protection

Electric power utilities generally use differential relays on large transformers of 10 MVA or more [16]. The following section describes the basic principles used in differential relays, a detailed discussion on transformer differential protection and problems with its application. Percentage-bias and harmonic restraint features used to avoid false operation are also discussed.

§2.5.1 Basic Principles of Differential Relays

Differential relays take a variety of forms depending on the equipment protected. Differential relays operate when the vector difference of two or more similar electrical quantities at the two ends of a protection zone exceeds a predetermined level. These relays may be used to detect faults in transformers. Almost any type of relay, when connected in a suitable way can be made to operate as a differential relay.

Most differential relay applications are of the current-differential type which use the current-balance principle [1]. That is the currents at two ends of the system can be continuously compared by a suitable relay. As the currents at both ends are equal and anti-phase, this balance will hold, and no tripping will occur. When a fault occurs, the directions reverse so that the currents are nearly in phase.

The simplest operating principle of a differential relay is shown in Figure 2.7. The zone from A to B represents the system element that is protected by the differential relay. This element can be for example, a transmission line, generator, bus, or transformer. Transformer protection will be explained in this section.

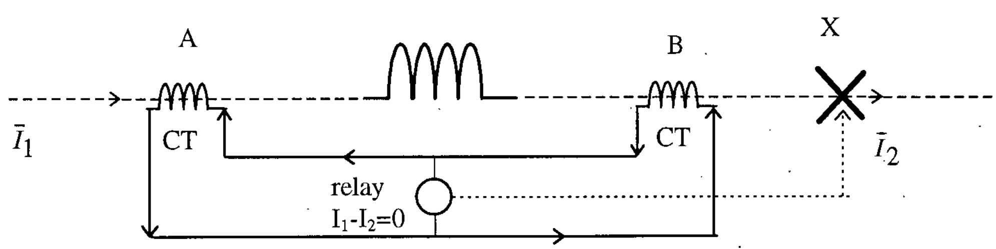


Figure 2.7: A Simple Differential Relay Application

Figure 2.8. shows a single phase transformer [4] using differential relay protection. Current transformers (CT's) are connected to the primary and secondary terminals of the

transformer to be protected. The secondaries of the CT's are interconnected and the coil of an overcurrent relay is connected across the CT secondary circuit as shown in the Figure 2.8. The current transformers installed on the two sides of the transformer define the boundaries of the protection zone. A fault at a location between two CT's is referred to as an internal fault.

If current flows through the primary circuit either to a load or to a short circuit located at X (healthy or external fault conditions), when the two current transformers have the same ratio, and are properly connected, their secondary currents will merely circulate between the two CT's as shown by Fig. 2.8(a) and no current will flow through the differential relay.

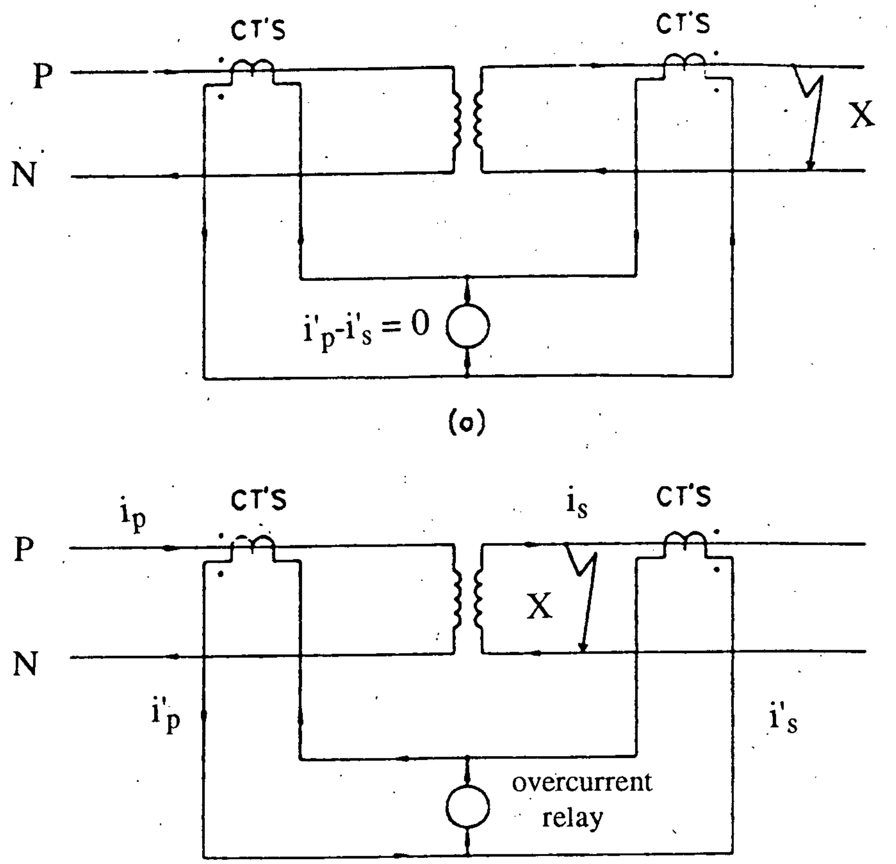
That is if external load or fault:

$$|i'_p - i'_s| = i'_p - i'_s = 0$$

But when a short circuit occurs between the two CT's region A and B (internal fault), the condition will be changed and the relay current will be non-zero. If current flows to the fault point X from both sides as shown in Fig. 2.8(b), the sum of the CT secondary currents will flow through the differential relay and will trip the relay.

That is for an internal fault:

$$|i'_p + i'_s| \geq i'_p \quad \text{or} \geq i'_s$$



(b)

Where:

i_p: Primary Current

i_s: Secondary Current

i'_p: Primary CT Current

i'_s: Secondary CT Current

Figure: 2.8. A typical differential protection circuit for a single-phase transformer

(a) an external fault, (b) an internal fault

It is not necessary that short-circuit currents flow to the fault from both sides to cause secondary current to flow through the differential relay. A flow from one side only, or even some current flowing out of one side while larger current enters the other side such as magnetizing inrush current in the transformer, will also cause a relay differential current. In other words, the differential relay current will be proportional to the vector difference between the currents entering and leaving the protected circuit; and if the differential current exceeds the relay's setting, the relay will operate.

In practice, differential relays suffer from drawbacks due to non-linear phenomena, such as CT characteristics, transformer ratio change, magnetizing inrush and transformer overexcitation [2,4]. These phenomena cause currents to flow in the operating elements of a differential relay resulting in its operation even when there is no fault in the transformer zone. In the next section these drawbacks are discussed and illustrates the significance of the percentage-bias and harmonic restraint features which make differential relays immune to magnetizing inrush and overexcitation.

§2.5.2. Limitations of Simple Differential Relays

1. Current Transformer Characteristics

The primary and secondary CT's used for differential protection are designed for operation at different voltage and current levels. Because of the slight difference in magnetic properties, different amounts of residual flux and different ratios, the secondary currents may not balance. If the CT becomes saturated the situation gets much worse.

Because the characteristics of the primary and secondary CT's are difficult to match over their entire operating ranges; the unbalance currents become progressively larger as the system currents increase above rated value.

The lengths of the leads connecting the primary and secondary CT's to a relay are not equal. This causes the burdens on the primary and secondary CT's to be different resulting in ratio errors.

2. Effect of Transformer Taps

Many transformers are equipped with off and on-load tap-changers which change the primary to secondary turns ratio as the system operating conditions change. The CT ratios are usually selected to match transformer operation at its mid-point tap setting. The outputs of the primary and secondary side CT's do not balance when the power transformer operates at an off-nominal tap setting, and unbalance current will flow in the differential relay. The relay should be designed to avoid mis-operation for this condition.

3. Magnetizing Inrush Current

When a transformer is energized, the inrush current may reach peak values many times the transformer full-load current and decay relatively slowly. This current flows in one side of the differential relay only, which will tend to operate the relay and hence circuit breaker if some form of restraint is not provided. This effect was explained in detail in the previous section.

4. Transformer Overexcitation

A transformer may be subjected to sustained over-voltage on load rejection or on clearing of an external fault. The flux density in the core increases as the voltage increases.

This results in the transformer drawing large magnetizing currents which can exceed the rated transformer current and can cause a differential relay to operate.

Conclusions: The above are the main problems in the simple form of differential relay and must be taken into account. To make a differential relay stable, in order to overcome the CT's characteristics and on-load tap changing problems as mentioned above, percentage differential relays have been developed and are now adopted in the protection of large power transformers. In order to avoid mis-operation of the differential relay because of the magnetizing inrush current and transformer overexcitation, early practice was to delay the relays for a short time until the magnetizing inrush currents had decayed to an acceptable value. Now however, practice is to provide some form of restraint (or blocking) to the relays which depends on the harmonic component of the magnetizing inrush currents.

§2.5.3. Percentage-Bias and Harmonic Restraint Relays

The principles of differential protection were described in the previous section. Factors that affect the operation of a differential relay were also reviewed. Electric power systems use transformer differential relays with percentage-bias and harmonic restraint features [1,4] to overcome incorrect operation during external faults, magnetizing inrush and transformer operation at different tap point settings.

The percentage-bias feature is used to inhibit relay operations due to mis-match of CT ratios and operations at off-nominal tap settings. A percentage-bias differential relay has a pair additional restraint windings as indicated [7] in Figure 2.9. The differential current required to operate this relay is a variable quantity, owing to the effect of the restraining windings. The current in the operating coil is proportional to the difference between the transformer primary and secondary currents referred to the CT level (I_1-I_2), and the equivalent current in the restraining coil is proportional to the sum (I_1+I_2) of the primary and secondary current.

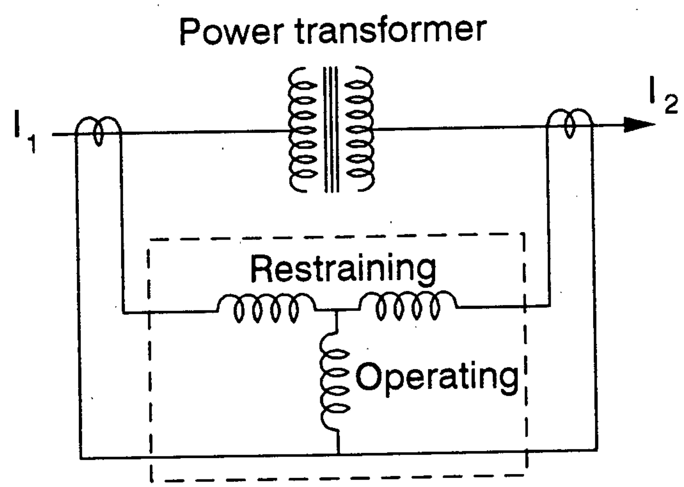


Figure 2.9 Percentage-bias Differential Relay

The differential current required to operate the relay must exceed a set percentage of the through current which is the total current that flows through the circuit from one end to the other. The ratio of the different operating current to the average restraint current is a percentage slope of the relay characteristic. A typical operating characteristic of a percentage-bias relay is shown in Figure 2.10.

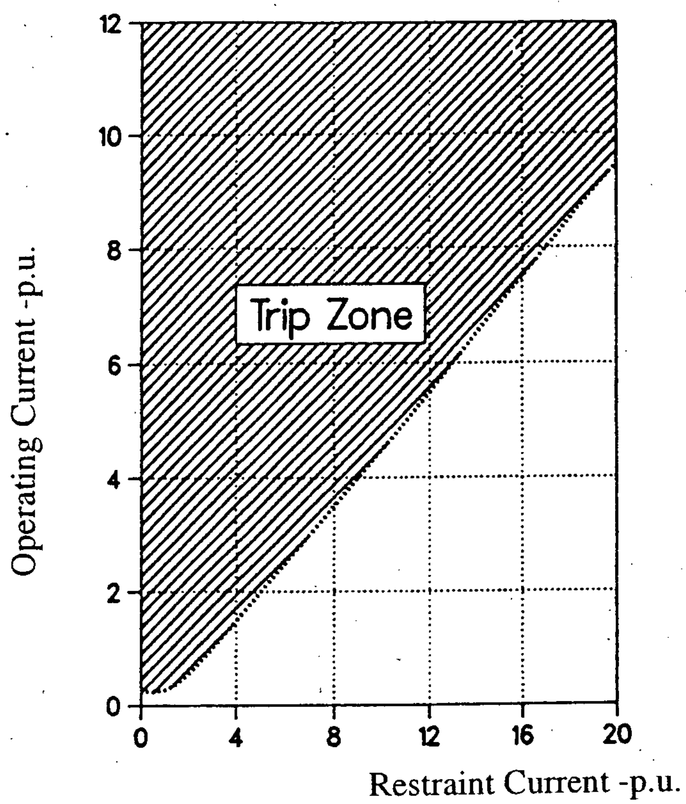


Figure 2.10. A typical Percentage-bias Characteristic of Differential Relay

Current transformers have ratio and phase errors which increase with current magnitude and transient content. The bias current is designed to take into account the above-mentioned errors as well as differences due to tap position.

If set correctly, this relay will be unconditionally stable. The percentage-bias characteristic increases the security of operation while it keeps the sensitivity at a reasonable level and the relay is restrained from operating incorrectly.

For the magnetizing inrush currents phenomena, there are large harmonics while fault currents are generally almost pure single frequency sinusoids. The magnetizing inrush current phenomenon was explained in the previous section. A typical amplitude spectrum of the harmonic component of inrush current is given in Table 2.1 [1].

TABLE 2.1: Amplitudes of Harmonics in a Magnetizing Inrush Current Wave-shape

Harmonic Component	Amplitude in Percentage of Fundamental Component
fundamental	100
d.c.	55
2nd	63
3rd	26.8
4th	5.1
5th	4.1
6th	3.7
7th	2.4

Since the second harmonic component is much larger than the others, a Harmonic-Current restraint method [17] is usually used to prevent operation during the magnetizing inrush current period. The relay uses the harmonic component to differentiate between faults and magnetizing inrush. The harmonics are filtered out and separated from the differential current, rectified, and fed back into the restraining coil. Only the current of fundamental frequency enters the operating coil, dc and harmonics components are filtered into the restraining coil. The relay is adjusted so that it will not trip when the second harmonic exceeds the setting value. However, it will operate during a short-circuit when current mainly contains fundamental component, so it can distinguish between the magnetizing inrush current and the fault.

Large differential currents may also be present during overexcitation of the transformer because of harmonics caused by saturation. This is particularly true for modern transformers because they operate close to the knee point of the magnetizing characteristics of their cores. The magnetizing currents contain mainly odd harmonic. Fifth harmonic component is used in the restraining coil for overexcitation condition [4,7].

§2.6. Summary

A protective relay operates when an operating quantity exceeds a specified amount. The main function of a protective relay is to operate in response to a fault on a power system so as to minimize the damage to equipment and the interruption to service by opening only those breakers which will isolate the faulty device from the power system.

In this chapter, the principle of transformer differential relay protection was introduced. Problems associated with the transformer differential relay and methods to overcome them were also discussed. The effect of magnetizing inrush current and how to distinguish between the magnetizing inrush current and internal fault were explained.

CHAPTER 3

DIGITAL RELAYS IN POWER SYSTEM PROTECTION

§3.1 Introduction

Power systems are protected by using combinations of relays and circuit breakers. Relays detect the faults and, if necessary, initiate the opening of circuit breakers to isolate the faulty equipment. Modern power systems are complex networks. The complexity of these networks demands that the relays used for protection be reliable, secure, accurate and take a short time to make decisions. To the present electro-mechanical and static analogue relays have been used. However, several individuals and organizations have been conducting substantial research in the area of computer relaying for the last several years. With the constant price reduction and reliability increase of VLSI chips, digital alternatives are becoming increasingly attractive.

Early research in the field of computer relaying considered the use of a single computer (a mini-computer) for all the relaying functions in a substation [3]. In case of computer break-downs, the use of a stand-alone computer would result in complete failures of substation protection. A standby computing system would be needed to avoid such failures. The use of two main-frame computers, a main and a standby, for a substation protection appeared too expensive to be commercially viable. However, recent advancements in microelectronics have resulted in the availability of low cost processors with enhanced capabilities. This has changed the present view to use individual microcomputers dedicated to specific relaying functions with facilities for data exchange among themselves [18]. It is expected that this concept will result in realizing the advantages of computer relaying without the drawbacks of using a main-frame computer.

This chapter briefly highlights the benefits that can accrue from the use of digital relays instead of the conventional relays and presents a typical block diagram of digital relay.

§3.2 Benefits of Digital Relaying

Recent developments in the field of micro-processors have enabled digital relays to be a viable alternative to electro-mechanical and static relays [19]. The cost of digital relays is becoming comparable or in even some cases cheaper than conventional relays. In addition to the relaying functions, a digital relay has the potential to perform other tasks, such as self diagnosis, data analysis etc. A brief summary [3,20] of the specific advantages of using digital relays is presented in this section.

1. Flexibility

A digital relay is a programmable device. Revisions and modifications in relay characteristics, necessitated by changes in operating conditions, can be made through pre-programmed modules. A single, general purpose hardware based relay can be designed to perform a variety of protection and control tasks. This would lead to a lower maintenance and replacement cost.

2. Reliability

The failure of a conventional relay becomes apparent only when it fails to operate upon encountering a fault or malfunctions under the normal operating conditions. However, most of the hardware failures in a digital relay can be detected as they occur. Additional diagnostic features, such as specific programs, can be executed to test the hardware. Therefore, it is expected that most of the failures in a digital relaying system can be detected immediately, an this can be used to alert the operator for corrective action.

3. Data-interface Access

A digital relay can be equipped with input/output ports for exchanging data and control commands. The pre-fault and post-fault signals can be stored in the relay memory and later transmitted to a central computer through a data link. This information can be used for further investigations that might lead to improved operating practices and relay designs.

4. Adaptive Capabilities

A digital relay can be programmed to automatically change its characteristics depending upon the operating status of the power system. The change can be made either by considering the information locally provided to the relay or on receipt of a command from the central computer via a data link. The change may consist of selecting a new setting, or selecting a new protection routine.

5. Mathematical Capabilities

Designs of conventional relays are constrained by the characteristics and limitations of the electro-mechanical or solid-state components. But digital relays can be programmed to provide almost any characteristics. Programming a complex characteristic is only nominally more difficult to implement than a simple characteristic.

§3.3 Functional Details of Digital Relay

Major functional blocks [4]of a digital processor based relay are shown in Figure 3.1. The analog sub-system receives low level voltage and current signals from voltage transformers and current transformers, respectively. The sub-system isolates the relay from the power system and provides protection from transient over voltages. It also uses low pass filters to band-limit the signals. As analog to digital (A/D) converters accept only voltage signals as inputs, the sub-system converts all currents into equivalent voltages and reduces their levels to avoid saturation of A/D converters.

The outputs of the analog sub-system are applied to the analog interface sub-system. This sub-system includes sample and hold, A/D conversion and multiplexing hardware. The processed signals from the analog sub-system are sampled at a selected sampling rate. The sampling rate and the cut-off frequency of the analog filters (in analog sub-system) are inter-dependent. The sampling rate must be at least twice that of the frequency of the highest frequency component expected to be present in the analog inputs.

The instantaneous values of the signals are held as voltages across capacitors. A multiplexer applies each voltage in turn to an A/D converter that converts the sampled values to equivalent digital representations Alternatively, dedicated A/D converters can be used for each sampled signal. A multiplexer can then be used to read each information sequentially into the computer.

The digital input sub-system conveys the status of the power system circuit breakers and switches to the relay. Input wiring must be properly shielded to protect the relay from transient voltages that may occur on the wiring.

The digitized data are then entered into the Random Access Memory (RAM). A record of significant events in the power system are saved in the Random Access Memory as historical files. The organizations and lengths of the data files depend on the needs of the users. The data stored in historical files should be moved to a secondary device (a local computer or a remote host) as soon as possible, thus freeing the RAM for storing information on the next occurrence of a transient. The relay programs reside in a non-volatile, Read Only Memory (ROM). The controllers, central processing unit (CPU) and the registers work as a group to execute the programs, one statement at a time.

The digital output sub-system conveys the decisions of the relay to the power system. The outputs from the relay, generally, provide signals for tripping circuit-breakers, annunciators etc.

A digital relay requires uninterrupted supply of power. A battery and an AC to DC converter are usually used to supply power to the digital relay. AC to DC converters used in these relays are designed for continuously supplying the power demand of the relay and sufficient power to keep the battery fully charged. Whenever the AC supply to the converter fails, the battery starts supplying uninterrupted power to the relay.

