A FAULT DETECTION AND PROTECTION SCHEME FOR A 200 MVA TRANSFORMER USING FUZZY LOGIC

BY

OKOLO OLISADEBE SOLOMON
PG/M.ENG/07/43974

A PROJECT REPORT SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR AWARD OF MASTER'S DEGREE IN ELECTRICAL ENGINEERING (M.ENG)

FACULTY OF ENGINEEIRNG
UNIVERSITY OF NIGERIA,
NSUKKA.

FEBRAURY, 2015.

APPROVAL PAGE

AN IMPROVED FAULT DETECTION AND PROTECTION SCHEME FOR A 200 MVA TRANSFORMER USING FUZZY LOGIC

BY

OKOLO OLISADEBE SOLOMON
PG/M.ENG/07/43974

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR AWARD OF MASTER'S DEGREE IN ELECTRICAL ENGINEERING (M.ENG)
FACULTY OF ENGINEERING
UNIVERSITY OF NIGERIA, NSUKKA.

SEPTEMBER, 2014.

Okolo Olisadebe Solomon (Student)	Signatureé é é é é é é é é é é é .. Dateé é é é é
Engr. Prof. T.C. Madueme (Supervisor)	Signatureé é é é é é é é é é é é é Dateé é é é é
Engr. Prof. E.C Ejiogu (Head of Department)	Signatureé é é é é é é é é é é é é Dateé é é é .
Engr. Prof. (External Examiner)	Signatureé é é é é é é é é é é é é .Dateé é é ..

DEDICATION

This work is dedicated to the Blessed Good Shepherd and the Giver of life Jesus Christ who takes care of all my steps. Again to my lovely Ezinne, my children Mmesoma and Chidiogo and all my family members, friends and well wishers who supported me in various ways toward the success of this programme.

ACKNOWLEDGEMENT

I am particularly grateful to my project supervisor Prof. T.C. Madueme who worked tirelessly to see me through in this project. I equally acknowledge Prof .E.C. Ejiogu (Head Electrical Engineering Department), Engr. D. Nnadi, Prof. E.S Obe, Prof. M.U Agu, Dr. B.O Anyaka and all staff of the Electrical Engineering Department.

ABSTRACT

Condition monitoring of Electrical power equipment has attracted considerable attention for years. The aim of this work is to use Fuzzy logic (FL) Tool Box in building a simulation system that will diagnose all kinds of incipient faults, phase to phase fault and overloading in a transformer and monitor its conditions. Current and rate of change of current with time have been identified as the input variables, duly represented in the programme as ñErrorò and ñError-Dotò. These variables have their universe of discourse from -1.5 to 1.5 and from -10 to 10 respectively. Fuzzy logic sensor is designed to monitor the current(i) conditions of the transformer at both ambient and full load. The results from the research show that whenever the output response is zero the current in transformer is normal. This is obtained when input values of [0] and [0] are injected into the system to produce a response of ñ$6e^{-017}$ò which is approximately zero. Whereas if the output response is greater than zero it implies that the transformer current is rising beyond normal and protection scheme should be alerted. This condition is achieved when input values of [-1.5] and [5] are used on the system to give a response of ñ+5ò. However, if the response is less than zero then the transformer current is below normal, hence the protection scheme should be alerted. To investigate this, input values of [1.5] and [-5] give a response of ñ-5ò. Fuzzy logic is used as an expert system that assesses all information keyed in at the front panel to analyze and predict the condition of the transformer at any time.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

I: Current

R: Resistance

DGA: Dissolved gas- in oil analysis

P.D: Partial Discharge

F.A : Furan analysis

F .R.A: Frequency response analysis

R.V.M: Recovery voltage measurement

KVA: Kilo Volt Ampere

VA: Voltage Ampere

EMF: Electro motive force

IE: Eddy current

PH: Hysteresis loss

V : Voltage

FL: Fuzzy logic

FLOPS: Fuzzy logic production system

DOM: Degree of membership

RSS: Root-sum-square

CHAPTER ONE

INTRODUCTION

Transformers are static electromagnetic machines designed for transformation of one alternating voltage to another with different voltage and current characteristics [1]. Large power transformers belong to a class of very expensive and vital components in electrical power system. In practice, they are protected against internal short circuit and over-heating of which capacity percentage differential relays are universally adopted for internal short circuit protection [2].

A transformer can be single or multiphase depending on the primary and secondary windings. There are so many faults and losses which can occur in transformer both on load and off load. Most of the losses like Eddy current and hysteresis in the core and the I^2R loss in the windings result to over current may culminate to other dangerous conditions like reduction of dielectric strength, earth fault and finally burning of the windings. Tests are carried out during commissioning and while in service to ensure reliability.

Transformers are designed such that as little energy as possible is wasted inside it, thus ensuring that its efficiency is as high as possible [3]. Hence:

1. Low resistance copper coils are used so that internal energy (I^2R) losses in the windings are small.
2. Laminated core is used to reduce eddy current losses.
3. The core is made of soft magnetic materials in order to reduce the energy required to bring about magnetic reversal (hysteresis loss).

4. Efficient core design is adopted to ensure that all the primary flux is linked with secondary.

Despite all engineering design and constructional efforts, an ideal transformer called ñlossless transformerò cannot be practically obtained because of the inherent and unavoidable losses and faults. Sequel to this, detection schemes are deviced to monitor and sieve out the occurrence of such faults. The inception of the faults introduces abrupt changes of amplitude and phase in voltage and circuit signals. Faults allow abnormal large currents to flow, resulting in over heating of power system components. If the fault is typically a short circuit, it can exist as an electrical arc in a fluid (such as air). The extremely high temperature in arcs will vaporize any known substances causing equipment destruction and fire [4]. Faults can cause three-phase system voltages to rise above their acceptable ranges or to be unbalanced causing three-phase equipment to operate improperly. They can cause the system to become unstable and loose synchronism. There are conventional fault detection schemes which include typical electrical sensors, which are of bimetal-strip, switch or thermostat type or thermocouple, thermo-resistor detectors and thermistor. Non electrical sensors are of gas or fluid filled type. Other constructional features are employed for the detection such as bulchholz relay and transformer breather with desiccant.

A fuzzy logic as an alternative method of fault detection and protection on power transformer has been adopted for this project research.

Soft computing has been proposed as a method to solve real-world problems, which defy conventional approaches. In fact, even when expert knowledge is available, it is often more easily stated in descriptive form i.e. as statement like ñIF a sign of certain type appears THEN one or more faults must be presentò.

From a practical point of view, diagnostic knowledge often comes in form of a kind of compendium of descriptive expert knowledge and relevant raw system data.

Fuzzy logic incorporates a simple rule-base if ñX AND Y THEN Zò approach to solving problems rather than attempting to model a system used which rely on the operator and experience rather than technical understanding of the system. Design of a fuzzy logic sensor needs qualitative knowledge about the system under consideration.

Unlike most conventional and modern detection schemes, fuzzy logic sensors are capable of tolerating uncertainties and imprecision to a greater extent. Hence they produce good results under changing operating conditions and uncertainties or imprecision in system parameters.

1.1 BACKGROUND OF THE STUDY

Fuzzy logic is a subset of conventional (Boolean) logic that has been extended to handle the concepts of partial truth-values, between ócompletely trueô and ócompletely falseô.

The ideas of fuzzy logic dates all the way back to Plato who proposed that there is a third region between true and false. Fuzzy logic is a technique of making a choice answer to question other than yes or no. It resembles human reasoning in the use of approximate information and uncertainty to generate decision. The fuzzy logic is a designed technique used in providing formalized tools for dealing with imprecision that are intrinsic to many problems. The fuzzy set theory implements clauses, of data that are not sharply defined. To that effect, since transformer is a vital component in power system, it needed such precision technique in its fault detections and protections.

1.2 STATEMENT OF THE PROBLEM

High voltage transformers are unavoidably subject to various faults and relays like differential, bulchholz and directional relays with sensors are usually adopted to detect and transmit (relay) the decision to a circuit breaker which trips or opens the power system. These modern detection schemes do not tolerate uncertainties or impression under changing operating conditions in a given system parameters, hence fuzzy logic sensors were investigated.

1.3 OBJECTIVE OF THE STUDY

The objective of this work is to use fuzzy logic method of sensing and protection on a high voltage transformer in place of the conventional protective scheme.

1.4 SIGNIFICANCE OF THE STUDY

One advantage that fuzzy sets offer to constructors of experts system is the ability to work in terms of familiar words. This eases the task of system construction, the domain expert can sketch out rules in English language terms, which are familiar, and this facilitates communication between expert and knowledge engineer [5].

It is more than relevant, contrary to opinions, that it lacks precision. However, the logic solves problems related to non-linear system in the same manner human beings do. For instance, the way we eat requires no measurement of our mouth size, and the ðbolusô size, yet we achieve this by more than 95% success every time. Similarly, fuzzy logic based appliances really do things with high degree of adaptability, self-adjustability and robustness. To this effect, many video and digital cameras do not need manual focusing ability, which make the object invariably focused. Fuzzy logic is found in a variety of control applications including chemical process control, manufacturing and in some consumer products like washing machine, video cameras and automobiles. Fuzzy logic can be used for condition monitoring of electrical power equipment and also in the design of a simple proportional temperature controller with an electric heating element and a variable-speed cooling fan, and so on.