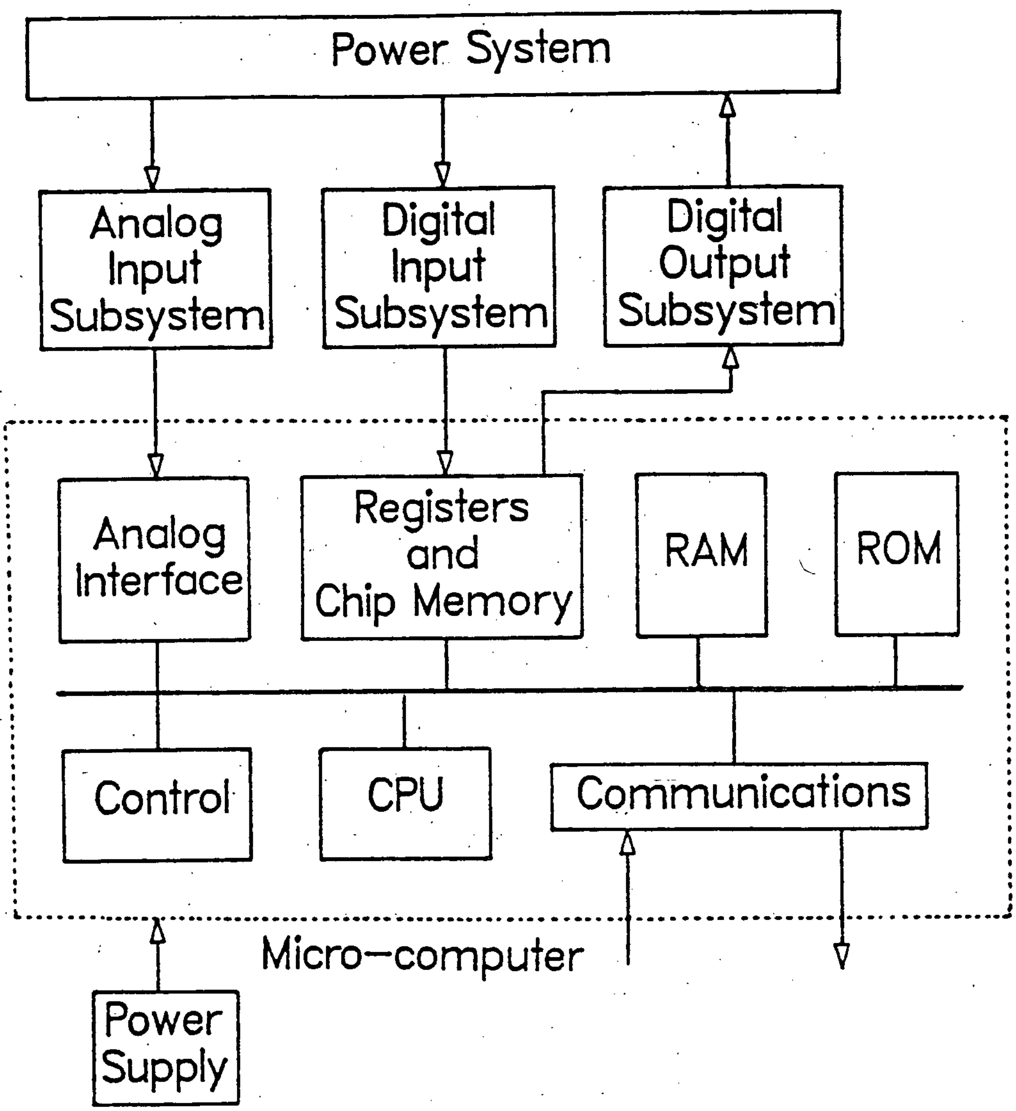


Figure 3.1 Functional Block diagram of a Digital Relay

§3.4 Summary

Digital relays are becoming commercial reality. This chapter first described the advantages of the digital relays over the conventional electro-mechanical and solid-state analog relays. The functional block of a typical digital relay is discussed.

Chapter 4

NEURAL NETWORK THEORY

§4.1. INTRODUCTION

Artificial neural networks (ANN) are computing devices, implemented in hardware and software, in which their operation is based on the properties similar to living neurons [21]. The term neural network is used to describe various architectures of highly interconnected simple processing elements that offer an alternative to conventional computing approaches.

Neural networks are radically different from traditional deterministic approaches in the following senses [22]: neural network do not execute instruction sequentially rather they respond in parallel to a set of inputs. Neural network are more concerned with transformation than procedure, and are comprised of a large number of simple nonlinear processors (neurons) connected in parallel to perform useful computational tasks such as to recognize pre-programmed or learned patterns. The neural approach is to gather examples of the input data that the system will encounter in practice, and to use these to train the network to respond appropriately. This involves adjusting the weights on each neuron until the network learns to behave satisfactorily.

Neural network have been developed in signal and image processing, control, data compression and many other fields [8]. The ANN theories have been applied to pattern recognition, pattern classification, learning, optimization, etc.. Rumethart, et al. [23] had proposed a neural network technique called Back Propagation (BP) with multi-layered perceptrons. The technique has been successfully applied to adaptive pattern recognition problem.

The back-propagation approach can also be used in power systems. Some applications have been made in solving electrical problems such as transient stability [24], high impedance fault detection [25], and capacitor control in distribution systems [26], etc. In this project, a neural network based transformer inrush current detector, trained using the back propagation approach is discussed.

In power transformer protection, the differential relay operates the circuit breaker for internal faults. The effect of the magnetizing inrush current due to the non-linear characteristic and residual of the magnetic material could cause mis-operation the relay. The main difference between the magnetizing inrush and fault current is that the second harmonic component in inrush current is much larger than it is in the fault current. The harmonic analysis of the transformer allows the artificial neural network to perform the pattern recognition. An ANN-based inrush detector is proposed to discriminate between power transformer magnetizing inrush and fault current.

In this chapter, the basic concept of neural networks is introduced first, and then the operation of an ANN is described. The emphasis is on the description of the back propagation algorithm.

§4.2. Basic Principles of Neural Networks

§4.2.1. Description of the ANN

In an Artificial Neural Network [22], or simply a neural net (ANN), the unit analogous to the biological neuron is referred to as a "processing element". An ANN is a system composed of many simple processing elements called artificial neurons or nodes. A processing element (PE) has many input paths and combines the values of these input paths by a simple summation. The combined input is then modified by a transfer function. This transfer function can be a threshold function which only passes information if the combined activity level reaches a certain level, or it can be a continuous function of the combined input. The output value of the transfer function is generally passed directly to the output path of the processing element.

The point where two neurons communicate is called a "connection". The strength of a connection is defined by its weight. The output path of a processing element can be connected to input paths of other processing elements through connection weights. Since each connection has a corresponding weight, the signals on the input lines to a unit are modified by these weights before being summed. The summation function is a weighted summation. A neural network consists of many processing elements joined together, usually organized into groups called layers. There are typically two layers with connections to form a neural network: An input layer where data is presented to the network, and an output layer which holds the response of the network to a given input. Layers between the input and output layer are called hidden layers.

The simplest form of a network has no feedback connections from one layer to another or to itself. Such a network is called a "Feedforward Neural Network" (FFNN) [22,27]. In this case information is passed from the input layer through intermediate layers to the output layer in a straightforward manner using the summation and transfer function of the particular network. FFNNs are very important because of the non-linearity in the transformations.

A typical feedforward neural net [9] with one hidden layer is shown in Fig. 4.1.

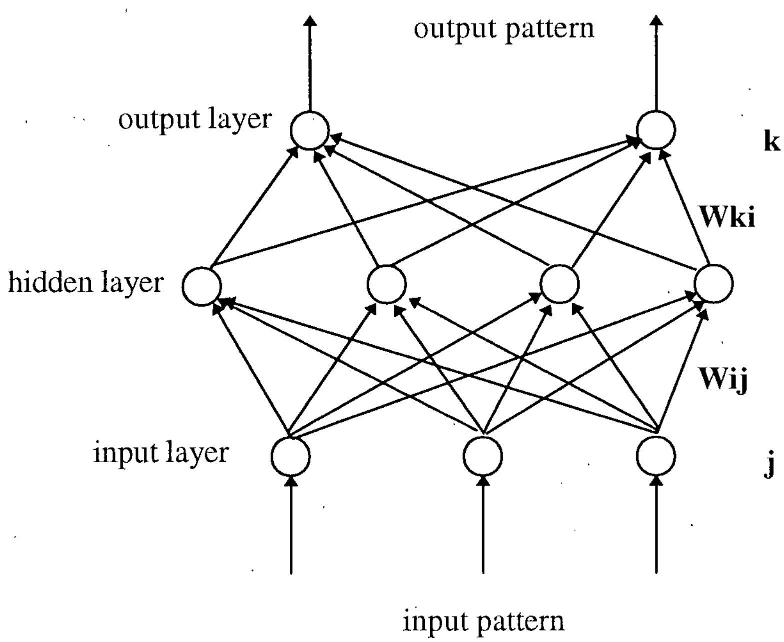


Figure. 4.1 Typical Feedforward Neural Network

If there are feedback connections, information will circulate around the network, across layers or within layers, until some convergence criterion is met. The information will then be passed to the output layer.

The main feature of the ANN is the learning operation (generally called training) [22,28]. Learning is the process of adapting or modifying the connection weights in response to the input value presented at the input layer and optionally the output layer. Learning in general, can be supervised or unsupervised. Supervised learning requires an external "teacher" that provides the desired output corresponding to a given input, evaluates the behavior of the system and directs the modification. Unsupervised learning requires no teacher, the network self-organizes to produce the desired change. But whatever kind of learning is used, an essential characteristic of any network is its learning rule which specifies how weights adjust in response to a learning example. Learning may require showing a network many examples, many thousands of times. The parameters governing a learning rule may change over time as the network progresses in its learning.

§4.2.2. ANN Architecture

The number of layers and PEs per layer are very important. There are a few rules in selecting a neural network configuration for a given application. In Ref[22] it is suggested, for a feedforward network with inputs and outputs, a three layer network with one hidden layer is sufficient to classify inputs that are limited to three dimensional regions. The two hidden layer network can classify arbitrarily shaped input signals and can be determined by experience.

Another problem is to predict the total number of neural nodes in a hidden layer. The PEs number in a hidden layer should be large enough so as not to restrict the range of the output patterns. But too many nodes will require more weights and will result in slowing the training process.

This implies a compromise between speed and accuracy. Because the FFNN classification time depends on the number of units in the network, it is very important to have the smallest number of units without reducing the quality of the classification.

Most back propagation networks will have one or two hidden layers. The number of PEs in the hidden layers are usually chosen to lie between the number of input and output PEs.

For a fully-connected feedforward network with one hidden layer (which can describe most back propagation networks), there are some general suggestions in Ref [22] for deciding how many PEs should be placed in the hidden layer. It normally depends on the complexity of given the application and the amount of the training data. The more complex relationship between the input data and the desired output, the more PEs are normally needed in the hidden layer. By experience, the maximum number of PEs in the hidden layer can be calculated by the following formula:

$$\frac{case}{10\times(m+n)}=h$$

where, case: is the number of rows or vectors in the training file

m: is the number of PEs in the output layer

n: is the number of PEs in the input layer

h: is the number of PEs in the hidden layer.

§4.3 Operation of a Feedforward Neural Network

A neural network consists of a set of connected nodes and a propagation rule. A general node model is represented in Figure. 4.2 [22,25]. The node, or neuron, receives its input through weighted links. This input may come from other nodes in the network or from threshold values. An activation function, usually a summation, acts on the input; the node's internal bias is then added to the summed and weighted inputs. The result is called node activation [11]. The node's output is determined by an output function, which responds to the activation. An example is the S-shaped sigmoid shown in Figure 4.2. The propagation rule of the node consists of its activation and output functions. The node's output travels along the links, or path, either to other nodes or to the output of the system.

A neural network is simply a layered collection of these nodes. The nodes are connected by links of varying weight. An n-node network with a given propagation rule is fully described by an n-dimensional internal bias vector **B** and an n-dimensional square weight matrix **W**.

There are many types of networks, but the work described here focuses on feedforward layered networks, with each node's activation and output determined by summation and sigmoid functions, respectively. In feedforward networks, all inputs are received on one layer, and the resulting signals propagate forward, one layer at a time, until the signals reach the last layer or output layer.

A typical feedforward neural network is shown in Figure. 4.1. and a general node model is given in Figure 4.2. to illustrate the idealized model operation. The nodes are processing units which receive input from their lower side and deliver output on the upper side. A set of input signals, comprising an input pattern, is applied to the input. The pattern is transmitted to the input of the hidden layer through the weighted network connections. The weighted pattern is received by the hidden layer units, while the signals are combined in an activation function.

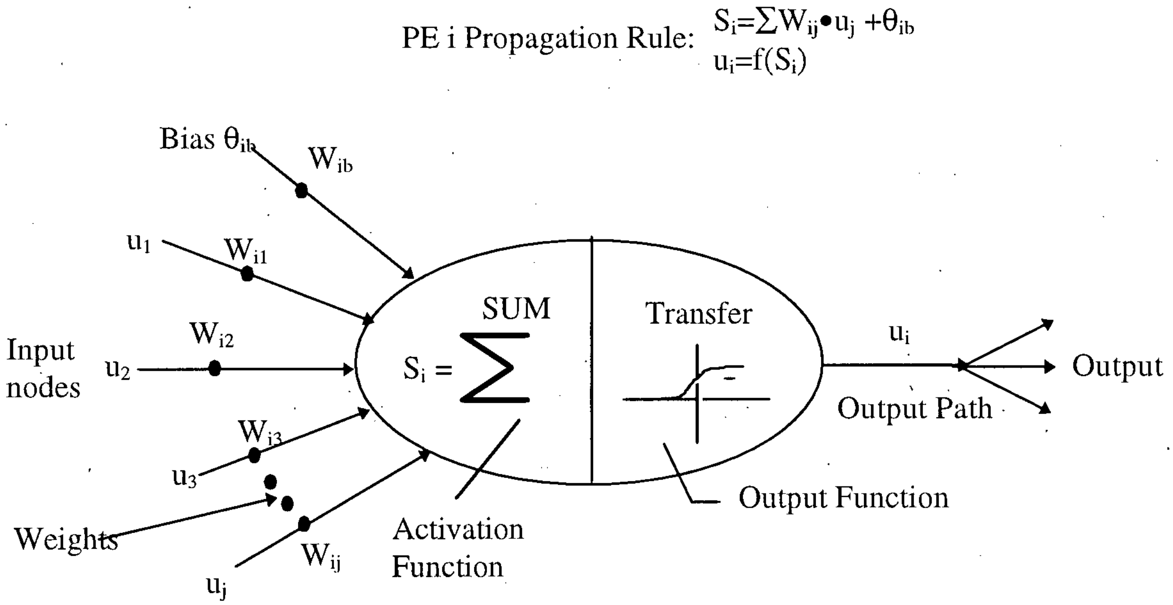


Figure 4.2 Idealized Neuron Model I Operation

Now, consider the relationship between the input and the output of a neuron (PE) [9,21,22].

Defining output of unit j at the previous layer as u_j, the activation or total input of unit i at the present layer can be written as:

$$S_i = \sum_j W_{ij} u_j + \theta_{ib} \qquad (4.1.)$$

where: W_{ij}: is the weight of the connection from unit j to unit i.

θ_{ib}: is the node threshold (or bias vector).

The output u_i of the unit i is expressed by unit i input S_i:

$$u_i=f(S_i) \tag{4.2}$$

where, f(x) is usually, but not necessary the sigmoid function such as:

$$f(x)=\frac{1}{1+\exp(-x)}=(1+e^{-x})^{-1} \qquad (-\infty<x<+\infty) \tag{4.3.}$$

The outputs of the hidden layer units i are then transmitted to the inputs of the next layer units through another weighed connections. Figure 4.2. shows the clearly relationship given by Eqn (4.1.) and Eqn (4.2.).

In general, the forward propagation consists of passing weighted and summed input signals through a chosen nonlinear function. It presumes knowledge of the network's bias vector and weight matrix. Again, once activation and output functions are chosen, a neural network is completely described by its weights and biases. Since a given neural network solves a specific problem, or function, finding weights and biases for the network is equivalent to finding the input/output relationship that describes this function. Thus, neural networks are especially appropriate and powerful when used to find relationships that are difficult to describe explicitly, because weights and biases can represent a given function. The FFNN training process consists of determining the weights W and the units' biasing (thresholds) B, in order to make the network respond in a given way.

The neural net used in this project is trained by the learning rule called the BACK PROPAGATION LEARNING ALGORITHM, alternately known as the Generalized Delta Rule which was developed by Rumelhart, et al [23].

§4.4 Back Propagation Algorithm

The error back-propagation algorithm is one of the most important and widely used learning techniques for neural networks. In this section, it is first explained how the algorithm works and how it is put to use. Then the theory behind the algorithm is derived.

The back-propagation network is a multi-layer feedforward network with a different transfer function in the artificial neuron and a more powerful learning rule. The learning rule is known as *back-propagation*, which is a kind of gradient descent technique with backward error (gradient) propagation, as depicted in Figure 4.3 [27]. The back-propagation consists of one input layer, one output layer and one or more hidden layers. The network are connected from input to output layers in a feedforward way.

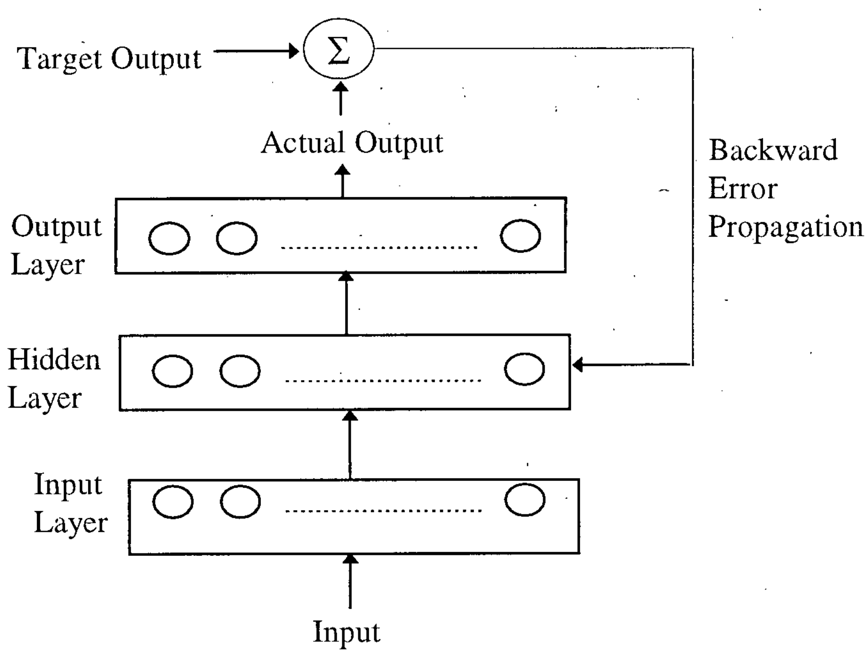


Figure 4.3: The back-propagation network

As been described in the section 4.3. the activation (input of the unit i) of the ith unit is expressed by the previous unit j is given by taken the sum of all inputs j of the unit (u_j) multiplied by the appropriate weight w_{ij} and adding to it the value of some threshold θ_{ib} , that is:

$$net_i=S_i = \sum_j w_{ij} u_j + \theta_{ib}$$

The output u_i of the unit i is determined by $f_i(net_i)$.

$$u_i=f_i(net_i)=f_i(S_i)=f_i(\sum_j w_{ij} u_j + \theta_{ib})$$

where:

w_{ij}: is the weight from an input u_j to u_i,

θ_{jb}: is the node threshold,

$f_i(x)$: is a sigmoid function:

$$f_i(x)=\frac{1}{1+\exp(-x)} = (1+e^{-x})^{-1}$$

The neural network is a pattern associator or classifier, receiving patterns directly from data at the input and delivering output patterns that will give some related information about the system. The object here is to "train" the network to find a way of altering the weights and thresholds so that the error is to be reached to the minimum.

The back-propagation algorithm to adjust the weights and thresholds is done by a training process [9,11,21,27],can be described as follows:

1). Provide Input Pattern:

Assign input pattern set of input signal at the input layer.

2). Weight Initialization:

Set all weights and node thresholds automatically to small random numbers. Note that the node threshold is the small value from the bias unit (whose activation level is fixed at 1).

3)Calculation of Activation:

Transform input signals at the hidden and the output layers using Eqns. (4.1) and (4.2). Regard output signals at the output layer as the final output of the network.

4) Error Function:

Compare the final output signals with a target signals, total squared error, E_p is produced which is the sum of squared difference between the desired output t_p and actual output u_{ip},

$$E_p = \frac{1}{2}\sum_i (t_p - u_{ip})^2 \tag{4.4}$$

where:

t_p: target signal of the unit u_i at the output layer, and

u_{ip}: actual output signal of the unit u_i at the output layer.

5) Weight Training:

The weights adjustment could be done by minimizing E_p in a gradient descent in which the derivation of the unit output functions, $f_i'(x)$ is made continuous function as following equation [27]:

$$f'(S_i) = f(S_i)(1 - f(S_i)) \qquad (4.5)$$

Start at the output unit and the weight change (Δw_{ij}) work backward to the hidden layers recursively.

The weights are adjusted by:

$$w_{ij}(t+1) = W_{ij}(t) + \Delta w_{ij} \qquad (4.6)$$

where:

$w_{ij}(t)$: is the weight from unit j to unit i at time t, and

Δw_{ij}: is the weight adjustment.

The new weight $w_{ij}(t+1)$ is straightforward to the next layer repeatedly.

The weights change between neurons are determined as follows:

The steepest descent method is utilized in order to minimize Eqn. (4.4). The change of the weights from unit j to unit i for input pattern p is defined by [9,22]:

$$\Delta w_{ij} \propto (\partial E_p / \partial w_{ij}) \qquad (4.7)$$

The change is proportional to gradient in error space. In other words, Eqn. (4.7) can be rewritten as

$$\Delta w_{ij} = \eta \delta_i u_j; \qquad (4.8)$$

where:

u_j: unit j output signal from unit j to unit i;

η: positive constant that indicates step size (learning rate);

δ_i: the error gradient at unit i;

The error gradient δ_i is decided by the unit i location and is given by:

- If the unit i is the output unit and T_i is the target output

$$\delta_i = f'(S_i)(T_i - u_i) \tag{4.9}$$

$$\delta_i = f(S_i)(1 - f(S_i))(T_i - u_i) \tag{4.10}$$

- If the unit i is the hidden unit

$$\delta_i = f'(S_i)\sum_h \delta_h w_{hi} \tag{4.11}$$

$$\delta_i = f(S_i)(1 - f(S_i)) \sum_h \delta_h w_{hi} \tag{4.12}$$

where:

δ_h: is the error gradient at unit h to which a connection points from unit i to hidden unit h.

Moreover, considering a momentum term to improve convergence characteristics, Eqn. (4.8) becomes:

$$\Delta w_{ij}(t) = \eta\delta_i u_j + \beta\Delta wij(t-1) \tag{4.13}$$

the new weight becomes

$$w_{ij}(t+1) = W_{ij}(t) + \eta\delta_i u_j + \beta\Delta w_{ij}(t-1) \tag{4.14}$$

where:

β: is positive constant that adjusts the momentum term.

The procedures mentioned above are repeated until convergence in terms of the selected error criterion so that the errors E_p are minimized. A repeated iteration includes presenting an instance, calculating activation, and modifying weights.

Incorrect local minima can be recognized by failure to converge to the desired output pattern during the training process. In this case, the gradient descent is started over again using new initial values for w_{ij}. The learning rate, η, and the momentum term, β, are between 0 and 1.0 to be determined by experience.

The name "back-propagation" comes from the fact that the error (gradient) of hidden units are derived from propagating backward the errors associated with output units since the target values for the hidden units are not given. In the back-propagation network, the activation function chosen is the sigmoid function, which compresses the output value into the range between 0 and 1. The sigmoid function is advantageous in that it can accommodate large signals without saturation while allowing the passing of small signals without excessive attenuation. Also, it is a smooth function so that gradients can be calculated, which are required for gradient descent search.

In order for a neural network to learn the "rules" for solving a problem, data sets describing the problem must be given. These data sets consist of input vectors and desired, or target, output vectors for each input vector. A full training set for a neural network describes the full range of expected inputs and desired outputs.

§4.5 Summary

The strategy presented in this chapter is a new technique by recent developments in parallel distributed processing, or connections theory. Neural network processing is distinguished from signal processing by the capability for nonlinear interpolation. Modern signal processing techniques perform linear interpolation of input signals. That is, when an unfamiliar input is presented to an adaptive filter, the corresponding output depends on some hyperplane between output for known inputs. In contrast, when a neural network is fully trained, it is capable of mapping an unfamiliar input vector to an arbitrary surface. In other works, a neural net generalizes general criterion instead of performing circulating searching. It can be used to classify patterns by selecting the output which best represents an unfamiliar (unknown) input pattern in cases where an exact input-output functional relationship is not easily defined.

In this chapter, the neural network structure, the operating principles and its advantage was introduced. The training algorithm, back-propagation learning technique was described. In the following chapter, a new method will be proposed using the ANN to discriminate between the magnetizing inrush and internal fault during the transformer protection.

CHAPTER 5

USING A NEURAL NETWORK FOR TRANSFORMER PROTECTION

§5.1. Introduction

A transformer can draw large transient magnetizing inrush currents when it is connected to a power supply because of its non-linear magnetization characteristic. Therefore, a transformer protection scheme has to take into account the effect of magnetizing inrush current, since this effect may cause mis-operation of the relay. The traditional method used to avoid undesired tripping due to the inrush current was to slow down the relaying during start-up conditions. Slowing the protection is unacceptable because of physical damage. Magnetizing inrush currents are rich in harmonic contents whereas internal faults mainly contain fundamental frequencies only. Therefore, modern differential relays use restraining (or blocking) of the relay operation according to the harmonic content of the current.

Different blocking schemes, such as second harmonic or total harmonic are used. However each harmonic restraint relay requires a setting to compare the relative level of the harmonic component with reference to the fundamental frequency component. When the relative level of harmonic component is greater than the setting, an inrush condition is identified and the operation of the relay is restrained. This setting is generally decided by the relay application engineer based on his experience and established rules-of-thumb. An incorrect setting can cause either false trippings during switching conditions or no tripping during some internal faults, especially when the transformer is connected to the receiving end of a long transmission line [2,4].

Digital relays are now becoming commercially available. This thesis contains a description of an artificial neural network (ANN) based inrush detector suitable for use in digital differential relays. This inrush detector avoids the relay setting problem.

This chapter first provides a brief introduction of the proposed digital transformer protection with an ANN-based inrush detector. A sample power network used for training and testing the ANN is then explained. The focus of the work reported herein is on the training and testing of the ANN. The results presented show that the designed ANN inrush detector can be used to distinguish between inrush and no-inrush currents.

§ 5.2. ANN-Based Inrush Detector

Figure 5.1 gives a functional block diagram of the proposed digital differential relay for power transformer protection. The ANN-based inrush detector is a part of the relay. The current transformer secondary currents are first passed through an analog low-pass filter which must have a cut-off frequency less than half the sampling frequency to avoid aliasing. The low-pass filtered currents are sampled and then digitized. The digitized samples of both primary and secondary currents are used to implement the differential relay algorithm. The differential relay algorithm is well known and is not part of this project. In the proposed scheme, only primary currents are used in the inrush detector, which is comprised of a pre-processor and an ANN. The use of primary currents will make it a general purpose inrush detector which could be used in conjunction with other devices, such as an overcurrent relay.

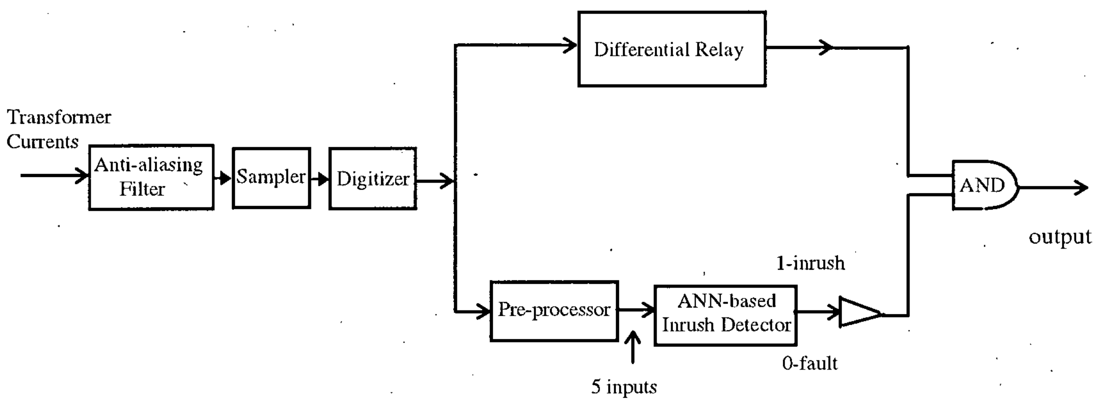


Figure 5.1. Simplified Block Diagram of the Implementation of the ANN-based Inrush Detector Function

In previously reported work [5] raw data samples were used as inputs to the ANN-based inrush detector. In this project, however, a pre-processor is used instead of directly applying raw samples. The pre-processor includes a discrete Fourier transform (DFT) [3] based filter and an amplitude estimator, which extracts the magnitudes of fundamental and up to fifth harmonic components of the input. The outputs of the pre-processor are applied as inputs to the ANN. The use of a pre-processor reduces the number of inputs to the ANN, thereby, reducing the training data and training time. The outputs of the ANN and the differential relay in practice would be applied to an AND gate to produce an output so as to trip or restrain the relay operation.

§5.3. Building a Sample Power Network

As mentioned above, the ANN-based inrush detector needed to be trained. A one line diagram of the sample power network for generating input patterns for training and testing the ANN-based inrush detector is given in Figure 5.2. The data for the transmission lines, the voltage sources, the modeled transformer along with its current-flux characteristic and loads are given in Appendix A. Training cases were generated through the use of the Electromagnetic Transients program (EMTP) [29]. Switches shown in the figure could be arranged to close and open at specified times for simulating different power system operations discussed later in this section. It should be noted that the system simulated in Figure 5.2. is a single-phase circuit, because the main aim of this project was to demonstrate ANN-based relay rather than to perform a detailed simulation of the power system.

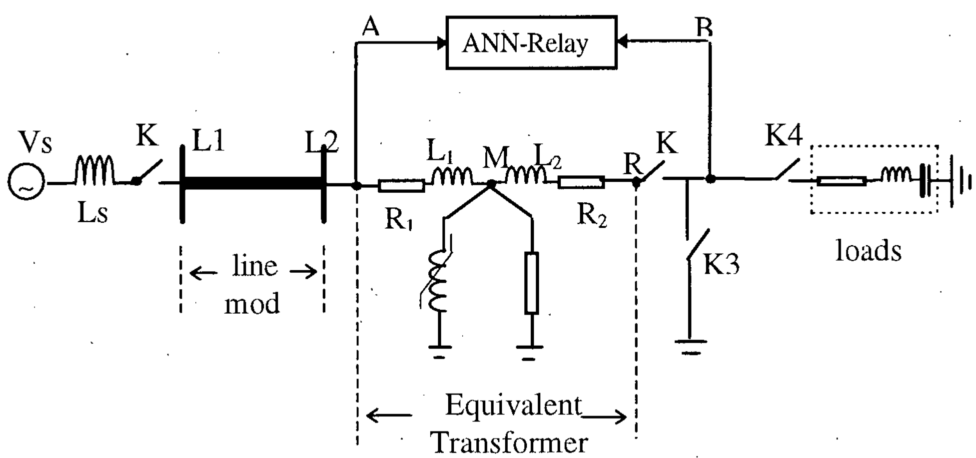


Figure 5.2. A One Line Diagram of the Sample Power System

The relay R_{AB} is an ANN-based relay that is simulated to study the proposed technique. Its function is to protect the transformer from faults that occur in the region from A to B. Faults that occur within this detection zone should cause the relay to operate the circuit breaker to disconnect the short circuit. Faults outside of the protection zone need to be removed as well, however the relay R_{AB} will not be responsible for this task. The function of ANN-based detector is to restrain the operation of the relay in the presence of large magnetizing inrush currents, which incorrectly appear as fault currents at the relay R_{AB}.

Since a typical power system includes constantly changing loads, tap-changing, switching at an arbitrary time and load switching, so various transients and other time-varying phenomena were simulated on a version of the EMTP program. Four types of cases were simulated as follows:

1. Inrush current by closing Switch K1 with Switches K2, K3 and K4 open.
2. Internal fault by closing Switch K2 with Switches K1 and K3 closed, and K4 open.
3. Fault including inrush current by closing Switch K1 with Switches K2 and K3 closed and K4 open.
4. Steady-state loads with Switches K1, K2 and K4 closed and K3 open.

A total of about 335 cases were simulated for all types of fault, inrush and load currents.

§ 5.4. Selection of Neural Network Input Data

For the training and testing pattern, the ANN had to be provided with a sufficient number of training and test cases. Even with a small network such as in Figure 5.2, there is still a large number of possible fault, inrush and load cases to be considered. Especially, the inrush current can vary with location of switch (K1) closing at the point on the waveform of 60 Hz source voltage. From all the possibilities, a reasonable subset had to be chosen for presenting to the neural network to avoid excessive training time. From the presented subset, the ANN-based inrush detector has to be able to make correct generalizations when confronted with a new and unknown situation.

The four types of cases previously mentioned were simulated on the EMTP. The integration time-step used was 83.33 micro-second (i.e. 1/12000 second) providing 200 samples in a 60 Hz cycle. Appendix A includes a typical EMTP data file that was used for generating inrush current.

Inrush Currents:

Inrush current drawn by the transformer varies with the phase angle of the applied voltage, which was controlled by changing the closing instant of Switch K1. A total of 210 inrush cases was simulated. The first 100 cases covered equi-space phase angles of the applied voltage between 0° and 180°. Because of waveform symmetry, only 5 cases were simulated between 180° and 360° spaced at every 45°. The data obtained in this manner included boundary cases of minimum inrush at 90° and 270° [13]. The remaining 105 inrush cases were obtained by repeating the above sequence except that, the transformer was connected to the sending end of the line instead of receiving end as shown in Figure 5.2. Some typical inrush waves from the EMTP are shown in Figure 5.3. Part (a) of the figure shows the most common inrush current waveform; Part (b) shows no inrush current, which is a boundary case at 90°; Part (c) shows inrush current and line transients with switching angle of applied voltage at 0°; Part (d) shows line transients with little inrush current as switch was closed at 90°. In simulations for Parts (a) and (b) the transformer was connected to the sending end and for Parts (c) and (d) the receiving end of the line. Table 5.1 shows the amplitude spectrum up to fifth harmonic component of these four waveforms. Pure inrush has considerable second harmonic content. In the case of the line transient (part (d)), the third harmonic is greater than the fundamental frequency because of resonance caused by the combined inductances of line, source and transformer with the line capacitance.

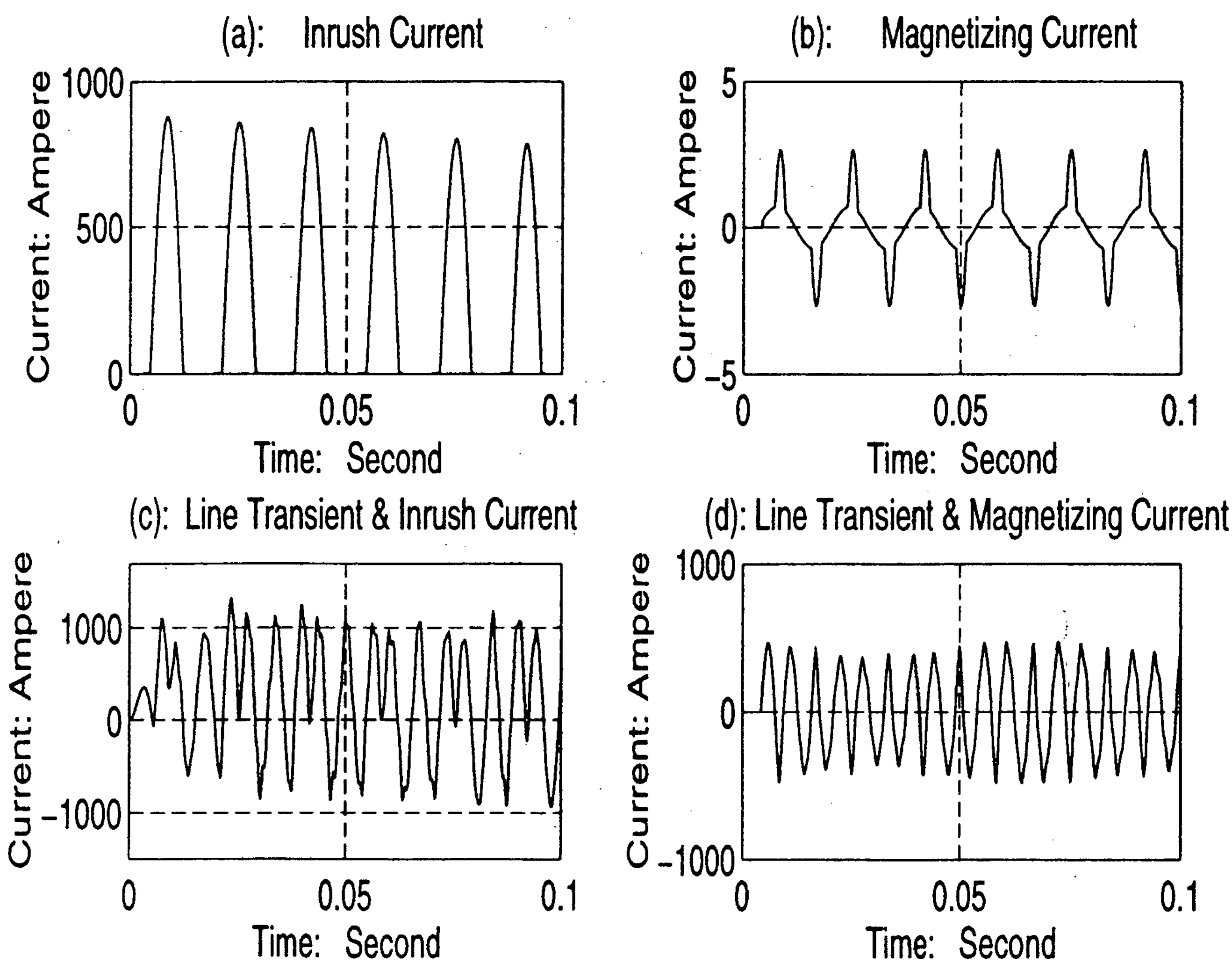


Figure 5.3: Typical Inrush Current Waveforms

The current shown in Figure 5.3 (b) is steady-state magnetizing current drawn by the transformer. This current is always presented even after switching transients die out. Its magnitude is too low (less than 1% of full load transformer current) to cause any mis-operation of the protection relays. Therefore, the neural network must recognize steady-state current (or currents drawn when phase angles of applied voltage are 90° and 270°) as non-inrush conditions [13].

Table 5.1: Amplitudes of Harmonics in Figure 5.3.

Harmonic Component	Harmonic Analysis of Waveforms in Figure 5.3. (Normalized to Fundamental Component)			
	a	b	c	d
Fundamental	1	1	1	1
Second	4.97807e-1	2.92205e-2	6.22802e-1	3.55754e-1
Third	1.65741e-1	3.24236e-2	1.11194e-1	3.30986e+0
Fourth	2.85803e-1	3.92130e-2	6.32364e-2	7.92762e-2
Fifth	1.18749e-2	5.72243e-2	1.87622e-2	6.81242e-1

***Internal Faults*:**

A total of 50 cases representing internal faults was simulated by varying the phase angle of the fault voltage, which was controlled by changing the closing instant of Switch K2. The first 20 cases covered equi-space phase angles of the fault voltage between 0° and 180° and another five cases covered between 180° and 360°. Again the remaining 25 cases were obtained by connecting the transformer to the sending end of the line. Two typical internal fault current waveforms are shown in Figure 5.4. Part (a) of this figure is the internal fault when the transformer was connected to the receiving end of the line and Part (b) is when it was connected to the sending end of line. In both cases, the voltage angle was 90° at the instant of fault application.

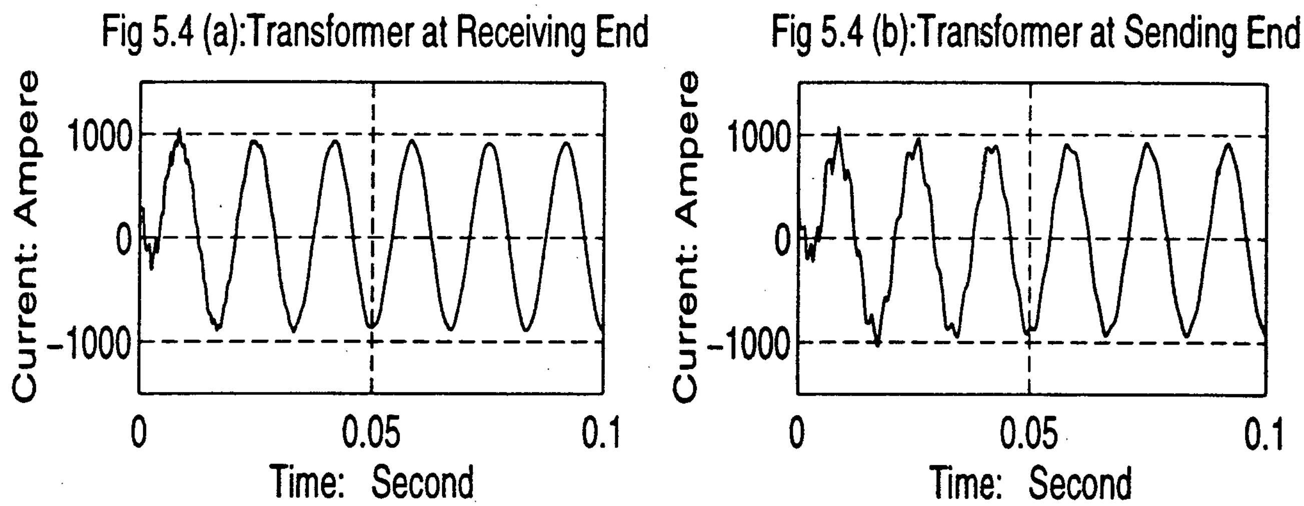


Figure 5.4: Typical Internal Faults

Inrush with internal faults:

A total of 50 cases was simulated identical to the internal fault except the phase angles of the applied voltage were equi-spaced instead of fault voltage. The phase angles were varied by controlling the time of closing Switch K1 with Switches K2 and K3 always closed. Figure 5.5 shows the inrush with internal faults current waveforms when the transformer was on the receiving and sending ends of the line. For Part (a) the phase angle of the applied voltage was 45° at switching instant and for Part (b) it was at 90°.