1.5 SCOPE OF THE STUDY

The scope of this work is limited to the study of the most prevalent faults, their detection and protection in high-voltage transformers of 200MVA power rating using fuzzy sensors.

CHAPTER TWO

LITERATURE REVIEW

2.1.0 THE TRANSFORMER

A practical transformerôs physical behavior may be represented by an equivalent circuit model as shown in fig 2.1 .

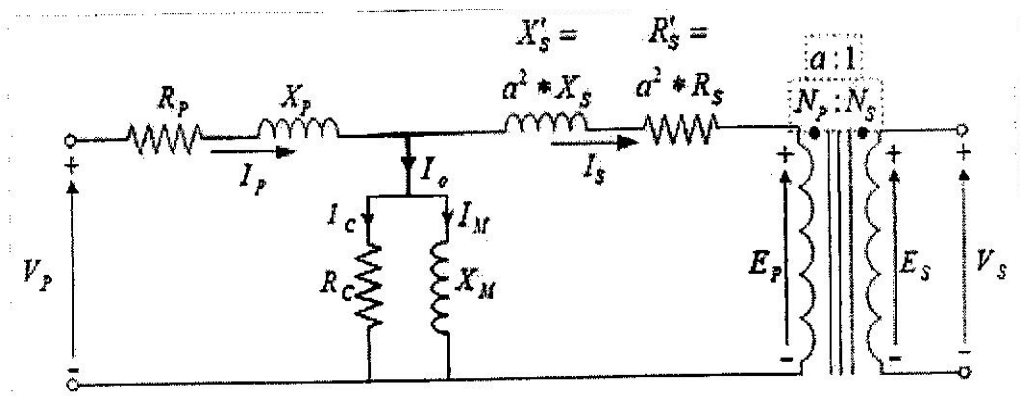


Fig 2.1: Real transformer equivalent circuit

Winding losses and leakages and leakage reactances are represented by the following series loop impedances of the model;

Primary winding: Rp,Xp.

Secondary winding: Rs,Xs.

In normal course of circuit equivalence transformation, Rs and Xs are in practice usually referred to the primary side by multiplying these impedances by the turns ratio squared,$(Np/Ns)^2 = a^2$.

Core loss and reactance is represented by the following shunt leg impedances of the model:

Core losses:Rc
Magnetizing reactance:Xm.
Rc and Xm are collectively termed the magnetizing branch of the model.

Core losses are caused mostly by hysteresis and eddy current effects in the core and are proportional to the square of the core flux for operation at a given frequency. The finite permeability core requires a magnetizing current *I*m to maintain mutual flux in the core. Magnetizing current is in phase with the flux, the relationship between the two being non-linear due to saturation effects. However, all impedances of the equivalent circuit shown are by definition linear and such non-linear effects are not typically reflected in transformer equivalent circuits. With sinusoidal supply, core flux lags the induced emf by 90^0.With open-circuited secondary winding, magnetizing branch current Io equals transformer no-load current.

The resulting model, though sometimes termed œexactô equivalent circuit based on linearity assumptions, retains a number of approximations. Analysis may be simplified by assuming that magnetizing branch impedance is relative high and relocating the branch to the left of the primary impedances. This introduces error but allows combination of primary and referred secondary resistances and reactances by simple summation as two series impedances.

Transformer equivalent circuit impedance and transformer ratio parameters can be derived from the following tests that will be discussed; open-circuit test, short-circuit test, winding resistance test, and transformer ratio test.

Contrasted with generators, in which many abnormal circumstances may arise, transformers may suffer only from winding short circuits, open circuits, or overheating. In practice relay protection is not provided against open circuits because they are not harmful in themselves. Nor in general practices, even for unattended transformers, is heating or overload protection provided; there may be thermal accessories to sound an alarm or to control bank of fans, but with only a few exceptions, automatic tripping of the transformer breaker is not generally practiced. An exception is when the transformer supplies a definite predictable load. External fault back-up protection may be considered by some as a form of overload protection, but the pickup of such relaying equipment is usually too high to provide effective transformer protection except for prolonged short circuits. There remains, then, only the protection against short circuits in the transformer or their connections, and external fault back-up protection. The actual working condition of transformers in power grid is an important aspect viewing the stability of the power supply. In order to conserve transformer ñhealthò, additional control devices are necessary. A monitoring system offers the possibility to measure transformers working condition over a long period of time. Trends which point out a degradation of transformers condition can be detected early by generating alarms and warning messages. Slowly developing faults can be repaired before they lead to damages.

It is worthy to note that information on name plates of transformers also gives guide to determine when fault condition arise; such as Change in oil quality, Earth fault, Rise in transformer temperature, Oil level, Abnormal noise, and damage to bushing insulator. Hence conventional fault detection and protection schemes can be applied on the transformer.

2.1.1 INFORMATION ON NAME PLATES OF THREE DOUBLE WOUND TRANSFORMER

The information gives guide to determine when fault condition arises:

1. Manufacturerôs name
2. Manufactureôs serial number

3. Continuous maximum rated load in KVA.

4. Continuous rated load in KVA for tertiary windings

5. Number of phases in higher voltage side.

6. Number of phases in lower voltage side.

7. Frequency

8. For continuous maximum rating (a) higher voltage VA and (b) lower voltage VA.

9. For special rating (a) higher voltage VA and (b) lower voltage VA.

10. Impedance voltage in percent for special continuous rating.

11. Vector diagram reference number and symbol.

12. Type of cooling.

13. Quantity of circulating oil in litre per minute.

14. Quantity of circulating water in litre per minute.

15. Quantity of air in cubic meter per minute.

16. Total quantity of oil in litre and weight in kg.

17. Total weight of transformer.

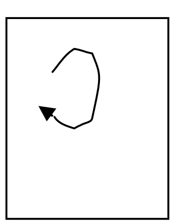
2.1.2 TRANSFORMER LOSSES

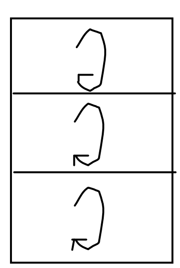
1 CORE LOSS

(i). **Eddy current loss:** As electromotive force (e.m.f) is induced on a transformer core, it generates current in the core in the same way as it does in a conductor. This current is called eddy current and would cause a large loss of power and excessive heating [7].

If the core is made of laminations insulated from one another, the eddy current is confined to their respective sheets and it is reduced.

Solid core





Split core

Fig 2.2a: Use of lamination core to reduce Eddy current

If the core is split into three as shown above, an emf per lamination is only a third of that generated in the solid core and the cross sectional area per path is also reduced to about a third. With reduced area, resistance is increased so that resistance per path is roughly three times that of the solid core. Consequently, the current is about $1/9^{th}$ of that in solid core.

Hence ,

$$\frac{I^2R \text{ loss per lamination}}{I^2R \text{ loss in solid core}}$$

$$= (1/9)^2 \times 3 = I^2 \times 3 = 1/27 \quad - \quad - \quad - \quad - \quad (2.1)$$

Since there are three laminations

Then:

$$\frac{\text{Total Eddy-current loss in lamination core}}{\text{Total Eddy-current loss in solid core}}$$

$$= 3/27 = (1/3)^2 \quad - \quad - \quad - \quad - \quad - \quad (2.2)$$

It follows that the eddy-current loss is approximately proportional to the square of the thickness of the lamination. Hence the eddy current loss can be reduced to any desired value not less than 0.4mm for economic justification. It can still be reduced considerably by the use of silicon-iron alloy, usually about 4% silicon. The resistivity of this alloy is much higher than that of ordinary iron. Therefore thin and high resistivity laminations effectively reduce the eddy current loss to small proportions. The induce emf is proportional to FBm (since 4.44FNØm) this causes the flow of eddy current.

$$I_e = \frac{\text{emf}}{\text{Impedance of core path}} \quad - \quad - \quad - \quad - \quad (2.3)$$

So $p_e = KF^2\ Bm^2$ watts/m^3 - - - - - (2.4)

Where k = constant
F = frequency of magnetic flux.
Bm = maximum flux density in tesla.

Eddy current is proportional to the square of mmf exciting the core.

Solid magnetic cores are electrical conductors, which would in effect form a single short-circuited turn that carries large induced eddy current. It is reduced by using high turn resistivity silicon steel made up in insulated lamination, which are usually 0.355mm. The length and resistance of eddy current path they increase. The lamination is usually oriented to the direction of flux.

ii. HYSTERESIS LOSS: When the coils of a transformer carry an alternating current it produces magnetic flux which is induced on the core. The magnetizing force rises and falls in accordance with magnetizing current, which is basically sinusoidal in nature. This variation does not cause magnetic field strength (B) and magnetizing force (H) to vary according to the magnetic characteristic but as a tool as shown in fig. 2.1.