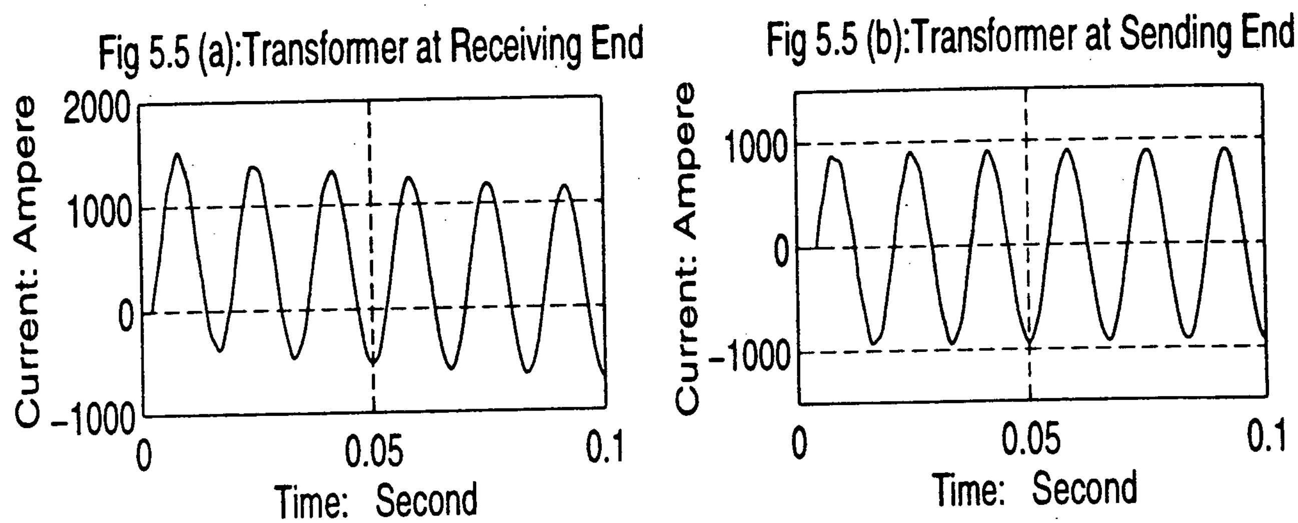


Figure 5.5: Two Typical Fault with Inrush Conditions

Load:

25 load cases were simulated with different combinations of resistances, inductances and capacitances. A typical load waveforms from EMTP is shown in Figure 5.6.

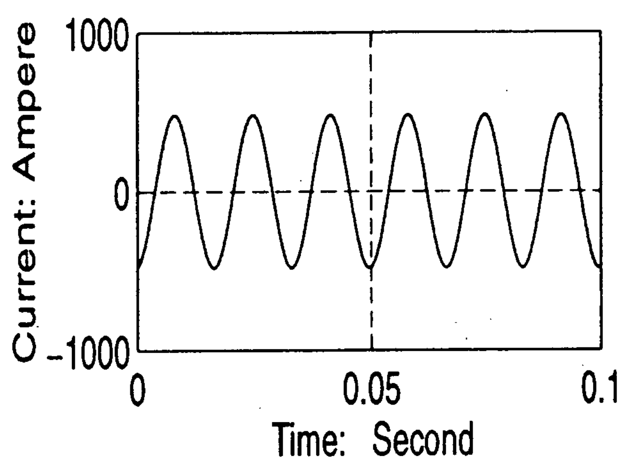


Figure 5.6: A Typical Steady-state Load Current

As discussed in section 5.2, the proposed ANN-based inrush detector uses magnitudes of fundamental up to fifth harmonic frequencies components of the input current. To avoid aliasing [3,20], it would require a minimum sampling rate of 600 samples/sec based on a 60 Hz fundamental. It was decided that for reasons of numerical accuracy, the sampling rate would be 1200 samples/sec or 20 samples for one 60 Hz period, or 4 samples per 5th harmonic period which more than adequately satisfied the Nyquists criterion [3]. In the simulations performed, the EMTP output produced 12000samples/sec. Before converting the data to the lower sampling frequency, it was processed by a 2nd order low-pass digital Butterworth filter [3,4] with a cut-off frequency 360 Hz. This filtered data was converted to a lower rate of 1200samples/sec samples by taking every tenth sample. In practice the input signal would be the analogue current from the CTs. In that case an analogue 2nd order Butterworth filter would precede the sampling circuit and analogue-to-digital (A/D) converter to avoid aliasing.

Another aspect that had to be considered is the number of current samples which will be applied to the relay. The time interval from the beginning of a fault to the interruption of the short circuit by the breaker should be very fast as required by power utilities. A time of one cycle is considered to be a fast response time for a differential relay, i.e. 16.67 ms in a 60 Hz network. Therefore, all simulations were performed using data samples acquired over the first significant cycle (20 samples). In practice the digital relay would use a moving window of 20 data samples. This data window would be updated by incorporating the latest sample and discarding the oldest sample.

The pre-processor of the proposed inrush detector includes a one cycle DFT-based filter and amplitude estimator which uses 20 samples in order to find the magnitude of the fundamental, and 2nd to 5th harmonics frequencies.

§5.5 Training and Testing File

All 335 cases were simulated on the EMTP using current in the primary winding of the transformer. For each case this current was low-pass filtered and re-sampled. The first significant cycle (20 samples) of data was given to the pre-processor, which provided five outputs representing fundamental and harmonic components of the currents. The outputs of the pre-processor were given as inputs to the ANN, whose desired output is either 0 for a no-inrush or 1 for an inrush current. From each simulation case, five inputs and one desired output formed a training or test vector. These vectors were split and written into two files called training and testing. Enough numbers of training cases had to be chosen for the ANN to generalize the pattern. For this particular study, approximately 23.8% of magnetizing inrush current cases (i.e. 50 cases) for output 1; 36% of the no-inrush cases (i.e. 45 cases) for output 0 were provided to the ANN-based inrush detector for training purpose. The remaining cases were used for the testing.

§5.6 Building and Training an ANN-Based Inrush Detector

A UNIX-based Neural Network computer program, XERION[30], was used to simulate the proposed ANN inrush detector. A feed forward ANN was built. The input layer of the network had five nodes to receive the outputs of the pre-processor. The output layer had a single node for indicating inrush or no-inrush condition corresponding to the inputs. The number of hidden layers and their sizes were determined heuristically, and which involved training and testing of different network configurations. A back-propagation algorithm was selected to train the network.

For each input/output vector in the training set, the algorithm computes changes in the network's weights that minimize the difference between the target output and that resulting from forward propagation of the vector's input signals. The entire training set is repeatedly passed through the neural net until the weights minimize output errors for all input/output vectors. Since these vectors were presented randomly, the weights should be capable of producing an output, for new input signals, that is similar in the value to targets specified for similar input vectors in the training set.

A number of networks having different structures were trained and tested. The neural network finally selected for this application had five nodes in the input layer, three nodes in the hidden layer and one node in the output layer. The network required eighteen weights and one bias node for full interconnection. Figure 5.7 below shows the ANN as it was designed for recognizing the inrush current.

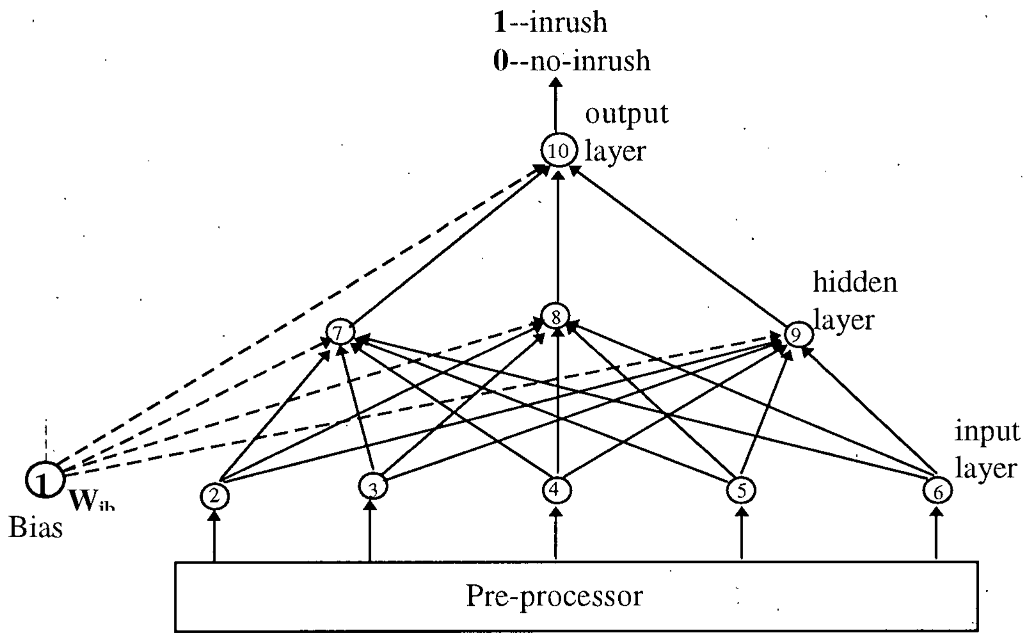


Figure 5.7: ANN Inrush Detector Architecture

The Sigmoid function, $f(z)=(1+e^{-z})^{-1}$, was chosen to be the transfer function for each node, because it helps in producing an arbitrary decision boundary with smooth curves and edges. The error threshold was set to 10% because in practice, a target tolerance of 0.1 was used, meaning that the network was trained to produce a response of 0.9 or greater to represent one class and 0.1 or less to represent the other class. This is necessary because the nature of the nonlinear Sigmoid function is such that it can never assume the precise values of 0.0 or 1.0.

In the training process for the neural network, a training run was initially tried assuming default values for learning rate,η, and momentum factor, β, with the error threshold set to 10%. The initial weights and bias thresholds were randomly selected about a very small number in the interval [-0.001, +0.001]. During the iterations, an exponential decrease of the root-mean-square (RMS.) error was noticed. After about 125 iterations the small oscillations in the error had vanished, and after some further iterations the error had converged to about 15%. There was no possibility that the error would decrease any further. For this reason conditions were changed in order to obtain a better result. In an extensive step-by-step learning procedure, network parameters such as learning rate, momentum factor and so on were varied successively until a reasonable convergence was achieved. Instead of using the default values, the parameters in the training process were the learning rate, which was varied from 0.2 to 0.8, and the momentum factor, which was set to 0.9 (constant). This time the ANN converged more rapidly (50 iterations) and the convergence was better than 10%. At this stage it was discovered that the neural network had a fault. It should have automatically normalized the inputs to a maximum value of unity to avoid saturation. To overcome the problem the inputs were normalized to the fundamental frequency component. The ANN now converged relatively quickly (23 iterations) with good results. Under certain conditions the fundamental may be smaller than one of the harmonics in which case saturation of the ANN would still occur. This happened, amongst other, when switching a long line connected to the transformer. The natural frequency was such that in the first cycle after switching the third harmonic was greater than the fundamental. Thus a further improvement in the speed of convergence was achieved when the inputs were normalized to the largest harmonic component. The ANN network converged in 8 iterations also providing outstanding results at the output node. The following Figure 5.8 shows the back-propagation network in its final form. The

RMS. error diagram shows the convergence of the error to a threshold of 0.005 during the 8 iterations.

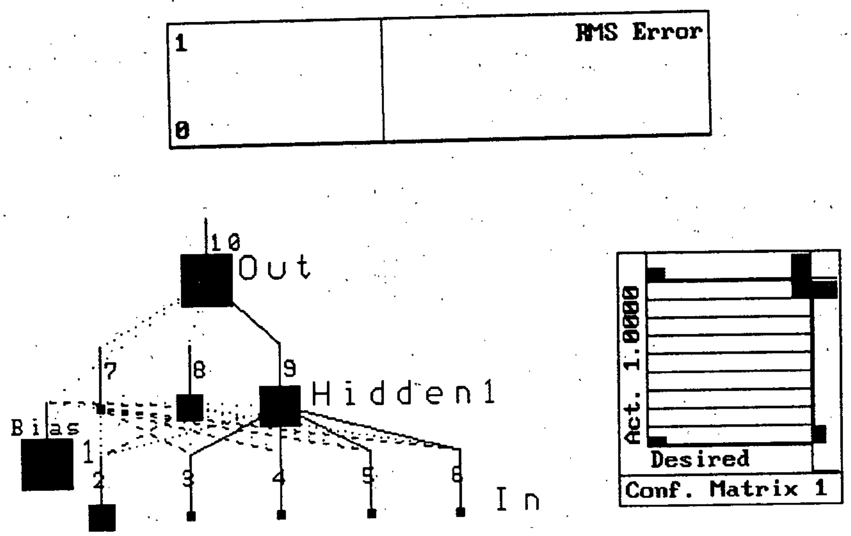


Figure 5.8: The structure of the ANN and convergence diagram

Table 5.2 shows the weights and bias values of the finally trained network. The training patterns with the actual outputs in Appendix B show that this simple ANN is able to discriminate between magnetizing inrush currents and fault currents.

Table 5.2: Artificial Neural Network Weights:

Bias node 1	input node / hidden node	2	3	4	5	6	10
0.29135	7	-4.32297	7.88459	10.8335	6.14422	1.84539	9.17310
0.07035	8	-1.97146	3.97913	5.87728	4.08063	0.44325	11.1841
4.37733	9	0.08288	6.91473	10.5944	6.30884	1.72951	-18.7156
7.25727	10	NC	NC	NC	NC	NC	output
NC - No Connection							

Once the network had been trained to the desired accuracy, back propagation was disabled, weights and bias of the ANN were fixed. The next step was to test the network with cases which were not contained in the training set.

§5.7 Testing of the ANN-Based Inrush Detector

It was necessary for the network to be able to generalize the situation from the provided training patterns and correctly identify the magnetizing inrush and no-inrush conditions. After the neural network was trained, it was tested for four conditions: fault currents, fault with inrush currents, loads and inrush currents only.

The testing was done with unfamiliar input vectors, 66.6% of which were magnetizing inrush currents. As discussed in section 5.5, the data for all tests were prepared in the same manner as those in the training set normalized to the largest of the input components and then presented to the ANN for testing using a test file. Unlike the training process, the detection required no iterations and only one input vector was given to the network at any one time.

Column 3 of Table 5.3 summarizes a few typical results selected from a number of test runs (i.e. Fig 5.3 to Fig 5.6).

Table 5.3: Test Results of The ANN-based Inrush Detector:

case # \ output	Target Output	Actual Output	Step-Function
Fig. 5.3 (a) Inrush Current	1	9.99464e-1	1
* Fig. 5.3 (b) Magnetizing Current	0	1.53840e-4	0
Fig. 5.3 (c) Inrush Current	1	9.99826e-1	1
Fig. 5.3 (d) Inrush Current	1	9.99860e-1	1
Fig. 5.4 (a) Internal Fault	0	7.03335e-5	0
Fig. 5.4 (b) Internal Fault	0	6.98566e-5	0
Fig.5.5(a)Internal Fault with Inrush	0	1.01864e-4	0
Fig.5.5(b)Internal Fault with Inrush	0	9.50694e-5	0
Fig. 5.6 Load	0	1.00017e-4	0
* Magnetizing current drawn when phase angle of the voltage is 90° at switch instant (steady-state inrush current)			

As can be seen in the table, the actual output values of the ANN correspond very closely to the desired output values. It can also be seen that the magnetizing current is correctly recognized as a non-inrush condition. It demonstrates the excellent capability of the network in recognizing the inrush current because steady-state magnetizing currents were not used as inputs during the training process. The table shows a few cases of particular interest. For completeness all test results are presented in Appendix C.

Once the networks with sigmoid function were trained and tested with good results, the output node's transfer function was changed to a step-function. This change increases the neural network computation speed since it takes less computation time to implement a unit step than a sigmoid. In fact a step function is equivalent to an IF statement. The implicit risk in this change is that in certain cases the approximation of the sigmoid by a unit step could produce an unexpected error. The results of the step-function are listed in Column 4 of the Table 5.3. The results also indicate that the ANN-based inrush detector is fairly efficiently after the output node's transfer function has been changed to a step-function.

§5.8 Summary

This chapter summarizes a new method for detecting the inrush current in transformer protection described in the thesis so for. This is based on recognizing the magnetizing inrush current waveform, by including the second up to the fifth harmonic component from the fault.

A feed forward neural network (FFNN) has been trained to discriminate between power transformer magnetizing inrush and fault currents. The training algorithm used here is back propagation learning technique. The differential relay measures the transformer primary current to indicate whether the transformer is experiencing an abnormal condition or not; the ANN-based inrush detector will identify the fault or inrush current and produce an output to determine whether the circuit breaker will be allowed to be opened or not. Five inputs were used to accept the magnitude of fundamental and up to fifth harmonics in the primary transformer current and one output represents the operation of the relay (1 to trip and 0 not to trip the circuit breaker).

In this chapter, the building of a sample network and how to select the input data used as training and testing files were explained. A new proposed ANN-based inrush detector was then presented. The emphasis was on the training and testing process of the ANN. Both the training and testing outputs indicated that this new approach can produce good performance for inrush and discrimination. This new approach should be verified on a real transformer from field test data. This process will be explained in the next chapter.

CHAPTER 6

FIELD TESTS AND RESULTS

§6.1 Introduction

An ANN-based inrush detector was successfully trained and tested, as described in Chapter 5, using the data generated by the EMTP. This network accepts five inputs, which are normalized to the highest magnitude frequency component. During testing, the network provided correct outputs as 1 for inrush and 0 for non-inrush conditions. Generalization ability of this network was tested using actual data acquired from a laboratory transformer. This chapter reports the testing results when the network was tested using laboratory acquired data.

§6.2 Field Data

In 1989, an experiment consisting of a three-phase 15 kVA, 240/480 V, delta-wye transformer was set up in the laboratory at the University of Saskatchewan for testing the differential and ground fault relays [4]. Figure 6.1 shows the schematic diagram of the set up used. The primary side of the transformer was connected to a 240 V three-phase supply system. The line cts, provided on transformer terminals, were interfaced with the isolation and scaling block of the data acquisition system. A miniature circuit breaker (MCB) was connected between the supply and transformer to disconnect supply and thus prevent any damage caused to the transformer due to excessive fault currents. A second MCB was connected in the short circuit paths. Inrush currents were generated by closing the first MCB and the fault by closing the second MCB.

Using the experimental set up and data acquisition software, transformer currents were acquired for various operating conditions and stored in data files which included inrush currents, winding faults, and simultaneous inrush and fault condition. Each test provided three primary currents (three-phase currents). Since the ANN discussed in Chapter 5 operates on single-phase current, therefore, currents recorded from each test were treated as three single-phase currents.

The recorded data included: a) 12 cases of inrush conditions, b) 20 cases of winding faults and c) 9 cases of simultaneous inrush and fault currents. Appendix D shows the current waveforms recorded for all cases. The data were recorded at 4800 Hz.

Since the pre-processor of the proposed ANN-based detector accepts data at 1200 Hz, the recorded data were decimated by taking every fourth sampling value. Before decimation, it was low-pass filtered using a second order digital Butterworth filter which had a cut-off frequency 360 Hz. After low-pass filtering and decimating, the first significant cycle (20-samples) of the recorded data were given as an input to the pre-processor. The pre-processor provided the fundamental and harmonic frequency components of the current. For each test, a component with maximum magnitude was used to normalize the all components. The performance of the ANN was then checked by comparing its outputs with the desired outputs. Figure 6.1 shows the testing process in flow-chart form.

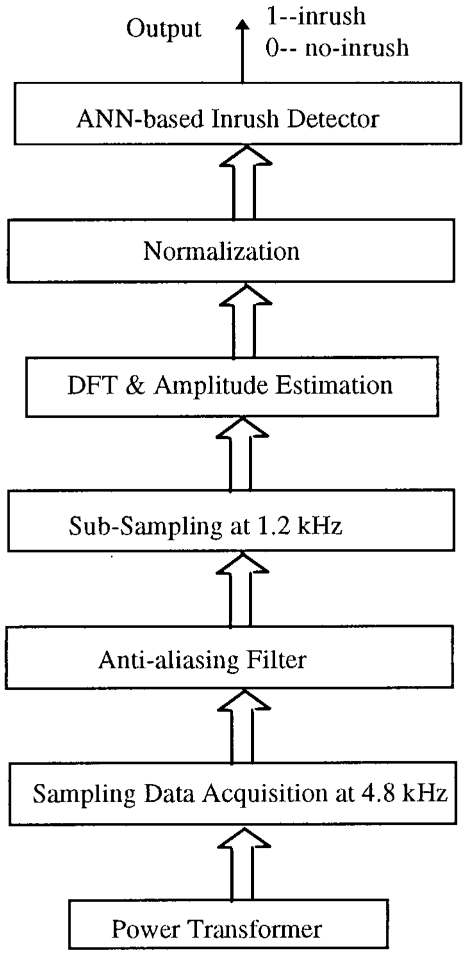


Figure 6.1: Testing Process

§6.3 Test Results

As discussed in the previous section, the ANN-based inrush detector's ability was tested using data acquired from laboratory transformer. Some results showing the performance of the ANN discriminator are presented here.

Inrush Current Condition:

Two examples of typical inrush currents obtained from the test are shown in Figure 6.2. It can be seen from Figure 6.2, the transformer was switched at approximately 16.67 ms. One cycle (20-samples) from switching instant were used as input to the pre-processor whose outputs were normalized to the highest component and given to the ANN. Test results from all inrush condition are shown in Table 6.1. In Table 6.1, Column 1 shows the nature of the test currents, Column 2 shows the desired output, Column 3 contains the actual output of network and Column 4 gives the ANN response when the transfer function in the output was changed to a step-function after the training process. As shown in Columns 3 and 4, the ANN produced the correct results for every inrush case.