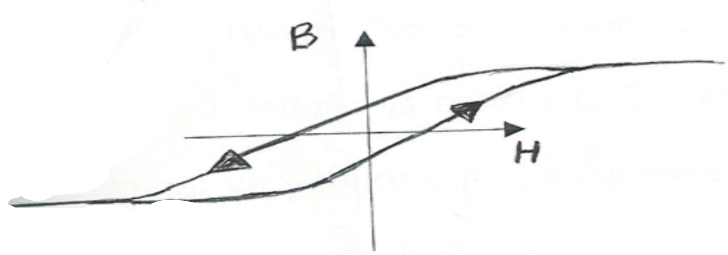


Fig 2.2b: Hysteresis loop

The larger the loop, the greater the energy required to create the magnetic field. This energy which is proportional to the area of the loop is a loss (as heat) per cycle, so it is called hysteresis loss. Again, it is proportional to the frequency of exciting magneto motive force.

Hysteresis loss (Ph) = kvfB m^x watts.

Or = $kfBm^n$ watts/m^2 - - -- - (2.5)

Where k = constant for a given specimen and range of flux density,

V = volume of iron in cubic metres,

F = frequency of alternating mmf,

Bm = maximum flux density in telsa,

X and n depends upon quality of iron empirically found to the in range of 1.5-2.5. So, hysteresis loss can be reduced by selecting good electrical steel having a narrow hysteresis loop.

Once the applied voltage is constant, Bm and f are constant. The core losses do not vary more than 2% between no and full load, so it is assumed to be constant at all loads.

2.1.3 TEST ON A TRANSFORMER

1. Open Circuit Test:- In this test, the rated voltage and frequency on the name plate is applied to the primary terminal with the secondary terminal open circuited by the voltage. The wattmeter reading on the primary side is taken as the measure of the total iron losses while the ratio of $\frac{v_1}{v_2}$ gives the ratio of the number of turns.

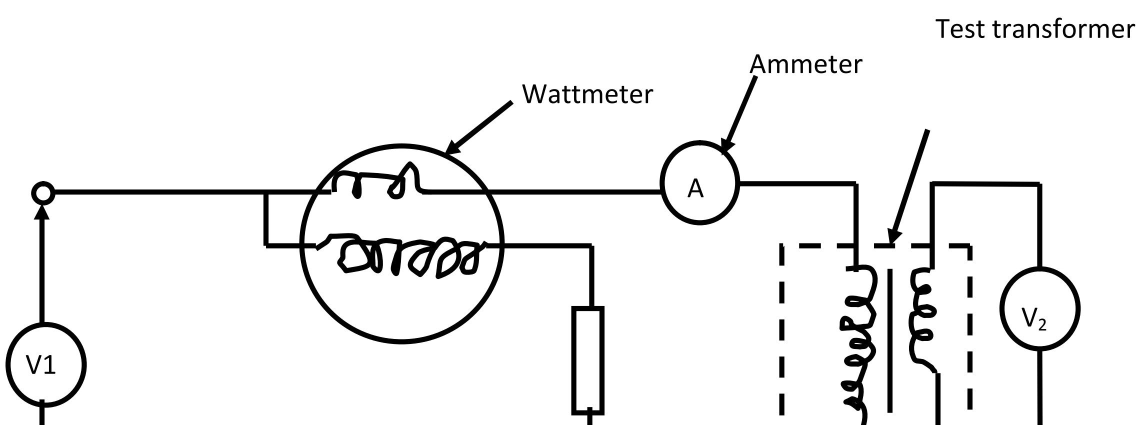


Fig: 2.3: Open Circuit test

2. Short Circuit Test:- The secondary terminals are short circuited through an ammeter. The primary winding is supplied with a considerable reduced voltage of such a value that the current in the short circuiting ammeter reads full load current while that of the ammeter in primary reads full load primary current. The wattmeter reading on the primary is taken as the measure of the copper losses in the transformer.[8]

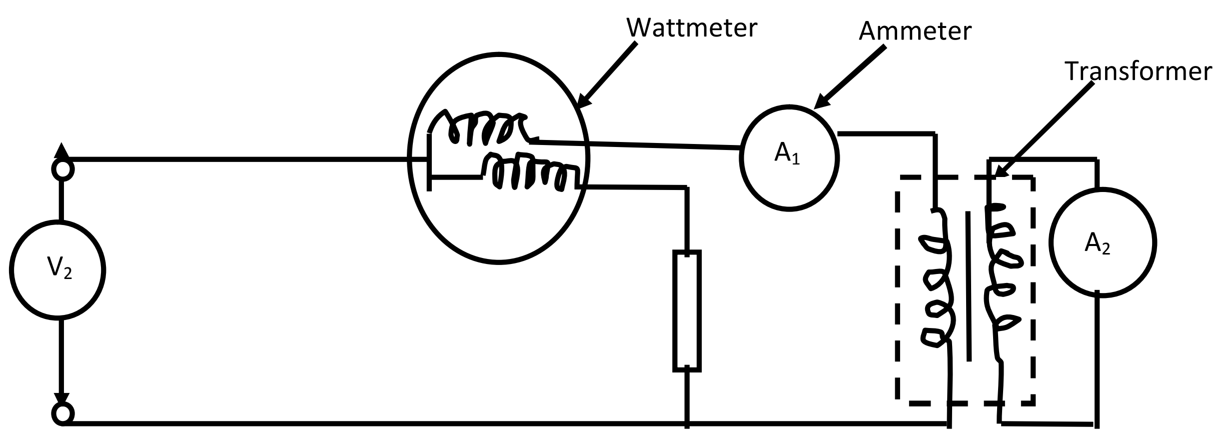


Fig. 2.4: Short Circuit Test

3. Ration Test:- This is done by employing a radiometer between higher and lower voltage side.

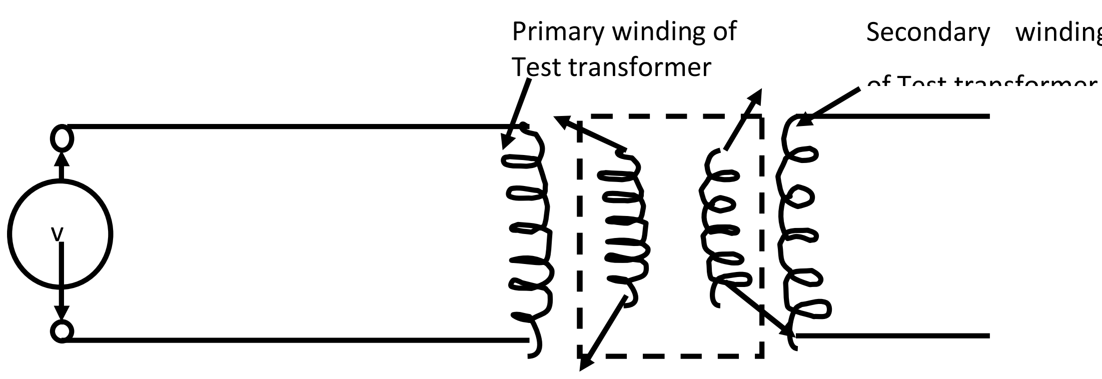


Fig. 2.5: Ratio Test Radiometer transformer

This consists of a primary winding connected in opposition to the test transformer primary; the secondary with tapped points is connected through an ammeter to the test transformer secondary winding. The taping are adjusted until a null reading is obtained on ammeter. At this, the ratio of the test transformer equals that of the ratio meter which can be determined from the known tapings.[9]

2.1.4. FAULTS IN TRANSFORMER

Though transformer is a static device, protected by the main circuit breaker thus there is almost no possibility of external fault to it other than internal faults like; open circuit fault, overheating fault or rise in transformer temperature, winding short circuit fault, change in oil quality, earth fault, change in oil level, abnormal noise and damage to bushing insulators.

1. Open Circuit Fault:-This occurs when one phase of transformer becomes open and as such cause temperature rise in the transformer.

2. **Change in Oil Quality:-**This could be as a result of the following reasons;

i. Presence of acid in the transformer oil (Acidity):- At a high temperature in presence of air and bare copper, the insulating oil breaks down to form acids. This results in corrosion of metal surface and lowers insulation level.

ii. Presence of Moisture in the transformer oil:- This comes in through the transformer breather. Large quality of moisture in the oil causes corrosion while small quality with the some contaminants like paper and fibre which may be introduced during construction, absorb the moisture and tend to line up across the insulating gaps to trigger off a breakdown [1].

iii. High Oil Temperature: This can crack the oil into lighter fractions with low flash points or into inflammable gases.

iv. Presence of carbon in the transformer oil: Due to arcs produced in an on-load tap-changer, carbon will be in the oil which lowers the quality.

v. Presence of Hydrogen and Carbon Dioxide: - Electrical faults may burn the oil and insulation, producing hydrogen and carbon dioxide. These gases lead to further burning of the core laminations.

3. Earth Fault:- Earth faults may occur in a transformer which include break in earthing arrangement, single phase to earth, two phase to earth and three phase to earth. That is to say that an earth fault involves a partial breakdown of winding insulation to earth.

4. Rise in Transformer Temperature: - Overheating of the transformer may arise which may be due to short circuiting of laminations in the core or faulty cooling system. Heat leads to decomposition of solid and liquid insulating material and may result in emission of inflammable gas.

5. Change in the Transformer Oil Level:- Oil leakage from gaskets, tank joints, bushings, etc leads to a reduction in oil level. Insulating liquid level below the permissible mark endangers the system. If below-20^0 C the danger is that it might have absorbed moisture.

6. Abnormal Noise:- Irregular or cracking noise from a transformer may be due to loosening of core bolts or other clamping parts or as a result of operating the transformer at a voltage higher than the rated value [1].

7. Damage To Bushing Insulators:- Leads from the windings are brought out to the bushing with its associated insulation or mechanical strength and connection. This can be damaged during shipping, off-loading or installation.

2.1.5 CONSTRUCTIONAL FEATURE TO REDUCE FAULTS AND INCREASE EFFICIENCY.

There are various transformer parameters and constructional features that could reduce faults and increase transformer efficiency. These include;

1.Core: The core is constructed from cold-rolled grain oriented material. The core plates are insulated on the sides. The 0.3mm thick laminations are also stress relieved. The sizes of the laminations are stepped to produce limbs and yokes of almost circular or rectangular cross section.

The core is the steel system, which forms the magnetic circuit. It is around the core that the windings are wrapped. A transformer is described as core type if the windings envelope the core, and shell type if the windings are partially enveloped by the core.

2. Windings:- The windings are either rolled or rectangular copper or aluminum conductors. Round conductor windings consists of individually wound coil sections connector in serial to produce the phase winding. Windings with rectangular conductors are of the continuous disc type or the layer type. Axial and radial ducts are channels in the windings that allow cooling and insulating liquid to quickly and uniformly dissipate heat due to losses. The low voltage windings are thicker because it carries more current and it is wound to rest round the core. The high voltage windings are thinner and are wound on the high voltage side of the transformer. The tertiary windings where it exists, is placed between the low voltage windings and the core.[7]

3. Insulation: The major insulation comprises the insulation between the low voltage winding and the core and between the high voltage winding and low voltage windings as well as between adjacent limbs and insulation between the coils and core yokes. The minor insulation consists of the insulation on individual turns and between layers.

Only high quality insulating material such as cable paper and pressboard are used, all moisture is removed from the insulating materials by careful drying. The insulation structure is designed from impulse voltage distribution to give adequate dielectric strength both for continuous steady-state loading and incoming surge voltages.

4. Dehydrating Breather:- This is the part through which transformer communicates with outside air. When the insulating liquid heats up It expands and the levels arises forcing air out of the tank through the breather. When the operating temperature of the transformer drops, the volume of the insulating liquid decreases and a corresponding quality of air is simultaneously sucked in from the atmosphere leaving behind particles dust and water into the lower part through the breathing openings.[7]

5. Desiccant:- Attached to the breather is the desiccant glass. The desiccant is either pure aluminum silicate gel impregnated with cobald chloride. Desiccants have sizes of about 3mm and a very good absorption power. In the active condition, their appearance is crystalline blue. On taking up moisture, the colour changes to pink. In the dehydrating breather, moisture is almost completely retrieved from the air flowing into the conservator by this desiccant when transformer cools down. The lowering of the dielectric strength of the insulants due to moisture ambient air and the formation of condensation. So the hydrating breather with the desiccant increase the operational reliability of transformers.[7]

2.1.7 CONVENTITIONAL FAULT DETECTION AND PROTECTION SCHEME.

Conventionally, faults are detected in transformer by the following methods:

1. Oil Quality detection:-This can be performed as follows;

i. **Smell:** Average sense of small will detect the characteristics smell of acid in oil.

ii. **Lab Test:** A laboratory test of acid in oil will indicate the presence. If it is higher than 1.0mg/kg/hg, it is unacceptable.

iii. **Sight:** Fresh oil is clearer than misty and muddy appearance of wet oil. Again fibre can be seen in a glass of oil under bright light.

iv. **Crackle Test:** To detect moisture, a red-hot wire plugged into a test tube containing wet oil will cause cracking [1].

v. **Temperature Monitoring Devices:** High oil temperature can be detected by the thermometer type transformer oil temperature control, which measures the temperature difference in the oil at various loads. Thermometer winding temperature control, measures the temperature difference between the windings and coolant in the transformer tank and it depends upon the current in the winding (I^2R).

vi. **Buchholz Relay:** This is a gas actuated relay which detects gas ingress that may lead to decomposition of oil evolution of gases.

vii. **Insulation Resistance:** This is carried out by applying a voltage between high voltage windings and earth, low voltage winding, and earth and between high and low voltage winding. This is done with a megger insulation tester. The result should not be less than one mega ohms.

viii. **Oil Level Indicator:** Shows the dielectric level in transformer tank at every moment.

ix. **Oil Level Gauge:** This gauge has a transparent glass like thermometer through which the oil level can be seen. Insulating liquid level below the permissible mark endangers the system. If below ï 20^{oc}, the danger is that it might have absorbed moisture.

x. **Dielectric Strength:** The quality of oil is determined by the ñfoster oil test ósetô which introduces a voltage that increases at 2KV per second to two electrodes immersed in oil. The voltage measure at the moment of breakdown determines the condition. Acceptable breakdown value for oil in service is 20KV while that of new oil is 24KV [7].

2. Sensors: A sensor like potentiometer is an electromechanical transducer that converts mechanical energy into electrical energy. The input is in form of mechanical displacement. A voltage is applied across the fixed terminals and the output voltage is measured across the variable terminal and ground, which is proportional to the input displacement.

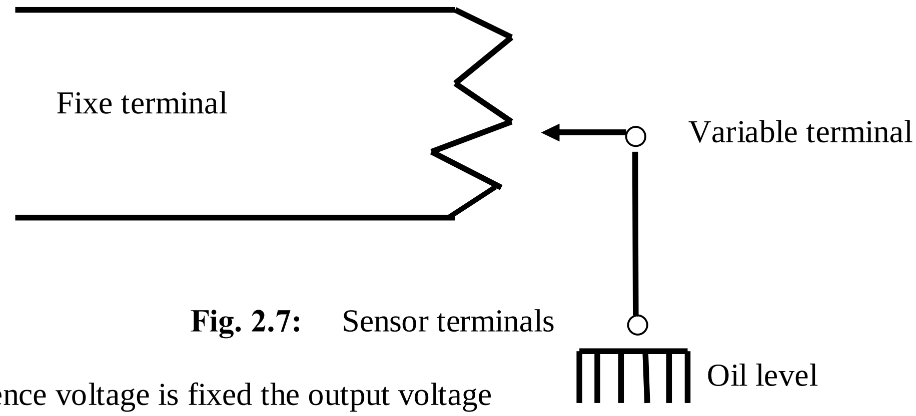


Fig. 2.7: Sensor terminals

When the reference voltage is fixed the output voltage

$e_{(t)} = k_S \text{Ø}c\,(t)$ - - - - - - (2.6)

Where $e_{(t)}$ = output voltage

Ks = proportional constant

Ø_C (t) = shaft position.

For rotary system

$Ks = E/2\pi N \quad (V/rad)$ - - - - - (2.7)

E = reference voltage.

N = Rotor Speed

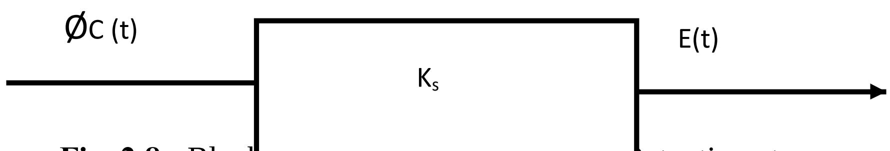


Fig. 2.8: Block Diagram Representation of Potentiometer

It can be used to indicate oil level, which may be calibrated to indicate the change in volume due to temperature change in the oil.

3. Relays: They are electric devices that are designed to interpret input conditions in a prescribed manner and after specified conditions are met to respond to cause contact operation or similar abrupt change in associated electric control circuits

[10]. Relays are classified as protective, regulating, enclosing, synchronism check monitoring and auxiliary types.

Now the principal relays and systems used for transformer protection are:

1. Buchholz devices providing protection against all kinds of incipient faults.
2. Earth-fault relays providing protections against earth faults only.
3. Over current relays providing protection mainly against phase-to-phase faults and overloading.
4. Differential system providing protection against both earth and phase faults.

Buchholz relay:

Buchholz relay is a gas-actuated relay installed in oil immersed transformers for protection against all kinds of faults. It is used to give an alarm in case of incipient (i.e. slow-developing) faults in the transformer and to disconnect the transformer from the supply in the event of severe internal faults. It is positioned between transformer oil reservoir and transformer main tank. The pipping system is inclined by 9.5 degree.

Constructional features of Buchholz relay.