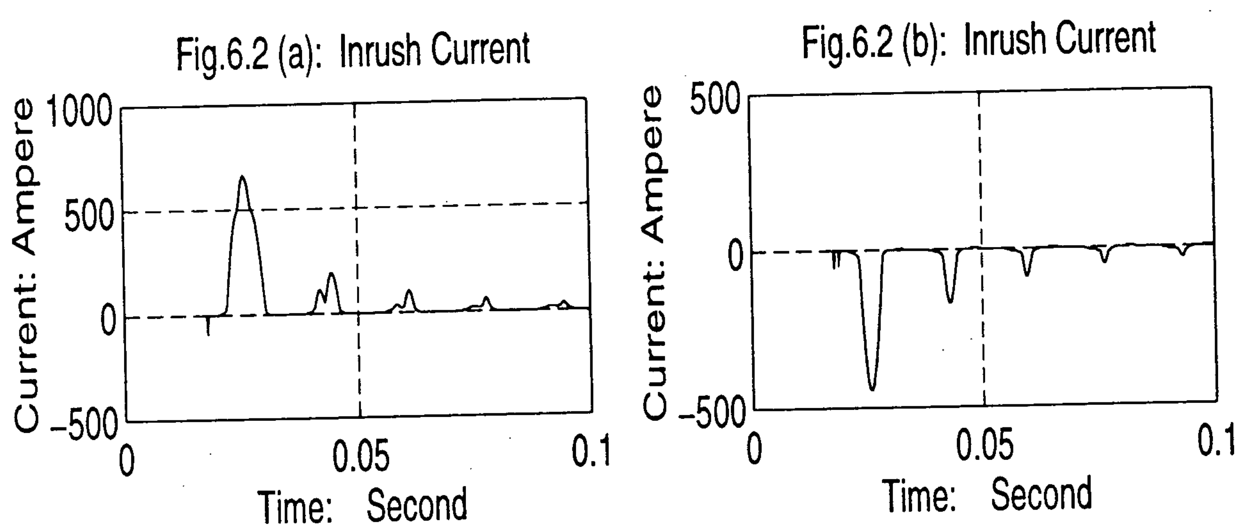


Figure 6.2: Two Typical Inrush Currents Recorded from Field Test

Table 6.1: Test Results of the Inrush Currents as Shown in Appendix D.

Inrush Current	Target Output "1"	ANN Actual Output	Step-Function
Inrush Current Fig.D.1	1	0.9957	1
Inrush Current Fig.D.2	1	0.9999	1
Inrush Current Fig.D.3	1	0.9999	1
Inrush Current Fig.D.4	1	0.9998	1
Inrush Current Fig.D.5	1	0.9992	1
Inrush Current Fig.D.6	1	0.9999	1
Inrush Current Fig.D.7	1	1.0000	1
Inrush Current Fig.D.8	1	1.0000	1
Inrush Current Fig.D.9	1	1.0000	1
Inrush Current Fig.D.10	1	0.9990	1
Inrush Current Fig.D.11	1	1.0000	1
Inrush Current Fig.D.12	1	0.9999	1

Winding Faults:

Two typical of primary currents recorded for transformer winding fault are shown in Figure 6.3. The fault was applied at approximately 16.67 ms by shorting 10% and 7.5% of the secondary winding. One cycle (20-samples) from switching instant were used as input to the pre-processor whose outputs were normalized to the highest component and given as inputs to the ANN. Test results from winding faults are shown in Table 6.2.

In Table 6.2, Column 1 shows nature of test currents, Column 2 shows the desired output 1, Column 3 contains the actual output of network and Column 4 gives the ANN response when the transfer function in the output layer was changed to a step-function after the training process. As shown in Column 3 and Column 4, the results indicate that ANN-based detector performed as required.

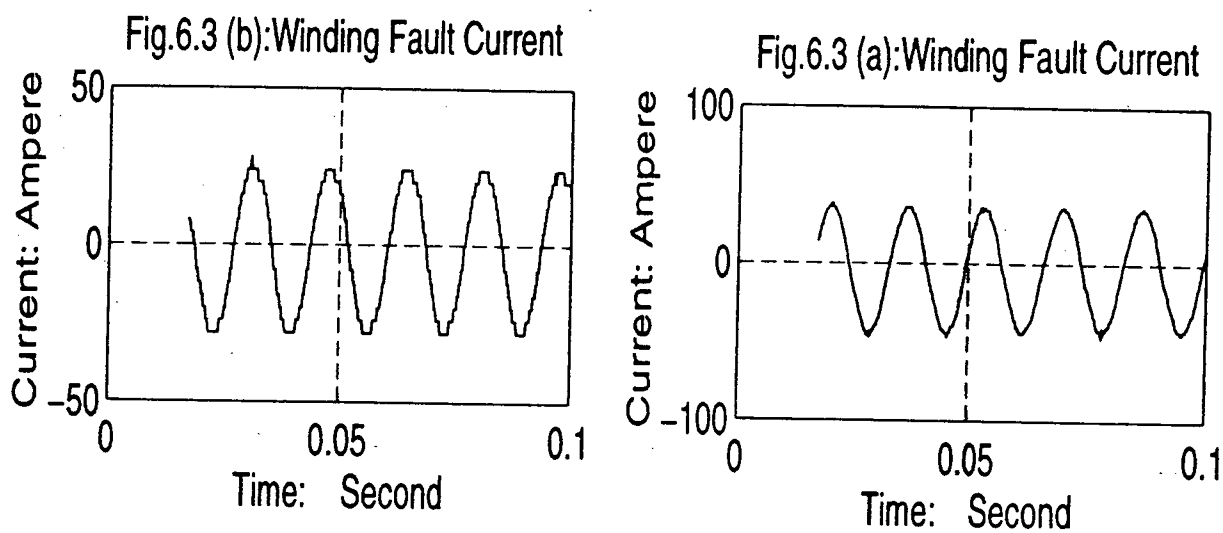


Figure 6.3: Two Typical Winding Faults Recorded from Field Test

Table 6.2: Testing Results of the Winding Faults Currents as Shown in Appendix D.

Winding Fault	Target Output "1"	ANN Actual Output	Step-Function
Winding Fault Fig.D.13	0	0.0006	0
Winding Fault Fig.D.14	0	0.0003	0
Winding Fault Fig.D.15	0	0.0005	0
Winding Fault Fig.D.16	0	0.0001	0
Winding Fault Fig.D.17	0	0.0003	0
Winding Fault Fig.D.18	0	0.0003	0
Winding Fault Fig.D.19	0	0.0003	0
Winding Fault Fig.D.20	0	0.0004	0
Winding Fault Fig.D.21	0	0.0003	0
Winding Fault Fig.D.22	0	0.0003	0
Winding Fault Fig.D.23	0	0.0003	0
Winding Fault Fig.D.24	0	0.0003	0
Winding Fault Fig.D.25	0	0.0003	0
Winding Fault Fig.D.26	0	0.0004	0
Winding Fault Fig.D.27	0	0.0003	0
Winding Fault Fig.D.28	0	0.0003	0
Winding Fault Fig.D.29	0	0.0004	0
Winding Fault Fig.D.30	0	0.0003	0
Winding Fault Fig.D.31	0	0.0003	0
Winding Fault Fig.D.32	0	0.0003	0

Simultaneous Internal Fault and Inrush Condition:

Two typical waveforms of simultaneous internal fault and inrush current are shown in Figure 6.4. The first waveform shows the case of 100% secondary winding shorted through a 1.4 Ω resistor and the second waveform shows the case of 10% of the secondary winding shorted. The transformer was switched at approximately 16.67 ms with faults already on it. One complete cycle (20-samples) from switch instant were applied as inputs to the pre-processor whose outputs were normalized to the highest component and given to the ANN. Table 6.3. shows the test results of the simultaneous fault and inrush condition. Column 3 and Column 4 of the Table 6.3 indicate that the ANN-based detector also produces the correct results except for case 8 and case 9. Case 9 corresponds to the second current waveform shown in Part (b) of Figure 6.4 and case 8 is shown in Figure D.40 in Appendix D. However, for both case 8 and case 9, the outputs of ANN can become close to 0 when 20-samples after time delaying 4.1667 ms from switching instant were used which is acceptable in practice.

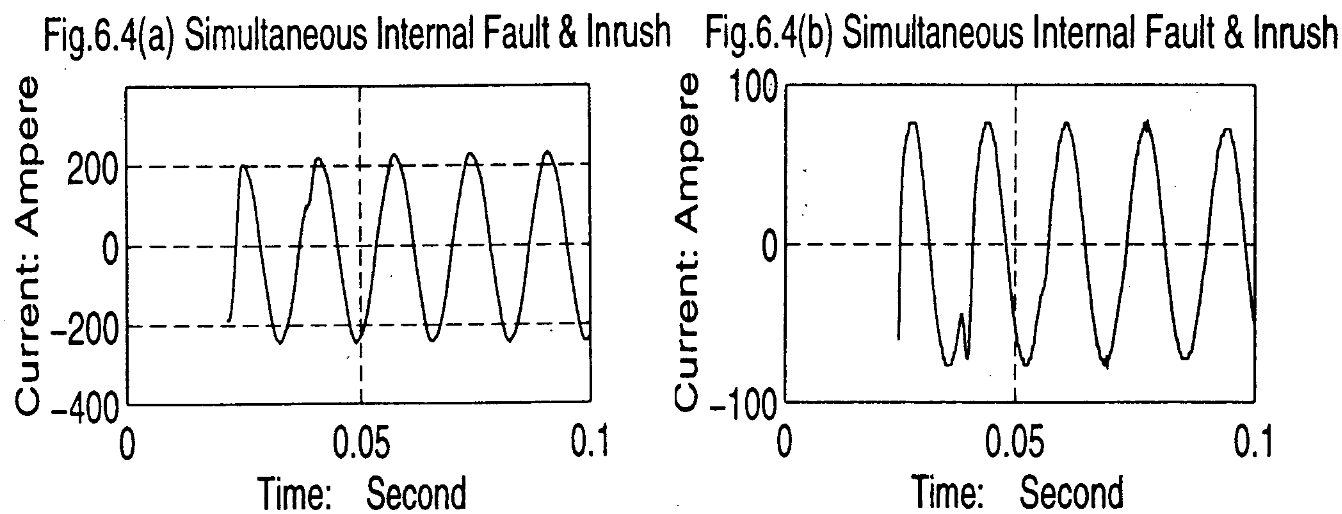


Figure 6.4: Two Simultaneous Fault with Inrush Currents Recorded from Field Test

Table 6.3 Testing Results of the Simultaneous Fault and Inrush as Shown in Appendix D.

Fault with Inrush	Target Output "1"	ANN Actual Output	Step-Function
Fault with Inrush FigD.33	0	0.0003	0
Fault with Inrush FigD.34	0	0.0003	0
Fault with Inrush FigD.35	0	0.0005	0
Fault with Inrush FigD.36	0	0.0001	0
Fault with Inrush FigD.37	0	0.0005	0
Fault with Inrush FigD.38	0	0.0005	0
Fault with Inrush FigD.39	0	0.0005	0
Fault with Inrush FigD.40	0	0.3678	0
Fault with Inrush FigD.41	0	0.3519	0
**** Delaying FigD.40***	**0**	**0.0002**	**0**
**** Delaying FigD.41***	**0**	**0.0004**	**0**
**** Delaying Fig.D40 and Fig.D41*** are the fault with inrush cases of Fig.D40 and Fig.D41 with the time delay 1/4 cycle (i.e. 4.1667 ms) and ANN produces the good results			

§6.4 Summary

Field test data used from a laboratory transformer and the data generated from the EMTP program used in chapter 5 were applied to the ANN-based inrush detector. The results show that the ANN discriminates between magnetizing inrush and fault currents correctly and efficiently for transformer protection.

This emphasizes the capability of the ANN-based inrush detector to perform correctly and reliably on both field data and simulated data from the EMTP program.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

Because of the large power capacity of modern power systems, a fault can cause extensive damage to equipment. For this reason, reliable protective devices must be provided in order to minimize the damage to the equipment and remove faults as speedily as possible when failure occurs. Besides being reliable, these devices must also be secure to avoid removal of the unfaulted equipment and unnecessary disconnection of supply. A power transformer is an important element of the power system. A transformer relay must operate correctly for internal faults but must restrain for magnetizing inrush currents which may appear as an internal fault. Commonly used transformer differential protection is prone to mis-operation due to incorrect setting by the relay application. This thesis demonstrated an ANN-based inrush detector for use in a transformer differential relay. The main advantage of this detector is that it requires no user-entered setting.

This thesis has described the building, training and testing of an ANN-based inrush detector. The training process consisted of building a sampled power system network including transformer; simulating a system on the EMTP, collecting and pre-processing the samples of the primary transformer currents for inrush and no-inrush condition; then applying these pro-processed samples as input to 'teach' the proposed ANN a rule for inrush detection. A feedfoward neural network was trained using the back propagation algorithm to discriminate between magnetizing inrush and internal fault currents. Appropriate transfer functions were used in the various layers of the ANN during the training and testing process. The performance of the detector trained using the EMTP data was checked by using data previously recorded on a 15 KVA 240/480 V laboratory transformer. From Tables of 6.1, 6.2 and 6.3, test results presented indicate that the detector could be used as a viable alternative to currently used harmonic restraint methods to correctly discriminate between magnetizing inrush and fault currents. Artificial neural networks provide a good alternative because they can handle most situations which can not be defined sufficiently by other methods.

The artificial neural network developed in this thesis catered only for a single-phase basic model for magnetizing inrush detection. Further work needs to be done to extend to a complete three-phase model and the algorithm needs to be tested with more data and different transformer systems. This will require additional training patterns, different neural network parameters and architecture. Also on-line testing will also be required.

Although a great deal of research still needs to be done, the neural network approach shows great potential as an effective strategy for transformer protection. Undoubtedly, many more applications will be found for this new technology, including other presently intractable problems in power systems.

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Appendix A

DATA FOR THE TEST SYSTEM OF FIGURE 5.2.

COMPONENT	PARAMETER		
Source	Vs:	138.00	kV
	L_s:	403.190	mH
Transmission Line	R:	6.0000	Ω
	Z_c:	220.00	Ω
	C:	3.1364	μF
	τ:	0.6900	ms
	l:	300.0	km
Transformer Parameters	KV:	138/13.8	KV
	MVA:	30.00	MVA
	I—φ Characteristics		
	I(Ampere)	φ(Wb-t)	
	0	0	
	1.86750	517.647	
	3.86750	529.4118	
	10000.0	6390.121	
	Equivalent Transformer		
	R_1:	0.0950	Ω
	R_2:	0.0095	Ω
	L_1:	12.630	mH
	L_2:	0.1263	mH
Loads * Total 25 loads changing were simulated. Typical parameters of loads are listed.	load #1:	R: 386.70 Ω	X_l: 38.870 mH
	load #2:	R: 370.74 Ω	X_l: 116.59 mH
	load #3:	R: 336.58 Ω	X_l: 194.32 mH
	load #4:	R: 310.92 Ω	X_l: 233.19 mH
	load #5:	R: 390.61 Ω	X_c: 257.30 μS
	load #6:	R: 407.41 Ω	X_c: 771.91 μS
	load #7:	R: 448.77 Ω	X_c: 1286.5 μS
	load #8:	R: 485.81 Ω	X_c: 1543.8 μS

APPENDIX.B

```
#
#
#
#
#                                  APPENDIX B
#
#
#
#
#           The ANN-based inrush detector training fiel is provided in this Appendix.
#
#
#           The inrush condition has 50 cases, target output should be 1.
#
#
#           The internal fault, fault with inrush and load changing conditions
#           have 45 cases, target output should be 0.
#
#
#           All the value are the magnitudes of fundamental up to the fifth
#           harmonic component which are normalized to the largest harmonic value.
#
#
#
###################################################################################
###################################################################################
#
#
#
#             (Total 95 case for the training pattern)
#
#
#
#     Fundamental      Second          Third           Fourth          Fifth           Output
```

Fundamental	Second	Third	Fourth	Fifth	Output
1.00000e+00	6.22802e-01	1.11194e-01	6.32364e-01	1.87622e-01	9.99826e-01
1.00000e+00	6.43116e-01	1.60046e-01	6.64042e-01	1.23989e-01	9.99842e-01
1.00000e+00	6.05778e-01	2.56483e-01	6.12188e-01	1.25279e-01	9.99846e-01
1.00000e+00	5.32024e-01	3.29405e-01	7.01902e-01	1.76093e-01	9.99853e-01
1.00000e+00	3.73782e-01	5.15382e-01	8.32150e-01	2.40631e-01	9.99860e-01
9.17880e-01	8.72050e-02	9.71993e-01	1.00000e+00	3.17193e-01	9.99863e-01
2.92883e-01	4.91184e-01	1.00000e+00	6.05527e-01	1.99223e-01	9.99863e-01
2.19909e-01	5.52741e-01	1.00000e+00	1.45722e-01	1.75718e-01	9.99863e-01
3.85326e-01	4.54108e-01	1.00000e+00	1.47657e-01	2.14701e-01	9.99863e-01
3.61505e-01	2.51717e-01	1.00000e+00	1.00062e-01	2.08043e-01	9.99862e-01
3.02128e-01	1.07483e-01	1.00000e+00	2.39515e-02	2.05822e-01	9.99860e-01
1.50238e-01	1.00000e+00	9.83047e-01	3.72612e-01	2.76943e-01	9.99863e-01
2.56432e-01	9.20317e-01	1.00000e+00	2.81021e-01	1.09303e-01	9.99863e-01
3.36577e-01	5.63481e-01	1.00000e+00	4.78120e-01	1.28305e-01	9.99863e-01
3.66634e-01	3.91071e-01	1.00000e+00	5.29554e-01	1.24334e-01	9.99863e-01
5.46858e-01	3.44743e-01	1.00000e+00	6.09567e-01	2.07603e-01	9.99863e-01
1.00000e+00	5.00396e-01	9.70837e-01	9.39962e-01	3.99276e-01	9.99863e-01
1.00000e+00	5.38767e-01	4.02735e-01	8.07112e-01	2.48897e-01	9.99860e-01
1.00000e+00	5.93397e-01	2.38556e-01	6.47485e-01	1.12784e-01	9.99846e-01
1.00000e+00	5.94924e-01	1.61379e-01	5.64126e-01	1.77523e-01	9.99822e-01
1.00000e+00	6.22802e-01	1.11193e-01	6.32364e-01	1.87622e-01	9.99826e-01
9.17883e-01	8.72036e-02	9.71988e-01	1.00000e+00	3.17193e-01	9.99863e-01
3.02128e-01	1.07480e-01	1.00000e+00	2.39512e-02	2.05822e-01	9.99860e-01
5.46855e-01	3.44743e-01	1.00000e+00	6.09566e-01	2.07601e-01	9.99863e-01
1.00000e+00	6.22802e-01	1.11192e-01	6.32364e-01	1.87623e-01	9.99826e-01
1.00000e+00	4.93468e-01	1.65580e-01	2.75661e-01	6.47726e-03	9.99412e-01
1.00000e+00	4.84144e-01	1.79289e-01	2.80028e-01	1.48144e-02	9.99467e-01
1.00000e+00	4.55441e-01	1.90170e-01	3.05618e-01	3.26039e-02	9.99508e-01
1.00000e+00	4.05709e-01	2.07747e-01	3.57028e-01	5.82725e-02	9.99576e-01
1.00000e+00	3.26388e-01	3.00234e-01	4.23386e-01	7.81023e-02	9.99734e-01
1.00000e+00	3.97752e-01	6.34386e-01	5.35840e-01	8.53065e-02	9.99858e-01
5.07187e-01	8.30267e-01	1.00000e+00	4.26116e-01	4.82268e-02	9.99863e-01
4.20833e-01	8.36485e-01	1.00000e+00	9.88728e-02	1.00644e-01	9.99863e-01
5.56514e-01	6.30086e-01	1.00000e+00	1.59934e-01	1.48210e-01	9.99863e-01
5.02288e-01	3.60816e-01	1.00000e+00	1.14944e-01	1.24630e-01	9.99862e-01
3.83847e-01	2.45049e-01	1.00000e+00	5.15531e-02	7.76867e-02	9.99861e-01
2.39371e-01	1.00000e+00	6.62969e-01	3.42695e-01	1.76090e-01	9.99863e-01
4.45580e-01	1.00000e+00	9.24962e-01	2.63973e-01	3.68969e-02	9.99863e-01

5.68435e-01	7.73277e-01	1.00000e+00	3.39502e-01	7.52337e-02	9.99863e-01
6.43646e-01	5.25642e-01	1.00000e+00	4.01811e-01	8.62040e-02	9.99863e-01
8.91536e-01	4.16517e-01	1.00000e+00	4.22415e-01	5.64744e-02	9.99863e-01
1.00000e+00	3.76595e-01	6.19359e-01	4.04548e-01	1.16656e-01	9.99852e-01
1.00000e+00	4.17222e-01	2.68264e-01	4.09836e-01	1.10396e-01	9.99758e-01
1.00000e+00	4.77826e-01	1.56506e-01	3.70282e-01	6.59918e-02	9.99600e-01
1.00000e+00	4.96433e-01	1.74185e-01	3.05258e-01	2.69102e-02	9.99551e-01
1.00000e+00	4.93468e-01	1.65580e-01	2.75661e-01	6.47734e-03	9.99412e-01
1.00000e+00	3.97749e-01	6.34381e-01	5.35839e-01	8.53065e-02	9.99858e-01
3.83849e-01	2.45044e-01	1.00000e+00	5.15524e-02	7.76871e-02	9.99861e-01
8.91533e-01	4.16517e-01	1.00000e+00	4.22415e-01	5.64741e-02	9.99863e-01
1.00000e+00	4.93468e-01	1.65580e-01	2.75661e-01	6.47725e-03	9.99412e-01