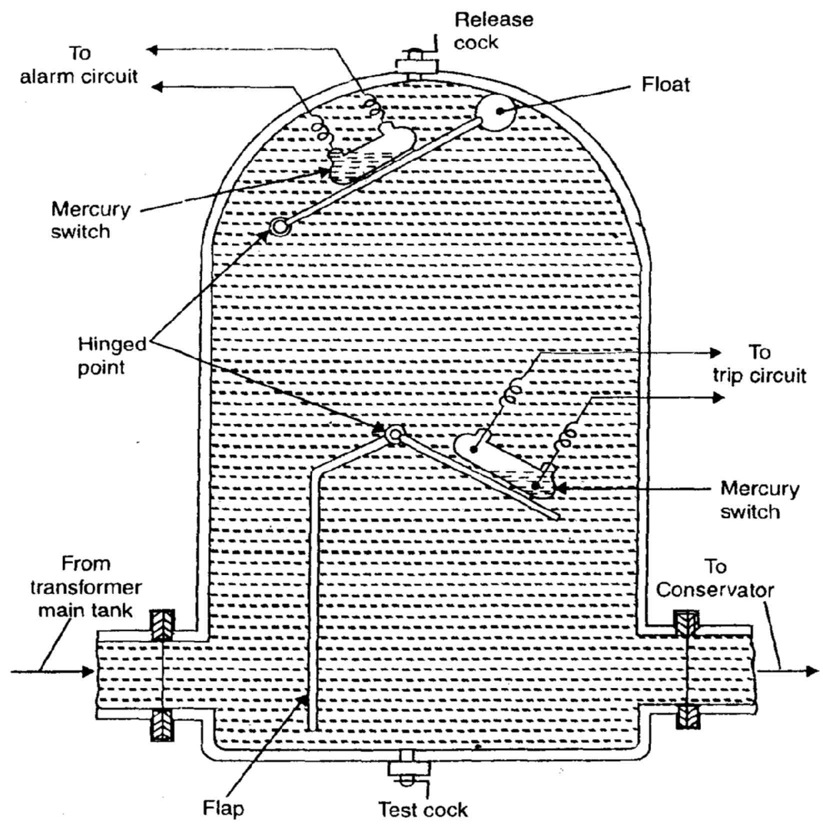


Fig. 2.9: Buchholz Relay

The operation of bucl

1. In case of incipient faults within the transformer, the heat due to fault causes the decomposition of some transformer oil in the main tank. The product of decomposition contains more than 70% of hydrogen gas. The hydrogen gas being light tries to go into the conservator and in the process gets entrapped in the upper part of relay chamber. When a predetermined amount of gas gets accumulated, it exerts sufficient pressure on the float to cause it to tilt and close the contact of the mercury switch attached to it. This completes the alarm circuit to sound an alarm.
2. If a serious fault occurs in the transformer, an enormous amount of gas is generated in the main tank. The oil in the main tank rushes toward the conservator via the Buchholz relay and in doing so tilts the flap to close the contacts of mercury switch.

This completes the trip circuit to open the circuit breaker controlling the transformer.

Advantages:

i It is the simplest form of transformer protection

ii. It detects the incipient faults at a stage much earlier than is possible with other forms of protections.

Disadvantages:

i. It can only be used with oil immersed transformers equipped with conservator tank.

ii. The device can detect only faults below oil level in the transformer. Therefore, separate protection is needed for connecting cables.

iii. The relay is slow, minimum operating time is 0.1second, average time 0.2 second. Such a slow relay is unsatisfactory.

Earth-fault or leakage protection

An earth- fault usually involves a partial break down of winding insulation to earth. The resulting leakage current is considerably less than the short-circuit current. The earth fault may continue for a long time and cause considerably damage before it ultimately develops into a short-circuit and removed from the system. Under these circumstances, it is profitable to employ earth-fault relays in order to insure the disconnection of earth fault or leak in the early stage. One method of protection against earth-faults in a transformer is the *core-balance leakage protection shown in Fig 2.10

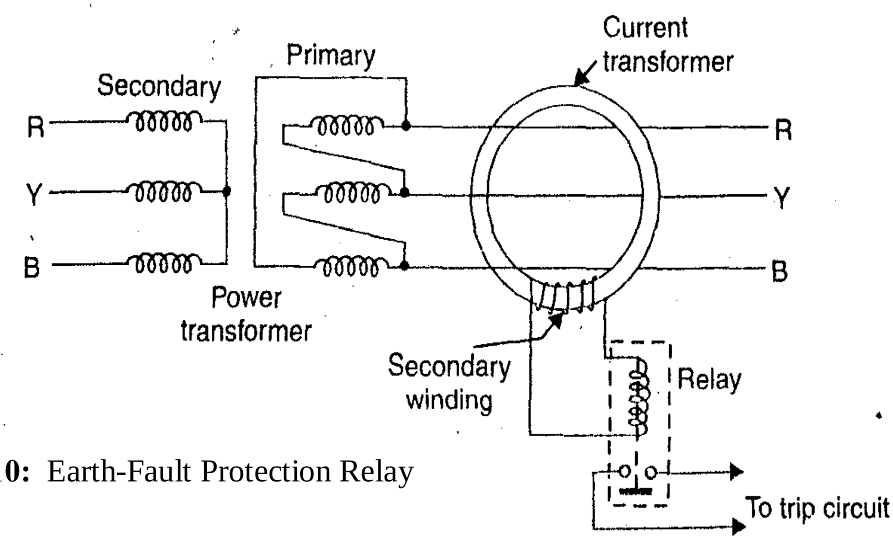
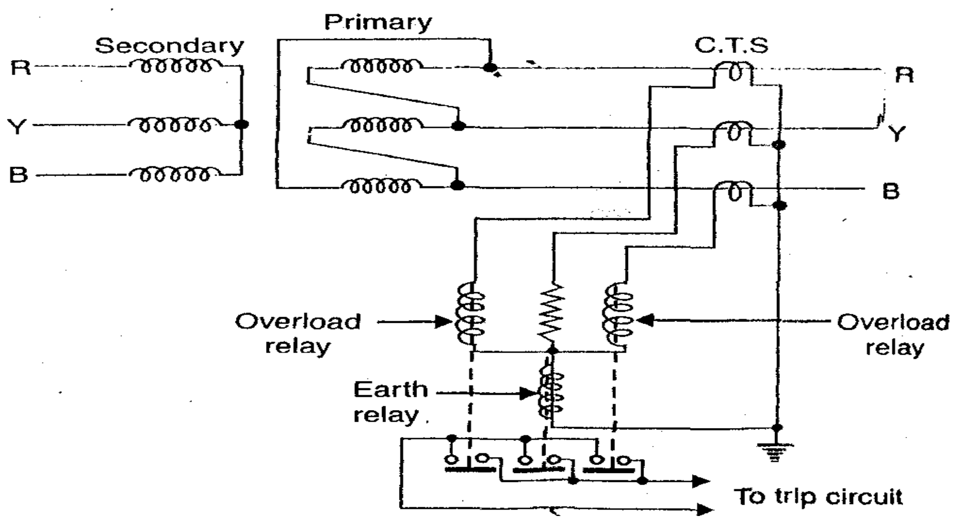


Fig. 2.10: Earth-Fault Protection Relay

The disadvantage of the core-balance protection described above is that it can not provide protection against overload. Also if a fault or leakage occurs between phases, the balance relay will not operate.

Combined leakage and overload protection

Here two overload relays can detect individual overload plus phase to phase fault and the earth fault relay is connected to the junction point of the secondaries of three phase current transformer. Under normal condition the current in the junction will be zero and in abnormal condition there will be current in the junction to actuate the earth fault relay as shown in fig 2.11



2.2.0 l **Fig. 2.11**: Combine Leakage and Overload Protection

Truly, fuzzy logic was a controversial subject before 1960s, before then; there have been comments on the issue. Plato said that there is a region of answers existing between true and false [11]. However, for many years prior to 1960, many scholars at various universities gave many concepts of fuzzy logic; even though their contributions were fuzzy.

The concept of fuzzy logic (FL) was conceived by Professor Lotfi Zadeh in 1960 as a way of processing data by allowing partial membership. In conventional logic, a statement is either true or false, was formulated by Aristotle some years ago as the law of ñthe excluded middleò .i.e. two valued logic rather than crisp set membership or non-membership.

Dr. Zadeh Lofti of university of California has since then given many works, papers and tutorial on the subject.[11-13]

Along the various developments on the fuzzy logic, developing countries especially Asian countries have also modeled many hardware for fuzzy computations.

In fact the word fuzzy means vgueness or unclearness, fuzzy logic hence is used to solve problems whose answers and requirements are more than simple Yes or No, true or False, on or off. Fuzzy logic also takes care of the forbidden state of digital circuits (0.8V-2V) which is the main stream of information technology.

Its applications are numerous; namely in chemical process control, electrically controlled machines, frequency converters manufacturing industries, video machines, automobiles expert systems and even in power system for heuristic optimization.

It resembles human reasoning in its approximation of information and uncertainty to generate decisions. It was specially designed to mathematically generate decisions. It was specifically designed to mathematically represent uncertainty and vagueness and provide formalizing tools for dealing with the imprecision to many problems. By contract, traditional computing, demands precision down to each bit. People do not require precise numerical information input, and be capable of highly adaptive control [14]. If feedback controllers could be programmed to accept noisy, imprecise input, they would be much more effective and perhaps easier to implement. Since knowledge can be expressed in a more natural way by using fuzzy sets, many engineering and decision problems can be greatly simplified.

Fuzzy logic offers a better way of representing reality or grading of thing in fuzzy logic a statement is true to various degrees ranging from completely true-through half-truth to completely false. The idea of multi-valued logic gives a new approach to the mathematics of thinking; it is a change of paradigm to Aristotelian logic.

The computer tool used in expert system development is ñFLOPSò which means Fuzzy Logic Production System. FLOPS is based on fuzzy system theory. Fuzzy sets, fuzzy logic and fuzzy numbers [12]. The use of fuzzy mathematics gives FLOPS the advantage to reason in terms of words such a small, medium, fast slow and so on, rather than in terms of numbers. Hence ambiguities and contradictions can be easily handled and uncertainties pose no problems.

Fuzzy set theory implement classes or groupings of data with boundaries that are not sharply defined (i.e. fuzzy) any theory implementing ñcrispò definitions such as classical set theory, arithmetic, and programming may be ñfuzzifiedò by generating the concept of a crisp set to a fuzzy graph theory and fuzzy data analysis, though the term fuzzy logic is often used to describe them.

Truth of a statement is defined as is correct. Truth is measured numerically in most fuzzy systems literatures, as ranging from zero (false) to one (true). A typical fuzzy system consists of a rule-base, membership functions and inference procedure. Today fuzzy logic is found in a variety of control applications including chemical process control, manufacturing and in some consumer products like washing machine, video cameras and automobiles.

There are several advance surveillance and diagnosis techniques of transformer fault for Oil and Dry Type Transformer as was presented by N.A. Muhamed of the power department, faculty of Electrical Engineering, University Teknologi Malasia and Dr Sam Ali, a program Director with school of Electrical and Information Engineering, University of South Australia [6]; such as dissolved gas-in-oil analysis (DGA), voltage and current Analysis.

Dissolved Gas Analysis (DGA): Like a blood test or scanner examination of the human body. DGA can warn about an impendent problem, give an early diagnosis and increases the chances of finding the appropriate cure. The detection of incipient faults in oil immersed transformers by examination of gases dissolved in oil, developed from original Buchholz relay application. The Gas Chromatograph (GC) is the most practical method available to identify combustible gases. GC involves both a qualitative and

quantitative analysis of gases dissolved in transformer oil [6]. Here, Gas Ratio method was used in the analysis because they overcome the issue of volume of oil in the transformer by looking into the ratio of gas pairs rather than absolute values. The ratio method considered here is the Roger Ratio method [6]. This Ratio method utilizes four ratios, CH_4/H_2, C_2H_6/CH_4, C_2H_4/C_2H_6 and C_2H_2/C_2H_4. Diagnosis of faults accomplished via a simple coding scheme based on rages of ratios.

An advantage of this is that it gives the present status of the transformer and provides information regarding faults that are growing inside the transformer, also identifies faults by considering the ratio of specific dissolved gas concentration. While the drawback of this ratio method is that it fails to cover all range of data, which can be overcome by fuzzy logic by combing both codes.

Voltage and current Analysis: Terminal value, primary and secondary currents and voltages of the transformer convey the information that can be used to detect internal transformer failures. Experiment done by Karen L et al [19] on single phase 7200V/240V/120V, 25KVA, 60Hz distribution transformer has shown the behaviours of the terminal values during internal short circuit and incipient faults. The behaviours of the faults are shown in the table 2.1.

Table 2.1: Interpretation of the Fault Behaviour

Short Circuit Type	**Terminal behaviours**

1	Primary winding with earth	Primary voltage Secondary voltage Primary Current Secondary Current	No change No change Increase higher than health value (3 times higher) No change
2	Winding to winding at secondary	Primary Voltage Secondary Voltage Primary Current : Secondary Current :	No change Reduce to much less than health value Increase very higher than current health value (more than 3 time higher) Increase higher than health value
3	Arching Behaviour	Primary Voltage : Secondary Voltage : Primary Current : Secondary Current :	No change Reduce to slightly less than health value Increase higher than current health value (more than 3 time higher) Reduce slightly less than health value
4	Catastrophic failure	Primary Voltage : Secondary Voltage : Primary Current : Secondary Current :	Highly reduce from health value Highly reduce from health value Increase very higher than current health value (more than 3 time higher) Less than health value

Source: [19]

Simulation Analysis

At the main simulation panel, select the type of transformer to be monitored and to predict the fault. After selecting transformer type, the system will automatically open the simulation panel for the chosen monitoring system. For dry type condition monitoring system, user need to key in all the inputs and run the program. As a result, the system will display the transformer condition. In this review, faults were analyzed for each phase, so position of the fault can be located and classified. The graph will show the history of the terminal voltage and current to see the trend of the current and voltage for 24 hours.

For oil type transformer, users are required to enter the value of each gas. As this system used ratio between the dissolved gases so there are no specific unit for the data entered but the data entered must be in uniform unit for all type of gases. The front panel design will show the percentage of each gas dissolved and show the condition of the transformer based on ratio value of each gas.

There are various methods of fault detection and protection schemes on a power transformer as were mentioned earlier [6]. These techniques however cannot provide a final conclusion of the fault type and position, besides; it may be intensive to subtle incipient fault.

Protective relays which were mentioned earlier in the conventional scheme respond only to internal faults and restrain from tripping on inrush currents and external faults and have their disadvantages as mentioned earlier. Microprocessor based algorithms like Artificial Neural Network is a traditional method used in diagnosing transformer faults, which produce correct response, but the choice of number of hidden layers and the number of neurons in each layer is one of the most critical problems in the construction of neural architecture. Artificial Neural Network with too many neurons will take long training time while that with too few neurons may prevent the training process to converge. Wavelet packet transform and improved frequency response analysis are the other approaches in protection of power transformers.

Although fuzzy logic and Artificial Neural networks produce correct responses despite minor variations differences between the techniques, some of which weigh heavily in favour of fuzzy systems in certain applications as stated in [12]. As we can see, a large number of A.I. (artificial intelligent) techniques have been employed in power systems, however, all these methods cannot withstand the complexity and influence by unexpected events and noise introduced during the transformer fault. Fuzzy logic is a powerful tool in meeting challenging problems in power systems. This is so because fuzzy logic is the only technique, which can handle imprecise vague or ófuzzyô information. It was found to have superior performance in developing the diagnosis systems and in identifying the practical transformer fault cases. It is an expert system which is preferred over others [13].

2.2.1 FUZZY SETS

The concept of set in mathematics is simply a collection of things. The things themselves can be anything such as number, trait and words or names. If we have a particular set, things either belong or do not belong to the set, and there is no in-between or grading of membership. Such set is called crisp. A fuzzy set is one to which object can belong to in different degrees it indicates how sure we are that the member belongs to the fuzzy set. In flops the term confidence replaces grade of membership. Conventionally grade of membership ranges from zero (does not belong) to one (belongs completely) but in flops, confidence is measured from zero (no confidence) to 1000 (full confidence). For instance if sick people is a set, a real person will belong to the set to some degree depending how sick he/she is. An Example of fuzzy sets is shown in table 2.2.

Table 2.2: Fuzzy Sets

FUZZY SET SIZE	
Member	Confidence
Tiny	0
Small	520

Medium	823
Large	672
Huge	300

Source: [11]

Fuzzy set speed and confidence in degree of membership is shown in table 2.3.
Table 2.3:
Fuzzy Set Speed Confidence In

VELOCITY KMPH	**SLOW**	**MEDIUM**	**FAST**
10	1000	0	0
20	500	500	0
30	0	1000	0
40	0	1000	0
50	0	500	500
60	0	0	1000
70	0	0	1000

Source: [11]

2.2.2 MEMBERSHIP FUNCTIONS

Membership function is a way of translating input confidence numbers into word descriptor and most easily comprehended when graphically displayed and may be curvilinear in shape. The best shape depends on its use. If the ultimate output is non-numeric, flat topped membership with adjacent function having maximum overlap is usually the best. If numeric output is desired, peak function intersecting at half confidence are usually the easiest to manage.

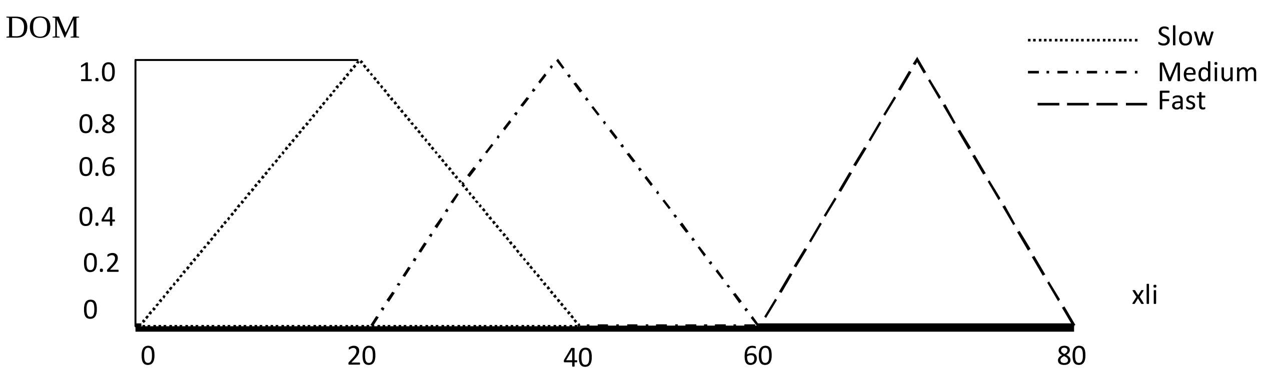


Fig 2.12: Member function for a fuzzy set of speed descriptor

At input 38, refering to fig 2.8

confidence in s = 0.2

In m = 0.8 and

In f = 0

Where s = slow, m = medium and f = fast.