1.00000e+00	3.52532e-02	2.49926e-02	1.88458e-02	1.31223e-02	1.18077e-04
1.00000e+00	1.90763e-02	2.57294e-02	2.78592e-02	4.13225e-02	1.15514e-04
1.00000e+00	1.66257e-03	6.39912e-03	2.39301e-03	4.12351e-03	7.03335e-05
1.00000e+00	2.64283e-02	2.68218e-02	3.28731e-02	4.90787e-02	1.30713e-04
1.00000e+00	3.82176e-02	3.12562e-02	2.89437e-02	3.68399e-02	1.46389e-04
1.00000e+00	1.16872e-02	1.55311e-02	1.87836e-02	2.87038e-02	9.07779e-05
1.00000e+00	3.53283e-03	3.22611e-03	5.30661e-04	1.86298e-03	6.86646e-05
1.00000e+00	2.92205e-02	3.24236e-02	3.92130e-02	5.72243e-02	1.53840e-04
1.00000e+00	4.25048e-02	3.76578e-02	3.84515e-02	5.17904e-02	1.85966e-04
1.00000e+00	2.96201e-02	1.33880e-02	5.26225e-03	1.63003e-02	9.08375e-05
1.00000e+00	1.16894e-02	8.32370e-03	6.33595e-03	5.74044e-03	7.73072e-05
1.00000e+00	1.00799e-03	3.61914e-03	5.38467e-03	8.09911e-03	6.98566e-05
1.00000e+00	2.40113e-02	1.77135e-02	1.58054e-02	1.55418e-02	9.79900e-05
1.00000e+00	1.39285e-02	3.54193e-03	1.41230e-02	2.09357e-02	7.95126e-05
1.00000e+00	9.87443e-03	6.56420e-03	4.50763e-03	3.97761e-03	7.45058e-05
1.00000e+00	1.18200e-03	2.53530e-03	4.23645e-03	6.61525e-03	6.89626e-05
1.00000e+00	2.35018e-02	1.72205e-02	1.53879e-02	1.54312e-02	9.67979e-05
1.00000e+00	1.18604e-02	4.76126e-03	1.39511e-02	2.04055e-02	7.92742e-05
1.00000e+00	2.73673e-02	1.84880e-02	1.38471e-02	1.07291e-02	9.93609e-05
1.00000e+00	2.33783e-02	1.95870e-02	1.87784e-02	1.88308e-02	1.01864e-04
1.00000e+00	1.46850e-02	1.54344e-02	1.65628e-02	1.78008e-02	9.03606e-05
1.00000e+00	2.01844e-02	1.37054e-02	1.02361e-02	8.27345e-03	8.77380e-05
1.00000e+00	2.73674e-02	1.84879e-02	1.38471e-02	1.07291e-02	9.93609e-05
1.00000e+00	2.33785e-02	1.95868e-02	1.87786e-02	1.88307e-02	1.01864e-04
1.00000e+00	1.46850e-02	1.54344e-02	1.65628e-02	1.78008e-02	9.03606e-05
1.00000e+00	2.01844e-02	1.37054e-02	1.02360e-02	8.27361e-03	8.77380e-05
1.00000e+00	2.73674e-02	1.84879e-02	1.38472e-02	1.07290e-02	9.93609e-05
1.00000e+00	2.73877e-02	1.85985e-02	1.41014e-02	1.12795e-02	9.97186e-05
1.00000e+00	2.37959e-02	2.03419e-02	1.94347e-02	1.92690e-02	1.03593e-04
1.00000e+00	1.66962e-02	1.76602e-02	1.85817e-02	1.93805e-02	9.50694e-05
1.00000e+00	2.13073e-02	1.54026e-02	1.26450e-02	1.11781e-02	9.15527e-05
1.00000e+00	2.73878e-02	1.85985e-02	1.41014e-02	1.12796e-02	9.97186e-05
1.00000e+00	2.37959e-02	2.03419e-02	1.94347e-02	1.92691e-02	1.03593e-04
1.00000e+00	1.66962e-02	1.76602e-02	1.85817e-02	1.93805e-02	9.50694e-05
1.00000e+00	2.13073e-02	1.54026e-02	1.26450e-02	1.11781e-02	9.15527e-05
1.00000e+00	2.73878e-02	1.85984e-02	1.41014e-02	1.12795e-02	9.97186e-05
1.00000e+00	2.74602e-02	1.87008e-02	1.42306e-02	1.14263e-02	1.00017e-04
1.00000e+00	2.37771e-02	2.03182e-02	1.94083e-02	1.92414e-02	1.03533e-04
1.00000e+00	1.66677e-02	1.76299e-02	1.85499e-02	1.93481e-02	9.50098e-05
1.00000e+00	2.12978e-02	1.53881e-02	1.26264e-02	1.11560e-02	9.15527e-05
1.00000e+00	2.73864e-02	1.85973e-02	1.41009e-02	1.12796e-02	9.97186e-05
1.00000e+00	2.37826e-02	2.03251e-02	1.94156e-02	1.92488e-02	1.03533e-04
1.00000e+00	1.66675e-02	1.76296e-02	1.85496e-02	1.93478e-02	9.50098e-05
1.00000e+00	2.12978e-02	1.53882e-02	1.26262e-02	1.11561e-02	9.15527e-05
1.00000e+00	2.73863e-02	1.85974e-02	1.41007e-02	1.12797e-02	9.97186e-05

APPENDIX.C

```
#
#
#
#
#                                  APPENDIX C
#
#        The ANN-based inrush detector testing file is provided in this Appendix.
#
#
#        The inrush condition has 160 cases, target output should be 1.
#
#
#        The internal fault, fault with inrush and load changing conditions
#        have 80 cases, target output should be 0.
#
#
#        All the value are the magnitudes of fundamental up to the fifth
#        harmonic component which are normalized to the largest harmonic value.
#
#
#
##########################################################################
##########################################################################
#
#
#
#                             (Total 240 case for the TESTING PATTERNS )
#
#
#
#      Fundamental      Second        Third        Fourth        Fifth        Output
#
```

Fundamental	Second	Third	Fourth	Fifth	Output
1.00000e+00	6.06840e-01	1.13205e-01	5.91138e-01	1.98522e-01	9.99816e-01
1.00000e+00	6.09281e-01	1.14157e-01	6.00662e-01	1.93080e-01	9.99819e-01
1.00000e+00	6.09441e-01	1.16056e-01	6.08309e-01	1.86413e-01	9.99821e-01
1.00000e+00	6.07548e-01	1.31442e-01	6.08981e-01	1.74738e-01	9.99825e-01
1.00000e+00	6.01614e-01	1.62232e-01	6.02409e-01	1.51575e-01	9.99830e-01
1.00000e+00	5.98778e-01	1.75864e-01	5.99204e-01	1.40547e-01	9.99832e-01
1.00000e+00	5.89977e-01	1.99431e-01	5.89329e-01	1.32861e-01	9.99834e-01
1.00000e+00	5.80952e-01	2.23894e-01	5.74036e-01	1.26696e-01	9.99835e-01
1.00000e+00	5.57019e-01	2.54439e-01	5.75748e-01	1.30317e-01	9.99838e-01
1.00000e+00	5.42649e-01	2.67582e-01	5.93000e-01	1.33897e-01	9.99840e-01
1.00000e+00	5.29387e-01	2.76969e-01	6.10100e-01	1.37806e-01	9.99842e-01
1.00000e+00	5.12114e-01	2.94090e-01	6.29107e-01	1.44138e-01	9.99845e-01
1.00000e+00	4.67243e-01	3.41991e-01	6.72064e-01	1.61517e-01	9.99850e-01
1.00000e+00	4.41391e-01	3.71511e-01	6.94542e-01	1.71350e-01	9.99852e-01
1.00000e+00	4.12070e-01	4.04509e-01	7.20121e-01	1.82408e-01	9.99854e-01
1.00000e+00	3.74021e-01	4.54543e-01	7.52780e-01	1.96619e-01	9.99856e-01
1.00000e+00	2.85441e-01	5.71224e-01	8.19258e-01	2.26802e-01	9.99860e-01
1.00000e+00	2.16767e-01	6.70910e-01	8.68304e-01	2.49263e-01	9.99861e-01
1.00000e+00	1.53880e-01	7.58075e-01	9.13550e-01	2.69228e-01	9.99862e-01
1.00000e+00	8.36781e-02	8.72864e-01	9.73837e-01	2.93567e-01	9.99863e-01
8.00587e-01	1.56990e-01	1.00000e+00	9.11875e-01	2.89789e-01	9.99863e-01
6.65437e-01	2.43944e-01	1.00000e+00	8.36576e-01	2.69923e-01	9.99863e-01
5.25362e-01	3.34629e-01	1.00000e+00	7.53619e-01	2.48507e-01	9.99863e-01
4.02717e-01	4.14829e-01	1.00000e+00	6.80553e-01	2.27941e-01	9.99863e-01
2.04882e-01	5.60756e-01	1.00000e+00	5.47182e-01	1.87535e-01	9.99863e-01
1.65811e-01	6.21731e-01	1.00000e+00	5.00102e-01	1.71458e-01	9.99863e-01
1.77446e-01	6.51470e-01	1.00000e+00	4.08400e-01	1.65829e-01	9.99863e-01
1.99487e-01	5.97773e-01	1.00000e+00	2.68585e-01	1.85621e-01	9.99863e-01
2.68192e-01	5.17837e-01	1.00000e+00	7.36253e-02	2.18512e-01	9.99863e-01
3.07995e-01	4.94276e-01	1.00000e+00	3.56213e-02	2.32034e-01	9.99863e-01
3.50376e-01	4.80287e-01	1.00000e+00	7.31746e-02	2.45314e-01	9.99863e-01
3.95927e-01	4.83536e-01	1.00000e+00	1.10065e-01	2.58403e-01	9.99863e-01
4.07902e-01	4.27458e-01	1.00000e+00	1.19747e-01	2.65061e-01	9.99863e-01
4.01566e-01	3.87940e-01	1.00000e+00	1.14568e-01	2.64801e-01	9.99862e-01
3.95179e-01	3.45665e-01	1.00000e+00	1.08455e-01	2.64301e-01	9.99862e-01
3.88512e-01	3.00162e-01	1.00000e+00	1.01599e-01	2.63620e-01	9.99862e-01
3.70779e-01	2.03676e-01	1.00000e+00	8.40227e-02	2.60777e-01	9.99861e-01
3.58633e-01	1.53764e-01	1.00000e+00	7.38373e-02	2.58468e-01	9.99861e-01
3.45867e-01	1.01891e-01	1.00000e+00	6.55684e-02	2.56654e-01	9.99860e-01
3.30117e-01	9.11868e-02	1.00000e+00	5.93714e-02	2.53402e-01	9.99860e-01
2.84746e-01	2.34308e-01	1.00000e+00	7.64994e-02	2.45972e-01	9.99862e-01
2.51739e-01	3.59988e-01	1.00000e+00	1.08835e-01	2.41681e-01	9.99863e-01

2.08389e-01	5.04825e-01	1.00000e+00	1.55405e-01	2.37474e-01	9.99863e-01
2.08015e-01	5.01924e-01	1.00000e+00	1.52976e-01	2.33480e-01	9.99863e-01
1.76060e-01	1.00000e+00	7.91624e-01	4.14089e-01	2.03986e-01	9.99863e-01
2.36699e-01	1.00000e+00	7.03763e-01	4.02008e-01	1.33897e-01	9.99863e-01
2.02319e-01	1.00000e+00	8.10884e-01	2.80324e-01	7.36778e-02	9.99863e-01
2.06284e-01	1.00000e+00	8.05471e-01	2.77017e-01	7.77223e-02	9.99863e-01
3.05921e-01	8.57002e-01	1.00000e+00	2.99569e-01	1.25522e-01	9.99863e-01
3.31051e-01	7.84430e-01	1.00000e+00	3.48056e-01	1.36874e-01	9.99863e-01
3.61500e-01	7.26061e-01	1.00000e+00	3.92218e-01	1.40198e-01	9.99863e-01
3.88822e-01	6.76036e-01	1.00000e+00	4.36249e-01	1.46568e-01	9.99863e-01
3.94102e-01	5.91478e-01	1.00000e+00	4.89330e-01	1.70767e-01	9.99863e-01
3.94749e-01	5.50827e-01	1.00000e+00	5.10871e-01	1.80696e-01	9.99863e-01
3.98803e-01	5.15095e-01	1.00000e+00	5.31281e-01	1.87378e-01	9.99863e-01
4.07182e-01	4.81347e-01	1.00000e+00	5.50117e-01	1.90498e-01	9.99863e-01
4.39125e-01	4.25571e-01	1.00000e+00	5.79329e-01	1.88376e-01	9.99863e-01
4.63470e-01	4.05646e-01	1.00000e+00	5.93171e-01	1.89196e-01	9.99863e-01
4.90658e-01	3.87355e-01	1.00000e+00	6.08010e-01	1.93691e-01	9.99863e-01
5.26057e-01	3.75899e-01	1.00000e+00	6.25514e-01	2.04473e-01	9.99863e-01
6.24216e-01	3.73967e-01	1.00000e+00	6.74975e-01	2.44882e-01	9.99863e-01
6.94516e-01	3.87651e-01	1.00000e+00	7.13348e-01	2.77559e-01	9.99863e-01
7.72817e-01	4.03171e-01	1.00000e+00	7.60354e-01	3.15576e-01	9.99863e-01
8.67310e-01	4.27592e-01	1.00000e+00	8.22186e-01	3.61162e-01	9.99863e-01
1.00000e+00	4.62086e-01	8.97308e-01	9.01901e-01	4.18650e-01	9.99863e-01
1.00000e+00	4.64991e-01	7.65893e-01	8.79660e-01	4.06754e-01	9.99863e-01
1.00000e+00	4.75356e-01	6.44081e-01	8.61292e-01	3.86924e-01	9.99863e-01
1.00000e+00	4.86912e-01	5.29152e-01	8.43632e-01	3.59848e-01	9.99862e-01
1.00000e+00	5.25095e-01	3.42260e-01	7.99137e-01	2.97093e-01	9.99858e-01
1.00000e+00	5.39428e-01	2.82860e-01	7.76013e-01	2.64980e-01	9.99855e-01
1.00000e+00	5.56194e-01	2.37830e-01	7.50368e-01	2.33016e-01	9.99851e-01
1.00000e+00	5.69673e-01	2.12782e-01	7.25268e-01	2.01231e-01	9.99848e-01
1.00000e+00	5.91935e-01	1.86624e-01	6.66981e-01	1.49021e-01	9.99841e-01
1.00000e+00	5.97800e-01	1.75868e-01	6.40682e-01	1.45091e-01	9.99837e-01
1.00000e+00	5.99713e-01	1.69707e-01	6.17401e-01	1.47780e-01	9.99833e-01
1.00000e+00	5.99174e-01	1.68173e-01	5.99240e-01	1.55615e-01	9.99830e-01
1.00000e+00	5.98059e-01	1.43667e-01	5.71791e-01	1.87982e-01	9.99819e-01
1.00000e+00	5.98676e-01	1.27948e-01	5.68079e-01	2.01118e-01	9.99814e-01
1.00000e+00	6.01103e-01	1.22501e-01	5.69871e-01	2.04855e-01	9.99813e-01
1.00000e+00	6.02471e-01	1.17565e-01	5.74634e-01	2.05057e-01	9.99813e-01

1.00000e+00	4.97807e-01	1.65741e-01	2.85803e-01	1.18749e-02	9.99464e-01
1.00000e+00	2.92205e-02	3.24236e-02	3.92130e-02	5.72243e-02	1.53840e-04
1.00000e+00	4.92853e-01	1.69762e-01	2.78689e-01	1.12788e-02	9.99444e-01
1.00000e+00	4.88473e-01	1.76905e-01	2.75778e-01	1.41622e-02	9.99456e-01
1.00000e+00	4.79375e-01	1.86130e-01	2.72838e-01	1.92359e-02	9.99464e-01
1.00000e+00	4.71720e-01	1.91147e-01	2.70890e-01	2.29264e-02	9.99458e-01
1.00000e+00	4.63670e-01	1.92656e-01	2.74443e-01	2.30417e-02	9.99450e-01
1.00000e+00	4.54865e-01	1.93700e-01	2.79895e-01	2.24940e-02	9.99442e-01
1.00000e+00	4.33178e-01	1.93765e-01	2.92072e-01	2.18141e-02	9.99404e-01
1.00000e+00	4.20819e-01	1.95628e-01	2.99986e-01	2.16945e-02	9.99395e-01
1.00000e+00	4.06415e-01	2.00012e-01	3.08074e-01	2.20120e-02	9.99393e-01
1.00000e+00	3.92135e-01	2.04397e-01	3.17565e-01	2.26373e-02	9.99397e-01
1.00000e+00	3.57346e-01	2.23740e-01	3.38485e-01	2.49598e-02	9.99445e-01
1.00000e+00	3.41509e-01	2.33795e-01	3.51219e-01	2.68246e-02	9.99481e-01
1.00000e+00	3.19549e-01	2.55632e-01	3.63406e-01	2.78518e-02	9.99540e-01
1.00000e+00	3.01554e-01	2.76918e-01	3.78419e-01	3.04030e-02	9.99599e-01
1.00000e+00	2.65473e-01	3.50277e-01	4.11575e-01	3.36652e-02	9.99729e-01
1.00000e+00	2.60412e-01	3.97561e-01	4.31850e-01	3.55649e-02	9.99780e-01
1.00000e+00	2.68450e-01	4.61525e-01	4.54472e-01	3.66984e-02	9.99819e-01
1.00000e+00	3.02962e-01	5.41993e-01	4.81039e-01	3.72557e-02	9.99844e-01
1.00000e+00	4.69133e-01	7.74637e-01	5.50043e-01	4.17704e-02	9.99862e-01
1.00000e+00	6.24410e-01	9.43011e-01	5.98908e-01	4.47136e-02	9.99863e-01
8.40870e-01	7.15255e-01	1.00000e+00	5.53571e-01	4.21378e-02	9.99863e-01
6.60511e-01	7.74718e-01	1.00000e+00	4.88254e-01	3.88401e-02	9.99863e-01
3.92877e-01	8.92918e-01	1.00000e+00	3.78321e-01	3.47854e-02	9.99863e-01
3.38401e-01	9.68960e-01	1.00000e+00	3.40324e-01	2.73557e-02	9.99863e-01
3.52852e-01	1.00000e+00	9.86769e-01	2.82348e-01	2.79812e-02	9.99863e-01
4.03497e-01	9.46156e-01	1.00000e+00	1.80395e-01	6.26207e-02	9.99863e-01
5.01511e-01	8.15855e-01	1.00000e+00	3.48529e-02	1.25949e-01	9.99863e-01
5.63120e-01	7.87487e-01	1.00000e+00	7.56615e-02	1.45240e-01	9.99863e-01
6.25386e-01	7.74007e-01	1.00000e+00	1.17476e-01	1.58334e-01	9.99863e-01
6.16904e-01	7.25699e-01	1.00000e+00	1.18333e-01	1.61171e-01	9.99863e-01
5.94097e-01	6.26487e-01	1.00000e+00	1.09369e-01	1.60442e-01	9.99863e-01
5.81801e-01	5.73338e-01	1.00000e+00	1.03209e-01	1.59110e-01	9.99863e-01
5.68238e-01	5.16386e-01	1.00000e+00	9.60586e-02	1.57114e-01	9.99862e-01
5.53788e-01	4.58622e-01	1.00000e+00	8.56135e-02	1.52942e-01	9.99862e-01

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5.18487e-01	3.30984e-01	1.00000e+00	5.99490e-02	1.42531e-01	9.99861e-01
4.97256e-01	2.69465e-01	1.00000e+00	4.17530e-02	1.35190e-01	9.99861e-01
4.71226e-01	2.21872e-01	1.00000e+00	2.12125e-02	1.26755e-01	9.99860e-01
4.39665e-01	2.20650e-01	1.00000e+00	1.38112e-02	1.15221e-01	9.99860e-01
3.48223e-01	4.07654e-01	1.00000e+00	8.86310e-02	9.23034e-02	9.99862e-01
2.85122e-01	5.79580e-01	1.00000e+00	1.41378e-01	8.86535e-02	9.99863e-01
2.09080e-01	8.06048e-01	1.00000e+00	2.10549e-01	1.00541e-01	9.99863e-01
1.51633e-01	1.00000e+00	9.27924e-01	2.88049e-01	1.28951e-01	9.99863e-01
2.87164e-01	1.00000e+00	6.96070e-01	3.68435e-01	1.58116e-01	9.99863e-01
2.73004e-01	1.00000e+00	7.33819e-01	3.31668e-01	1.12970e-01	9.99863e-01
3.00337e-01	1.00000e+00	7.95081e-01	3.02116e-01	8.96542e-02	9.99863e-01
3.66564e-01	1.00000e+00	8.64491e-01	2.78889e-01	6.63278e-02	9.99863e-01
5.16584e-01	1.00000e+00	9.95030e-01	2.80164e-01	3.13108e-02	9.99863e-01
5.63020e-01	9.53715e-01	1.00000e+00	2.84521e-01	2.39050e-02	9.99863e-01
5.85813e-01	9.11440e-01	1.00000e+00	2.88657e-01	3.11387e-02	9.99863e-01
6.01650e-01	8.71173e-01	1.00000e+00	2.96741e-01	4.98005e-02	9.99863e-01
6.33663e-01	7.84781e-01	1.00000e+00	3.30447e-01	8.84798e-02	9.99863e-01
6.51002e-01	7.40486e-01	1.00000e+00	3.52641e-01	1.03740e-01	9.99863e-01
6.70924e-01	6.96007e-01	1.00000e+00	3.74375e-01	1.13585e-01	9.99863e-01
6.94112e-01	6.53006e-01	1.00000e+00	3.95848e-01	1.19956e-01	9.99863e-01
7.53515e-01	5.75516e-01	1.00000e+00	4.33131e-01	1.25668e-01	9.99863e-01
7.91231e-01	5.41544e-01	1.00000e+00	4.46855e-01	1.24589e-01	9.99863e-01
8.35484e-01	5.12332e-01	1.00000e+00	4.57306e-01	1.20431e-01	9.99863e-01
8.88540e-01	4.89447e-01	1.00000e+00	4.64300e-01	1.12681e-01	9.99863e-01
1.00000e+00	4.51919e-01	9.70769e-01	4.65655e-01	9.70042e-02	9.99863e-01
1.00000e+00	4.16678e-01	8.89490e-01	4.38908e-01	9.25664e-02	9.99862e-01
1.00000e+00	3.92268e-01	8.03514e-01	4.16783e-01	9.64501e-02	9.99860e-01
1.00000e+00	3.76436e-01	7.18066e-01	4.01333e-01	1.03713e-01	9.99857e-01
1.00000e+00	3.63145e-01	5.58699e-01	3.90314e-01	1.18328e-01	9.99844e-01
1.00000e+00	3.64789e-01	4.85710e-01	3.89810e-01	1.23983e-01	9.99833e-01
1.00000e+00	3.70273e-01	4.18160e-01	3.90860e-01	1.27901e-01	9.99816e-01
1.00000e+00	3.80960e-01	3.51512e-01	3.93793e-01	1.30439e-01	9.99792e-01
1.00000e+00	4.09489e-01	2.34940e-01	3.98403e-01	1.27411e-01	9.99710e-01
1.00000e+00	4.24661e-01	1.88758e-01	3.99219e-01	1.21555e-01	9.99649e-01
1.00000e+00	4.39408e-01	1.52227e-01	3.99269e-01	1.14016e-01	9.99580e-01
1.00000e+00	4.55588e-01	1.24703e-01	3.96425e-01	1.03455e-01	9.99514e-01
1.00000e+00	4.81246e-01	1.16746e-01	3.84194e-01	8.49990e-02	9.99513e-01
1.00000e+00	4.88492e-01	1.28068e-01	3.73974e-01	7.64295e-02	9.99546e-01
1.00000e+00	4.94921e-01	1.38344e-01	3.60950e-01	6.70586e-02	9.99563e-01
1.00000e+00	5.00124e-01	1.47413e-01	3.47925e-01	5.69694e-02	9.99573e-01
1.00000e+00	5.02531e-01	1.57406e-01	3.22716e-01	3.72426e-02	9.99551e-01
1.00000e+00	5.03121e-01	1.57816e-01	3.12345e-01	2.82086e-02	9.99526e-01
1.00000e+00	5.02323e-01	1.60713e-01	3.03894e-01	2.21382e-02	9.99511e-01
1.00000e+00	5.01164e-01	1.62571e-01	2.96992e-01	1.73687e-02	9.99495e-01