This process of converting numerical measurement to confidences or degree of membership is ñfuzzificationò. And ñFLOPSò supplied a command ñfuzzy to do the translation, in one step.

The shape of membership functions follows definite pattern as the input member increase, the membership function either start at full confidence and come down to zero, start at zero, come up to full confidence and then decline to zero again, or start at zero, confidence and stay there.

2.2.3 RULE BASE

The rule base of fuzzy logic controller consists of all the necessary relationships among the input and output (control) variables. These relationships are expressed in the form of ñif then statementsò. These are usually derived from analytical heuristically or expert knowledge about the system behaviours.

2.2.4 INFERENCE

In the inference stage, the rules are evaluated to determine the values of fuzzy output variable. The logical products for each rule must be combined or inferred. There are many methods of inference such as max-min, max dot or max product, averaging, root-sum-squared etc before being passed on the defuzzification process for crisp output generation [12].

2.2.5 DE-FUZZIFICATION

Defuzzification is the process of combining the result of inference process to fine crisp outputs. There are various methods used in defuzzification. Flops has a command ñdefuzzifyò which will do the defuzzification.

However, without this command a simple defuzzification rule can be used. Suppose we have a fuzzy set amount which has three members: zero, medium and high. We assign to each member a corresponding output value of 0 for zero, 40 for medium and 100 for high. Earlier rules have given the confidence in each of the fuzzy set members.

Simple output rule

IF AMOUNT ZERO = < Z >

AND AMOUNT MEDIUM = < M >AND AMOUNT HIGH = < H >

THEN OUTPUT = $$\frac{(\langle Z\rangle * 0 + \langle M\rangle *40 + \langle H\rangle *100)}{(\langle Z\rangle + \langle M\rangle + \langle H\rangle)} \qquad \text{-----------------}(2.8)$$

In FLOPS language, AMOUNT, ZERO is the confidence of ZERO fuzzy set AMOUNT. It requires knowing the respective values that correspond to each fuzzy set member. This value is multiplied and divided by sum of the confidences.

$$\text{OUTPUT} = \frac{\text{Sum (respective value *confidence)}}{\text{Sum (confidence)}} \qquad - \quad - \quad - \quad - \quad (2.9)$$

This is average of maxima (maxav) methods, and the procedure returns the same value fuzzified, so it is intuitive.

CHAPTER THREE

METHODOLOGY

A complete circuit diagram of an improved fault detection and protection for a transformer using fuzzy logic fault detector is shown in Figure 3.1

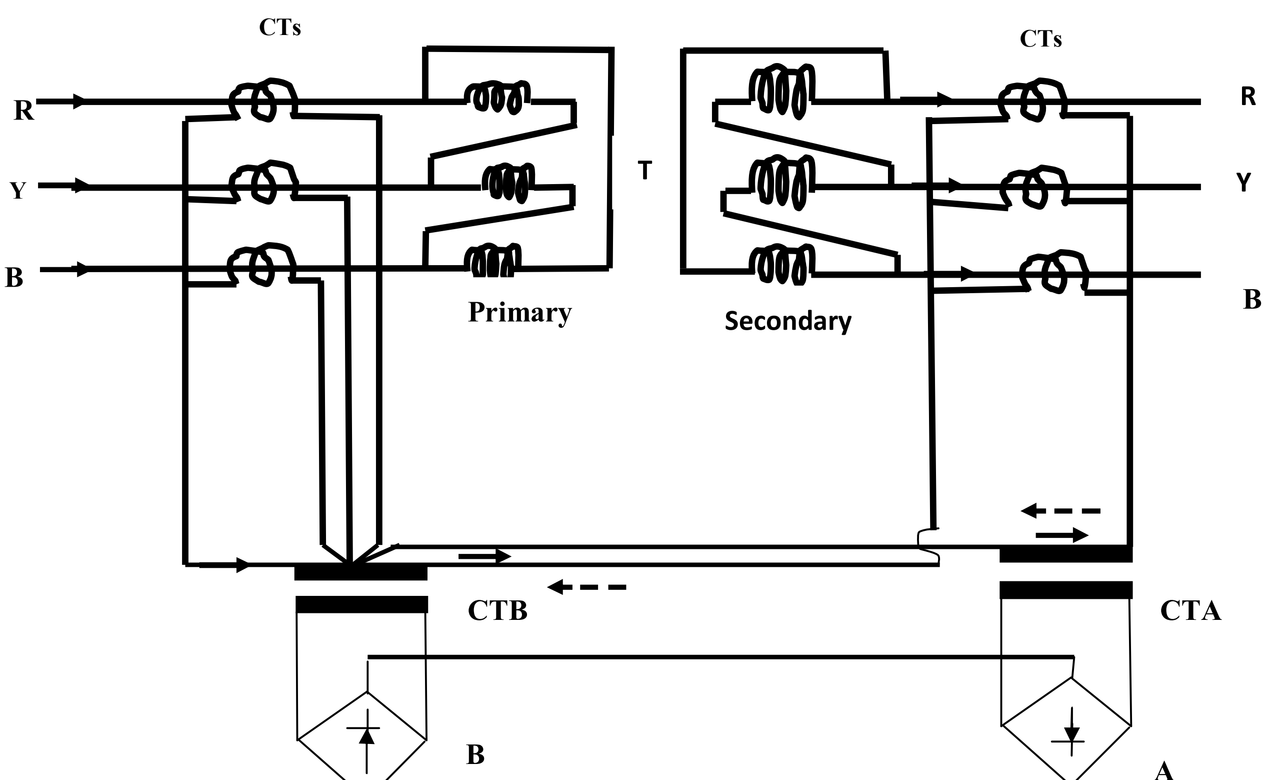


Fig. 3.1: Circuit diagram of a Fuzzy fault detector

R, Y and B represent the voltage lines from both side of the power transformer while CTs is the current transformer on both sides of the power transformer.

T = Transformer Protected.

At HT side of the transformer, current $I_1 = \frac{MVA}{\sqrt{3}\ MV}$ or $\frac{KVA}{\sqrt{3}\,KV}$

$\frac{I_1}{I_2} = \frac{N_2}{N_1}$ é 3.0

$I_2 = I_1 \times \frac{N_1}{N_2}$ = input current (error) -------------------------------- 3.1

During differential, at time t, our second input I_3 now becomes

dI_2/dt = error-dot.

Note that; I_2 which is the output current from the transformer becomes the input current ñErrorò to the fuzzy detector, while dI_2/dt which is the output current at time t, becomes the second input current error-dot to the fuzzy detector.

CTA = Auxiliary current transformer at operating side.

CTB = Auxiliary current transformer at restraining side.

IA = Operating current.

IB = Restraining current.

The circuit of Figure 3.1 shows the circulating-current scheme for the protection of a 3-phase delta/delta power transformer against over current. Note that the CTs on the two sides of the transformer are connected in star. These compensate for the phase difference between the power transformer primary and secondary. The fuzzy logic fault detector is connected to the current transformer on the power transformer to be protected. Differential relay is equally connected. The currents at both sides of the transformer are compared by the differential circuit. An auxiliary CTA and CTB are connected in the operating and restraining current circuits respectively. The secondary of these auxiliary CTs are connected to the rectifier bridge comparator. The output of the operating auxiliaries CTA and CTB is given to Rectifier Bridge A and B respectively, whose output values give forward currents to the fuzzy logic detector as input1 and input 2.

These input values undergo the process of fuzzification according to the rule structure one after the other. The initial results from each input values are feedback into the system and back to the controller through the rectifier as seen in Figure 3.2. Similarly, depending on the number of possible fuzzy rules as illustrated in Figure 3.6, these input values are fuzzified logically to produce output response values, which are combined to produce a crisp output via the controller (fuzzy logic fault detector). The fuzzy logic fault detector will detector the fault and tries to rectify the fault within a pre-set time, but if the fault persist an alarm as well as signal will be send to the control room before the system trips off.

This research investigates the feasibility of using fuzzy logic method to predict and detect faults at early stage in distribution transformer. The fuzzy logic based detector has been developed to monitor and predict faults at an early stage on particular section of the transformer. The detector for this early warning faults detection device only requires external measurement taken from the input and output nodes of the transformer as shown in Figure 3.1.

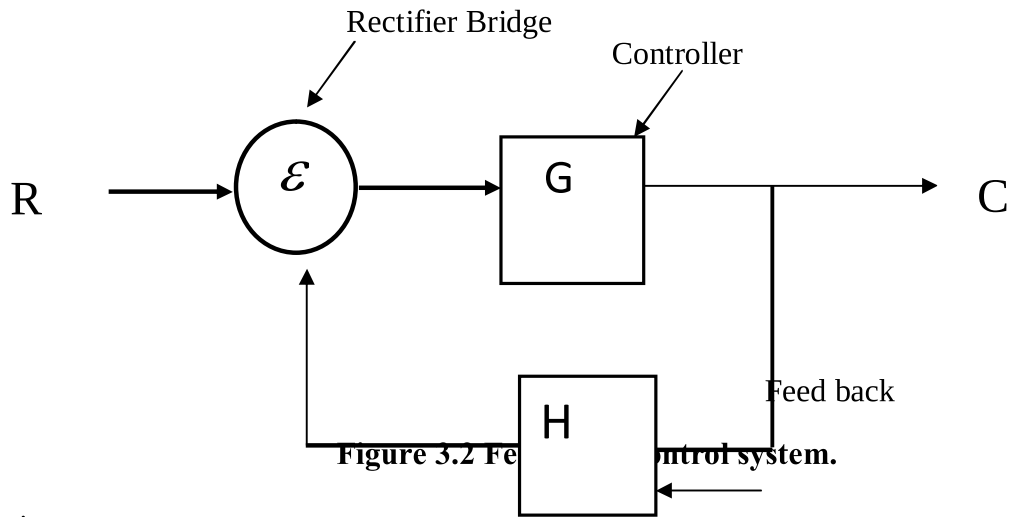


Figure 3.2 Fe ntrol system.