1.00000e+00	2.84461e-02	1.57361e-02	2.45026e-02	4.04479e-02	1.08123e-04
1.00000e+00	2.85629e-02	2.70391e-02	2.63567e-02	4.29455e-02	1.25647e-04
1.00000e+00	2.19457e-02	6.99663e-03	1.09079e-02	2.46533e-02	8.48174e-05
1.00000e+00	2.70429e-02	2.29775e-02	3.30190e-02	4.25606e-02	1.24574e-04
1.00000e+00	6.13945e-03	2.98934e-03	1.01179e-02	2.33132e-02	7.40290e-05
1.00000e+00	7.66397e-03	5.39999e-03	1.06394e-02	1.32012e-02	7.58767e-05
1.00000e+00	1.06086e-02	1.78751e-02	1.88901e-02	2.79456e-02	9.22084e-05
1.00000e+00	1.47222e-03	3.61093e-03	9.04867e-03	1.76583e-02	7.18236e-05
1.00000e+00	1.58395e-02	2.12667e-02	2.41882e-02	3.47107e-02	1.03593e-04
1.00000e+00	9.55218e-03	8.70202e-03	1.50607e-02	2.53096e-02	8.17776e-05
1.00000e+00	8.81614e-03	1.29552e-02	1.31115e-02	1.87132e-02	8.31485e-05
1.00000e+00	2.83676e-02	3.20501e-02	3.76539e-02	5.21064e-02	1.48773e-04
1.00000e+00	2.59069e-02	2.61750e-02	2.97181e-02	4.13744e-02	1.24693e-04
1.00000e+00	3.83967e-02	3.82281e-02	4.13824e-02	5.46338e-02	1.85788e-04
1.00000e+00	3.84560e-02	3.38357e-02	3.61105e-02	5.05160e-02	1.65045e-04
1.00000e+00	3.82404e-02	3.53879e-02	3.57443e-02	4.69401e-02	1.66953e-04
1.00000e+00	2.71278e-02	1.02593e-02	3.07293e-03	1.30417e-02	8.52346e-05
1.00000e+00	2.60877e-02	1.78110e-02	1.12362e-02	5.78114e-03	9.55462e-05
1.00000e+00	2.29339e-02	1.79690e-02	1.66597e-02	1.70170e-02	9.81688e-05
1.00000e+00	1.74545e-02	8.96642e-03	4.20182e-03	1.91939e-03	7.92146e-05
1.00000e+00	1.31963e-02	1.42132e-02	1.63535e-02	1.88242e-02	8.83341e-05
1.00000e+00	7.68971e-03	3.27751e-03	3.46353e-03	6.61425e-03	7.14064e-05
1.00000e+00	8.54173e-03	8.03735e-03	8.52455e-03	1.08034e-02	7.68900e-05
1.00000e+00	1.22035e-02	1.35903e-02	1.55785e-02	1.82876e-02	8.67844e-05
1.00000e+00	9.32860e-03	7.70580e-03	8.06941e-03	9.96990e-03	7.68304e-05
1.00000e+00	1.60767e-02	1.53336e-02	1.62876e-02	1.82474e-02	9.10163e-05
1.00000e+00	1.32044e-02	1.20233e-02	1.27852e-02	1.54655e-02	8.44002e-05
1.00000e+00	1.69617e-02	1.32658e-02	1.25369e-02	1.43608e-02	8.72612e-05
1.00000e+00	2.86352e-02	2.20529e-02	1.85875e-02	1.74638e-02	1.08600e-04

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1.00000e+00	2.36014e-02	2.03653e-02	1.63012e-02	8.97006e-03	1.00195e-04
1.00000e+00	1.35290e-02	8.41881e-03	1.60280e-02	2.04046e-02	8.38041e-05
1.00000e+00	2.03985e-02	3.33483e-03	8.93758e-03	1.62809e-02	7.98106e-05
1.00000e+00	2.74602e-02	1.92034e-02	1.52455e-02	1.28583e-02	1.01388e-04
1.00000e+00	2.70655e-02	1.96835e-02	1.64993e-02	1.48100e-02	1.02699e-04
1.00000e+00	2.62174e-02	1.99083e-02	1.75340e-02	1.64898e-02	1.03295e-04
1.00000e+00	2.49664e-02	1.98735e-02	1.83028e-02	1.78419e-02	1.02997e-04
1.00000e+00	2.15392e-02	1.90667e-02	1.89456e-02	1.94343e-02	1.00136e-04
1.00000e+00	1.95624e-02	1.83416e-02	1.87991e-02	1.96379e-02	9.78708e-05
1.00000e+00	1.28537e-02	1.09273e-02	1.11185e-02	1.32824e-02	8.23736e-05
1.00000e+00	1.58863e-02	1.64575e-02	1.75878e-02	1.88189e-02	9.27448e-05
1.00000e+00	1.42813e-02	1.44862e-02	1.53126e-02	1.63982e-02	8.84533e-05
1.00000e+00	1.48104e-02	1.37363e-02	1.39119e-02	1.46491e-02	8.72016e-05
1.00000e+00	1.61629e-02	1.33097e-02	1.24761e-02	1.26199e-02	8.66652e-05
1.00000e+00	1.80573e-02	1.32951e-02	1.11759e-02	1.04255e-02	8.69036e-05
1.00000e+00	2.68381e-02	2.08639e-02	1.77059e-02	1.47876e-02	1.04785e-04
1.00000e+00	2.41664e-02	1.54590e-02	1.02131e-02	5.95311e-03	9.14931e-05
1.00000e+00	2.56915e-02	1.65359e-02	1.11336e-02	6.79677e-03	9.41157e-05
1.00000e+00	2.67737e-02	1.75770e-02	1.24198e-02	8.59448e-03	9.68575e-05
1.00000e+00	2.74424e-02	1.92887e-02	1.53892e-02	1.31411e-02	1.01566e-04
1.00000e+00	2.70692e-02	1.98349e-02	1.66556e-02	1.49942e-02	1.03056e-04
1.00000e+00	2.63011e-02	2.02028e-02	1.77956e-02	1.66887e-02	1.03891e-04
1.00000e+00	2.51877e-02	2.03738e-02	1.87378e-02	1.81332e-02	1.04070e-04
1.00000e+00	2.22117e-02	2.01116e-02	1.98560e-02	2.00585e-02	1.02520e-04
1.00000e+00	2.05466e-02	1.96971e-02	1.99837e-02	2.04759e-02	1.00911e-04
1.00000e+00	1.89456e-02	1.91236e-02	1.98100e-02	2.05055e-02	9.90629e-05
1.00000e+00	1.75927e-02	1.84275e-02	1.93375e-02	2.01395e-02	9.69768e-05
1.00000e+00	1.64385e-02	1.68883e-02	1.75744e-02	1.82445e-02	9.34601e-05
1.00000e+00	1.68965e-02	1.61939e-02	1.63706e-02	1.67675e-02	9.22084e-05
1.00000e+00	1.79955e-02	1.56660e-02	1.50568e-02	1.50143e-02	9.14931e-05
1.00000e+00	1.95429e-02	1.53855e-02	1.37590e-02	1.30926e-02	9.12547e-05
1.00000e+00	2.30748e-02	1.57186e-02	1.19072e-02	9.54881e-03	9.23872e-05
1.00000e+00	2.46722e-02	1.62842e-02	1.17039e-02	8.59256e-03	9.36985e-05
1.00000e+00	2.59730e-02	1.70155e-02	1.20794e-02	8.64044e-03	9.55462e-05
1.00000e+00	2.68934e-02	1.78167e-02	1.29378e-02	9.65658e-03	9.76324e-05
1.00000e+00	2.74734e-02	1.93362e-02	1.54541e-02	1.32203e-02	1.01745e-04
1.00000e+00	2.70702e-02	1.98401e-02	1.66672e-02	1.50130e-02	1.03056e-04
1.00000e+00	2.62872e-02	2.01864e-02	1.77794e-02	1.66746e-02	1.03831e-04
1.00000e+00	2.51693e-02	2.03508e-02	1.87123e-02	1.81074e-02	1.04010e-04
1.00000e+00	2.21924e-02	2.00878e-02	1.98298e-02	2.00310e-02	1.02401e-04
1.00000e+00	2.05253e-02	1.96722e-02	1.99568e-02	2.04479e-02	1.00851e-04
1.00000e+00	1.89215e-02	1.90967e-02	1.97812e-02	2.04759e-02	9.90033e-05
1.00000e+00	1.75658e-02	1.83986e-02	1.93070e-02	2.01083e-02	9.69172e-05
1.00000e+00	1.64109e-02	1.68582e-02	1.75424e-02	1.82118e-02	9.33409e-05
1.00000e+00	1.68722e-02	1.61655e-02	1.63398e-02	1.67356e-02	9.21488e-05
1.00000e+00	1.79761e-02	1.56411e-02	1.50285e-02	1.49842e-02	9.14335e-05
1.00000e+00	1.95288e-02	1.53656e-02	1.37347e-02	1.30658e-02	9.11951e-05
1.00000e+00	2.30689e-02	1.57096e-02	1.18951e-02	9.53309e-03	9.23872e-05
1.00000e+00	2.46691e-02	1.62794e-02	1.16980e-02	8.58447e-03	9.36985e-05
1.00000e+00	2.59713e-02	1.70137e-02	1.20779e-02	8.63878e-03	9.55462e-05
1.00000e+00	2.68923e-02	1.78159e-02	1.29380e-02	9.65754e-03	9.76324e-05

APPENDIX D

This appendix provides the current waves that recorded on a laboratory transformer as discussed in Chapter 6.

Inrush Currents: 12 Cases

Fig.D1 Inrush Current

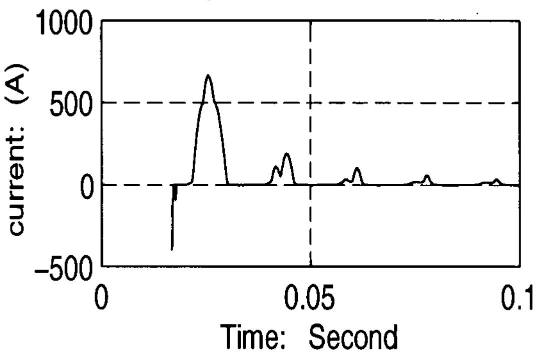


Fig.D2 Inrush Current

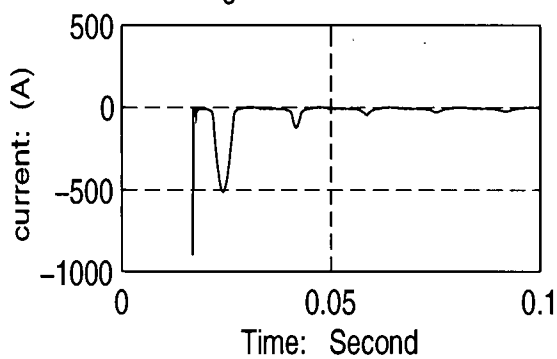


Fig.D3 Inrush Current

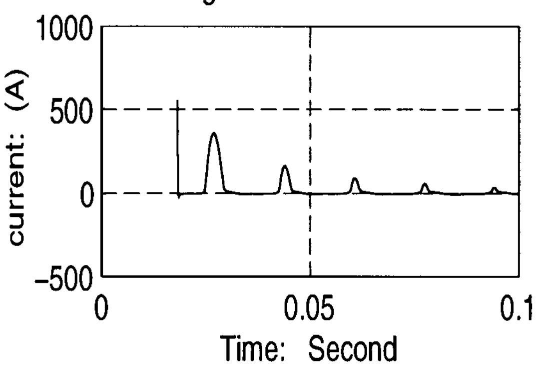


Fig.D4 Inrush Current

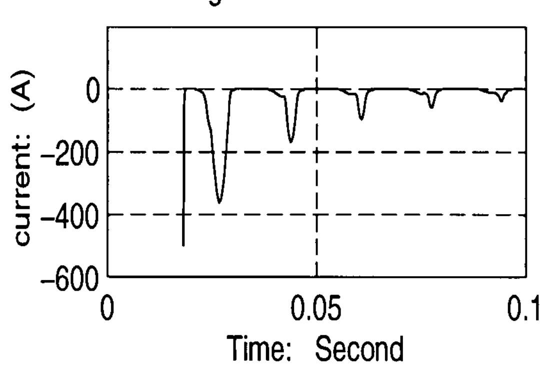


Fig.D5 Inrush Current

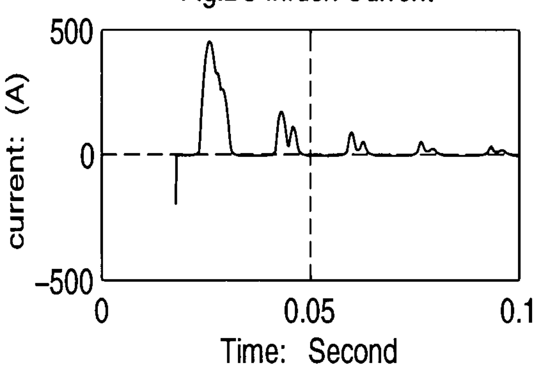


Fig.D6 Inrush Current

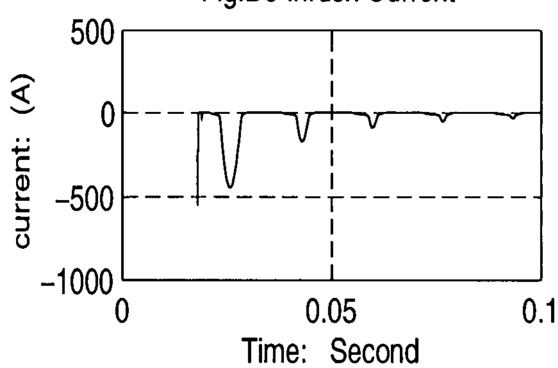


Fig.D7 Inrush Current

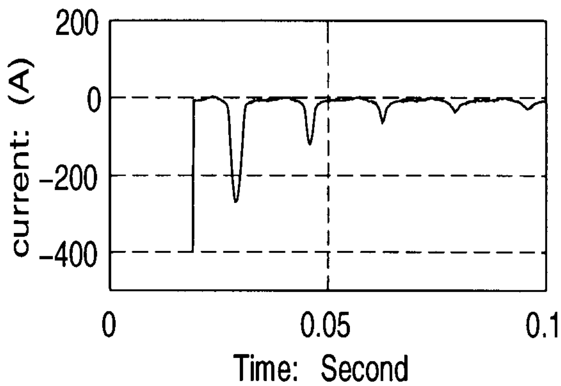


Fig.D8 Inrush Current

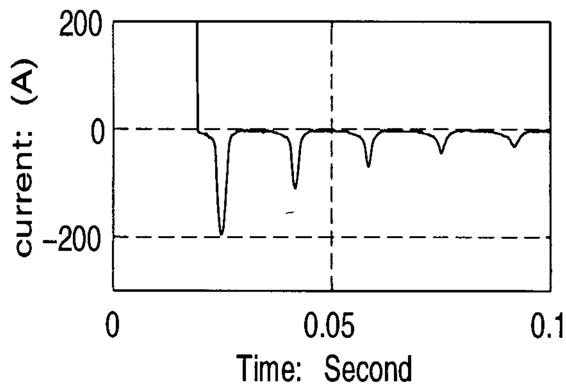


Fig.D9 Inrush Current

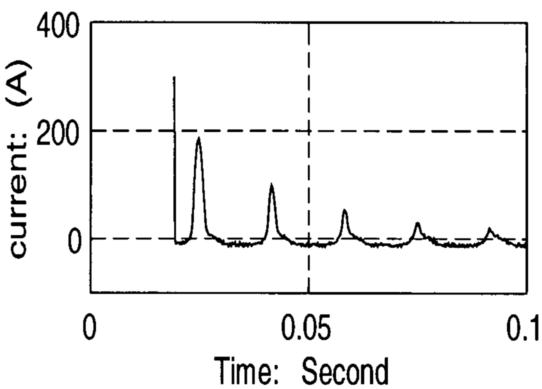


Fig.D10 Inrush Current

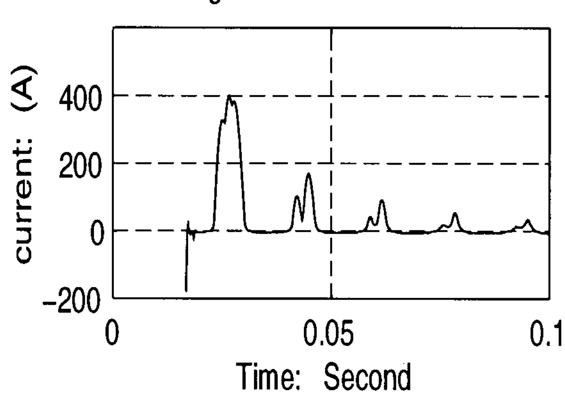


Fig.D11 Inrush Current

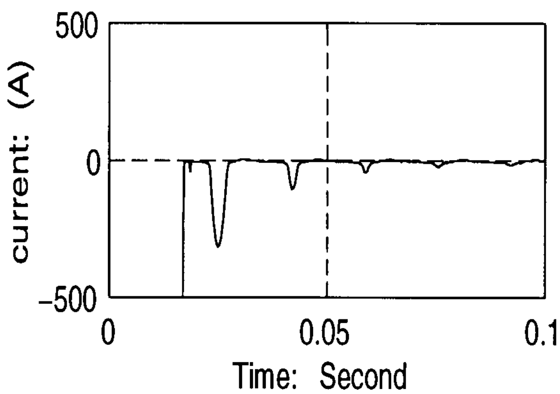
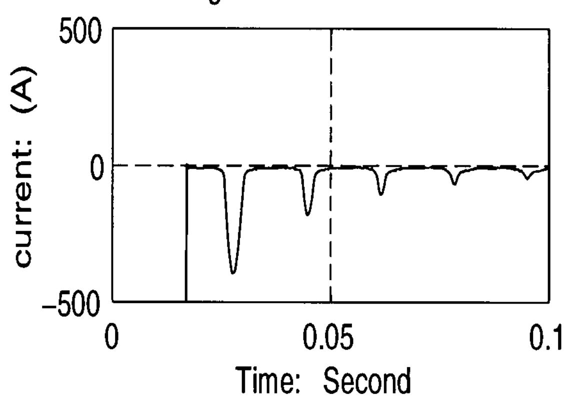


Fig.D12 Inrush Current



Winding Fault Currents: 20 Cases

Fig.D13 10% Winding Fault

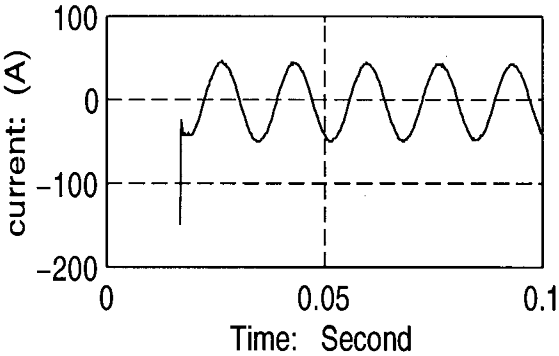


Fig.D14 10% Winding Fault

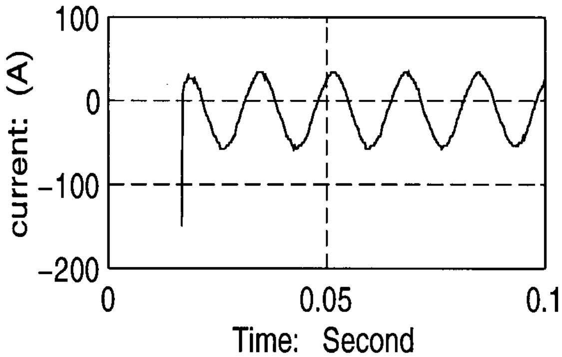


Fig.D15 10% Winding Fault

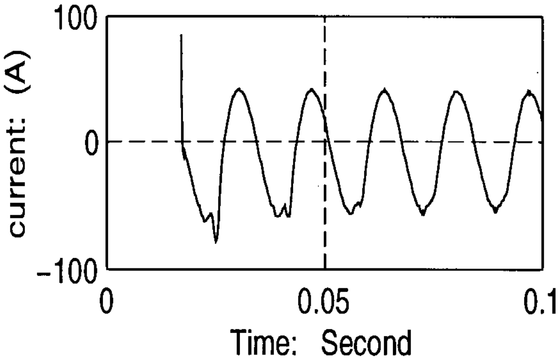


Fig.D16 10% Winding Fault

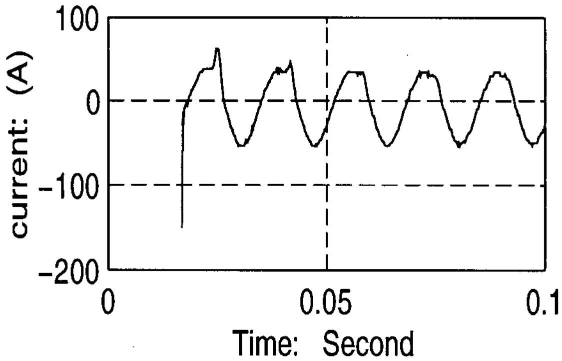


Fig.D17 10% Winding Fault

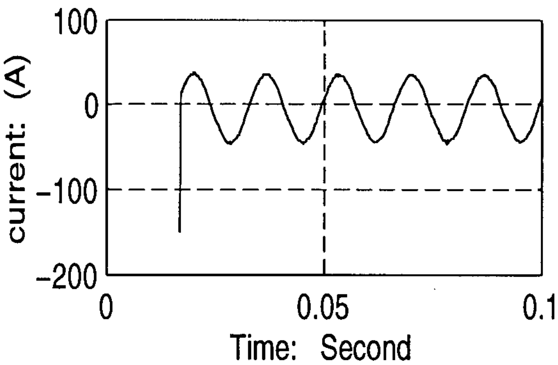


Fig.D18 10% Winding Fault

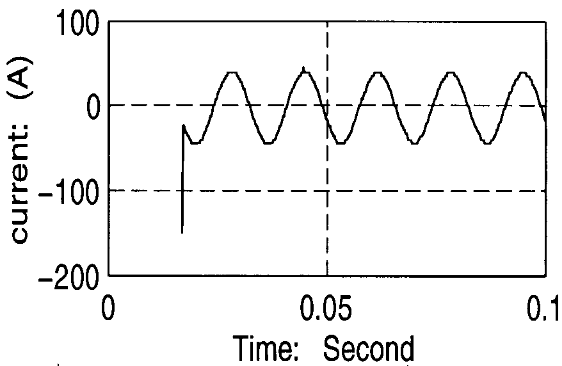


Fig.D19 7.5% Winding Fault

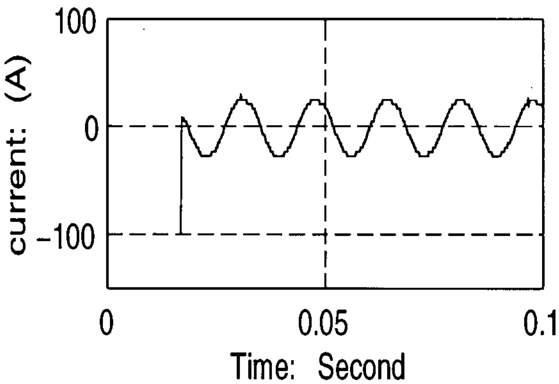


Fig.D20 7.5% Winding Fault

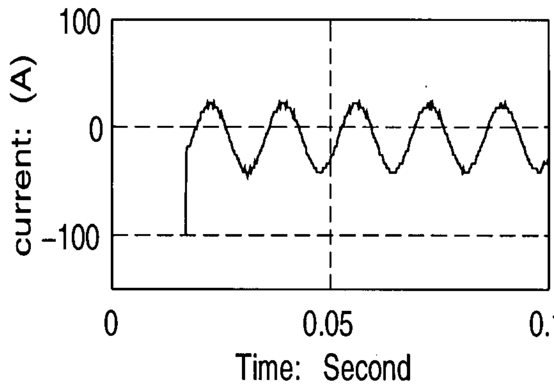


Fig.D21 10% Winding Fault

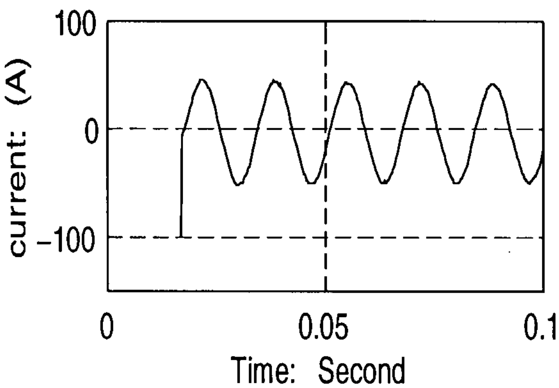


Fig.D22 10% Winding Fault

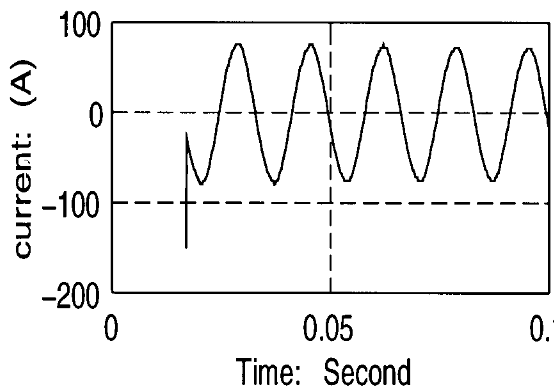


Fig.D23 10% Winding Fault

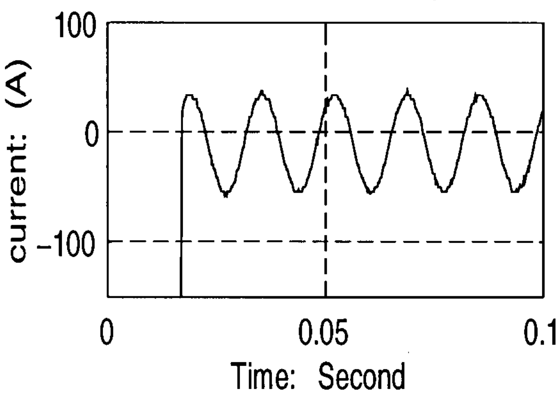


Fig.D24 10% Winding Fault

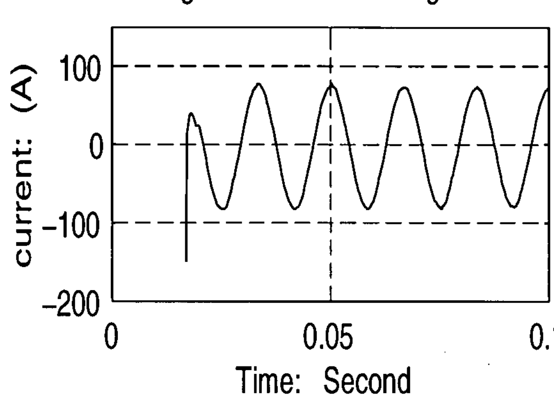


Fig.D25 10% Winding Fault

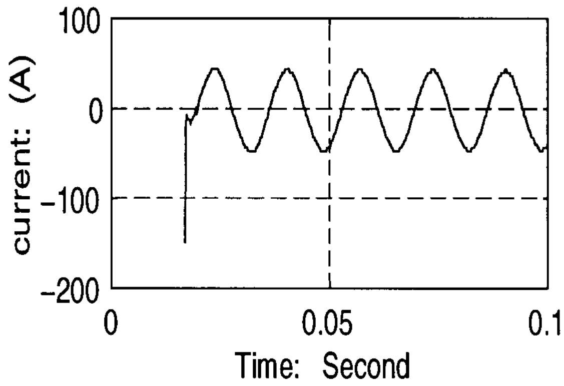


Fig.D26 10% Winding Fault

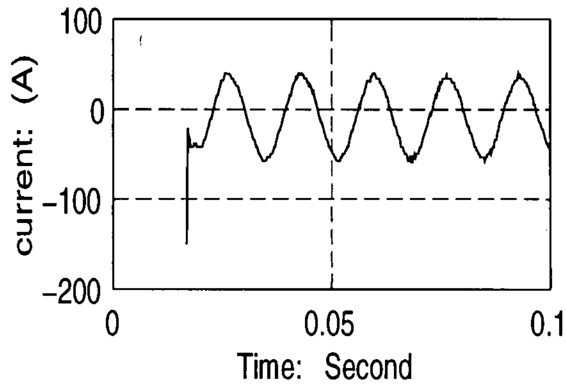


Fig.D27 7.5% Winding Fault

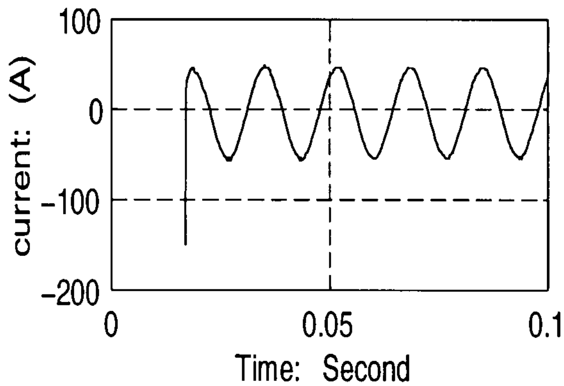


Fig.D28 7.5% Winding Fault

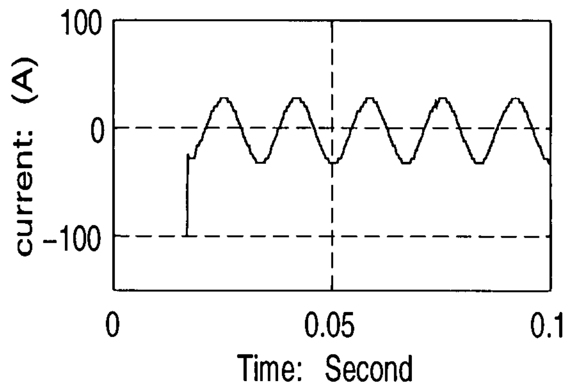


Fig.D29 7.5% Winding Fault

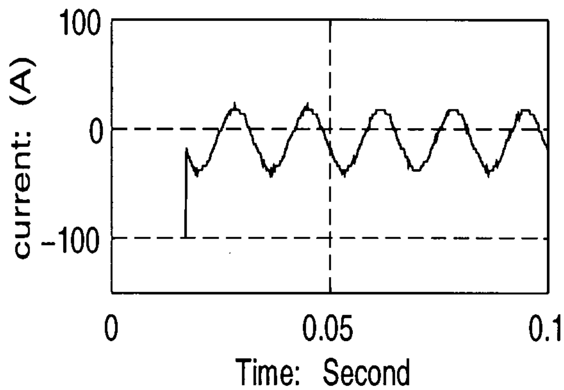


Fig.D30 10% Winding Fault

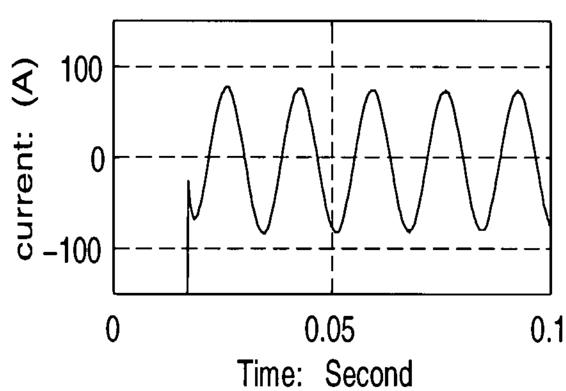


Fig.D31 10% Winding Fault

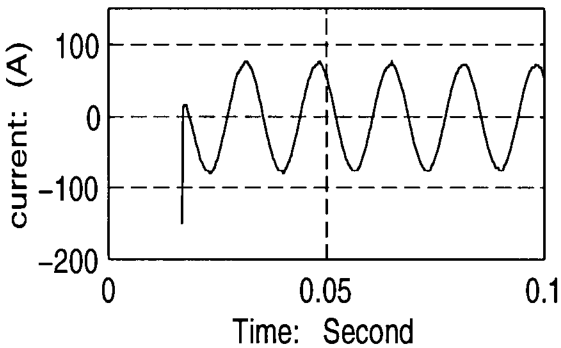
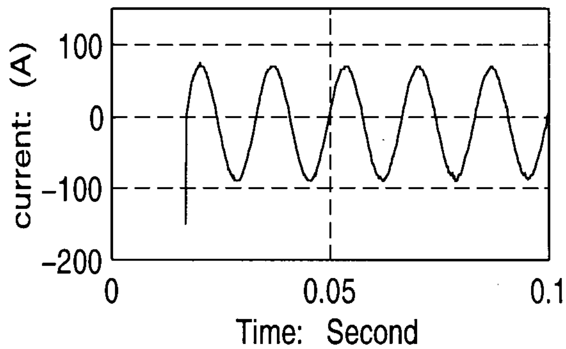


Fig.D32 10% Winding Fault



Simultaneous Internal Fault with Inrush Currents: 9 Cases

Fig.D33 100% Fault & Inrush

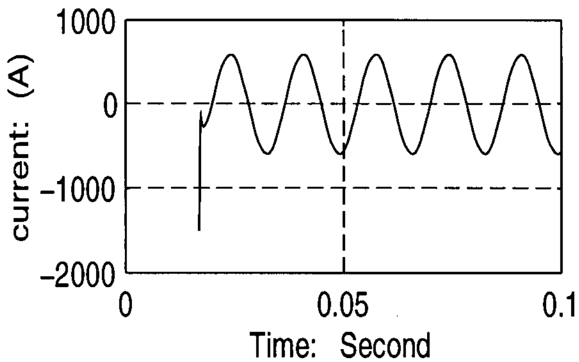


Fig.D34 100% Fault & Inrush

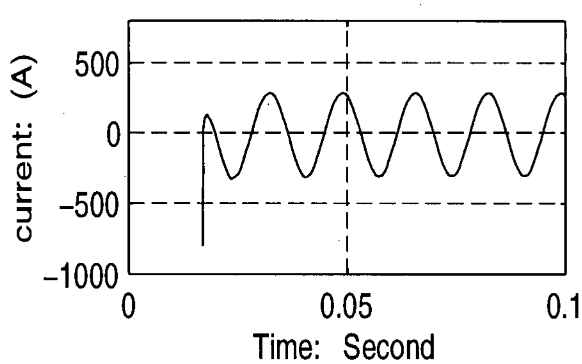


Fig.D35 100% Fault & Inrush

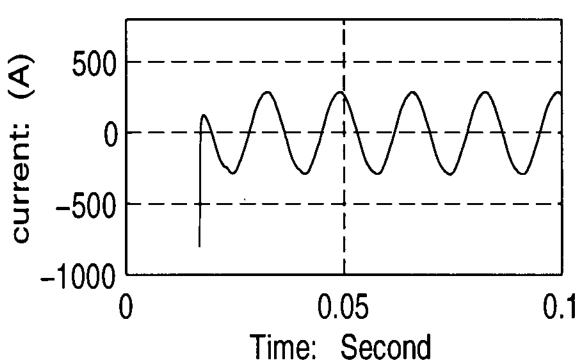
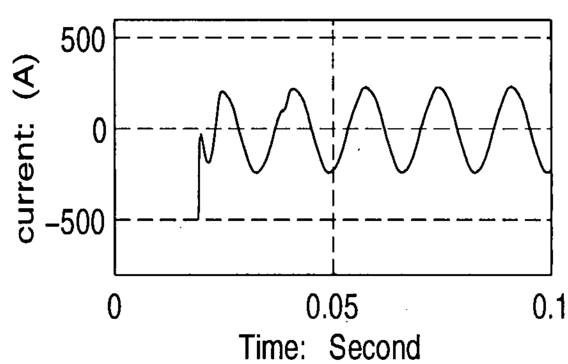


Fig.D36 100% Fault & Inrush



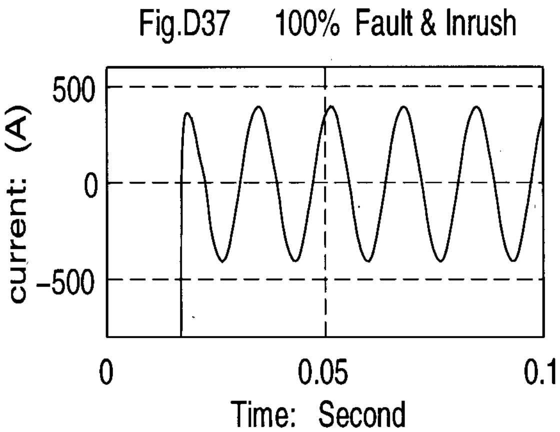


Fig.D37 100% Fault & Inrush
500
0
-500
current: (A)
0
0.05
0.1
Time: Second

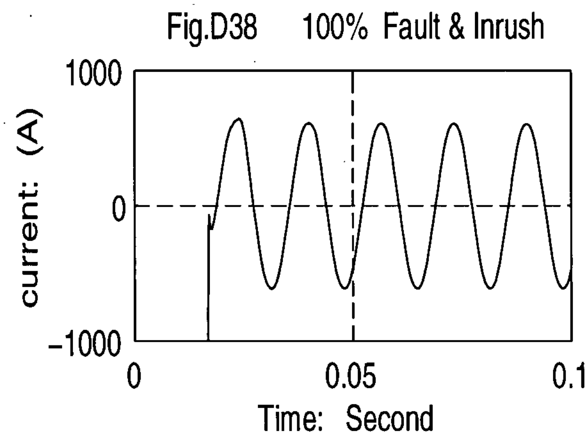


Fig.D38 100% Fault & Inrush
1000
0
-1000
current: (A)
0
0.05
0.1
Time: Second

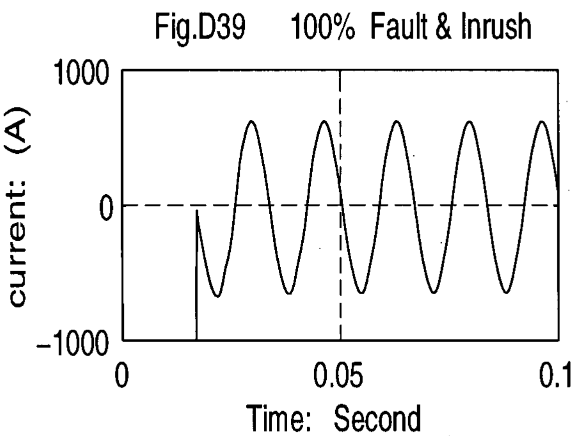


Fig.D39 100% Fault & Inrush
1000
0
-1000
current: (A)
0
0.05
0.1
Time: Second

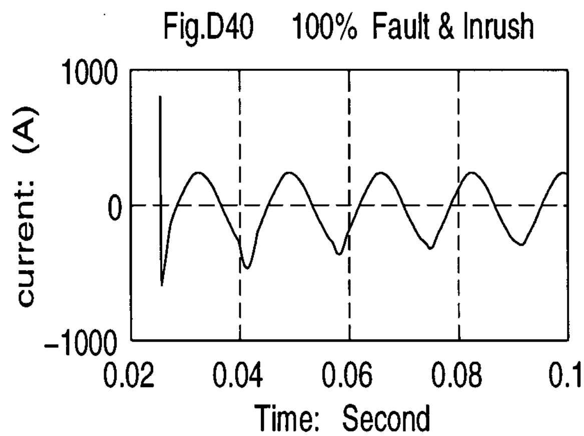


Fig.D40 100% Fault & Inrush
1000
0
-1000
current: (A)
0.02
0.04
0.06
0.08
0.1
Time: Second

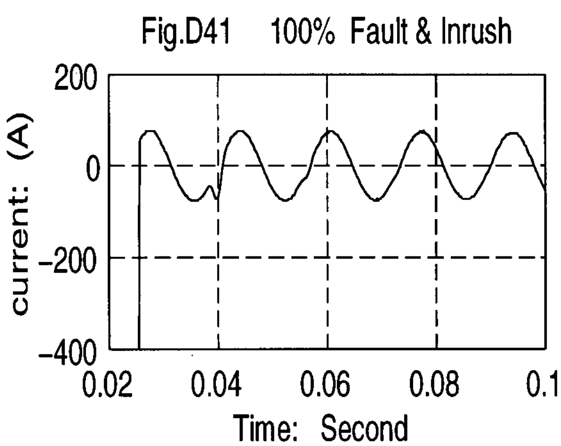


Fig.D41 100% Fault & Inrush
200
0
-200
-400
current: (A)
0.02
0.04
0.06
0.08
0.1
Time: Second