R = Excitation

E = Rectifier bridge

G = Controller

C = Response

H = Feedback.

$\sum = R - HC$

$C = G\sum$

$$\frac{C}{R} = \frac{G}{1+GH}$$

Here the controller G is the transformer relay. H represents the meter used to measure the current (Ammeter), output current and feed the electrical signal back for comparism .The value of G depends on the induction of current Transformer.

GH is the loop gain or return ratio to know whether the system go to zero with input signal going tozero. Hence it is used to determine the stability of the system.

The measurement taken from the transformer will be processed by the fuzzy logic controller available in MATLAB Tool Box.

Generally, fault detection and protection of high voltage transformer using fuzzy logic consist of the following steps.

- Identification of input and output variable
- Construction of control rules
- Fuzzification and fuzzy membership functions
- Selection of composition rule of inference
- Defuzzification method [8].

3.1 IDENTIFICATION OF INPUT AND OUTPUT VARIABLE

FL does not require precise inputs, is inherently robust, and can process any reasonable number of inputs but system complexity increase rapidly with more inputs and outputs. Distributed processors would probably be easier to implement. Simple, plain-language IF X AND Y THEN Z rules are used to describe the desired system response in terms of linguistic variable rather than mathematical formulas. The number of these is dependent on the number of inputs, outputs, and the designerȏs control response goals.

In practice, large power transformers are protected against internal short circuit and overcurrent. Most losses in transformer like the windings (I^2R) loss and core (hysteresis and eddy current) losses result to fault to an extent. Hence over current or current rise in a transformer is the major cause of fault in transformer.

3.2 CONSTRUCTION OF CONTROL RULES/THE RULE MATRIX

The fuzzy parameters of error (command-feedback) and error-dot (rate-of-change-of-error) were modified by the adjectives ñnegativeò, ñzeroò, and ñpositiveò. To picture this, imagine the simple practical implementation, a 3-by-3 matrix. The columns represent ñnegative errorò, ñzero errorò, and ñpositive errorò inputs from left to right. The rows represent ñnegativeò, ñzeroò, and ñpositiveò ñerror-dotò input from top to bottom. This planar construct is called a rule matrix. It has two input conditions, ñerrorò and ñerror-dotò, and one output response conclusion (at the intersection of each row and column). In this case there are nine possible logical products (AND) output response conclusions.

Although not absolutely necessary, rule matrix usually have an odd number of rows and columns to accommodate a ñzeroò center row and column region. This may not be needed as long as the functions on either side of the center overlap somewhat and continuous dithering of the output is acceptable since the ñzeroò regions correspond to ñno changeò output responses the lack of this region will cause the system to continually hunt for ñzeroò. It is also possible to have a different number of rows than columns. This occurs when numerous degrees of inputs are needed. The maximum of possible rules is simply the product of the number of rows and columns, but definition of all these rules may not be necessary since some input conditions may never occur in practical operation. The primary objective of this construct is to map out the universe of possible inputs while keeping the system sufficiently under control.

3.3 RULES

The inputs are applied to a set of IF, AND THEN control rules. See the rule structure and rule matrix shown in table 3.1.

Table 3.1: The Rule Structure

	Antecedent Block	Consequent Block
1	If CMD-CURR. = N AND d (CMD-CURR.)/dt=N	THEN output = L
2	IF CMD-CURR.=Z AND d(CMD-CURR.)/dt=N	THEN output =H
3	IF CMD-CURR.=P AND d(CMD-CURR.)/dt=N	THEN output =H
4	IF CMD-CURR.=N AND d(CMD-CURR.)/dt=Z	THEN output = L
5	IF CMD-CURR.=Z AND d(CMD-CURR.)/dt=Z	THEN output =NC
6	IF CMD-CURR.=P AND d(CMD-CURR.)/dt=Z	THEN output =H
7	IF CMD-CURR.=N AND d(CMD-CURR.)/dt=P	THEN output = L
8	IF CMD-CURR.=Z AND d(CMD-CURR.)/dt=P	THEN output = L
9	IF CMD-CURR.=P AND d(CMD-CURR.)/dt=P	THEN output =H

The ñIF AND THENò control rules in Matrix form for error and error-dot membership function is shown in table 3.2.

Table 3.2: The Rule Matrix

Error (CMD-CURR.)

Erro r –dot(d(Cmd –Curr.)/ dt)

	N	Z	P
N	L	H	H
Z	L	NC	H
P	L	L	H

Where	L	=	Call for Low Current
	NC	=	No change in Current
	H	=	Call for High Current
	CMD-CURR.	=	input current I
	d(CMD-TEMP)/dt	=	$\frac{dI}{dt}$

After transferring the conclusion, from the nine rules to the matrix, there is a noticeable symmetry to the matrix. This suggests a reasonably well-behaved (linear) system. This implementation may prove to be too simplistic for some control problems; however it does illustrate the process.

Additional degrees of error-dot may be included if the desired system response call for this. This will also increase the quantity of the control. Linguistic variables are used to represent a fuzzy logic (FL) system operating parameters. The rule matrix is a simple graphic tool for mapping the fuzzy logic control rules. It accommodates two input variables and expresses their logical product (AND) as one output response variable. To use, define the system using plain-English rules based upon the inputs, decide appropriate output response conclusions.

At this point, the fuzzy inference system has been completely defined, in that the variables, membership functions and the rules necessary to calculate the temperature are in place. We now employ the use of rule editor for editing the lists of rules that defines the behaviour of the system.

The first step in implementing FL is to decide exactly what is to be controlled and how. For example, suppose we want to design a simple proportional temperature controller with an electric heating element and a variable-speed cooling fan. A positive signal output calls for 0-100 percent heat while a negative signal output calls for 0-100 percent cooling. Control is achieved through proper balance and control of these two active devices.

3.4 MEMBERSHIP FUNCTIONS

The membership function is a graphical representation of the magnitude of participation of each input. It associates a weighting with each of the inputs that are processed, define functional overlap between inputs, and ultimately determines an output response. The rules use the input membership values as weighting factors to determine their influence on the fuzzy output sets of the final output conclusion. Once the functions are inferred, scaled, and combined, they are defuzzified into a crisp output which drives the system. There are different memberships functions associated with each input and output response. Some features to note are:

SHAPE ï triangular is common, but bell, trapezoidal, haversine and, exponential have been used. More complex functions are possible but require greater computing overhead to implement.

- ❖ HEIGHT or magnitude (usually normalized to 1),
- ❖ WIDTH (of the base of function),
- ❖ SHOULDERING (locks height at maximum of an outer function. Shouldered functions evaluate as 1.0 past their centre),
- ❖ CENTRE points (centre of the member function shape)
- ❖ OVERLAP (N&Z, Z&P, typically about 50% of width but can be less).

The graphical presentation of the magnitude of participation of each input in the membership function.

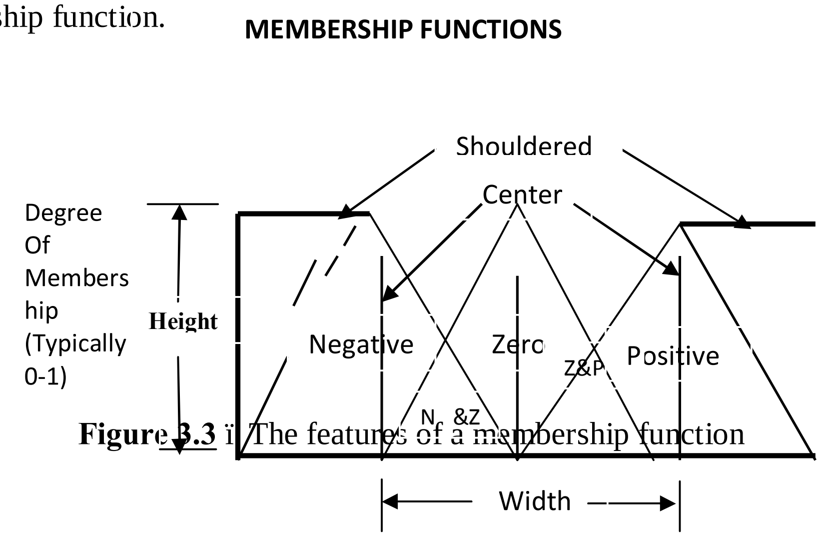


Figure 3.3 ï The features of a membership function

The degree of membership (DOM) is determined by plugging the selected input parameter (error or error-dot) into the horizontal axis and projecting vertically to the upper boundary of the membership function(s).

An illustration of inputs Error and Error-dot membership function is shown in fig 3.5

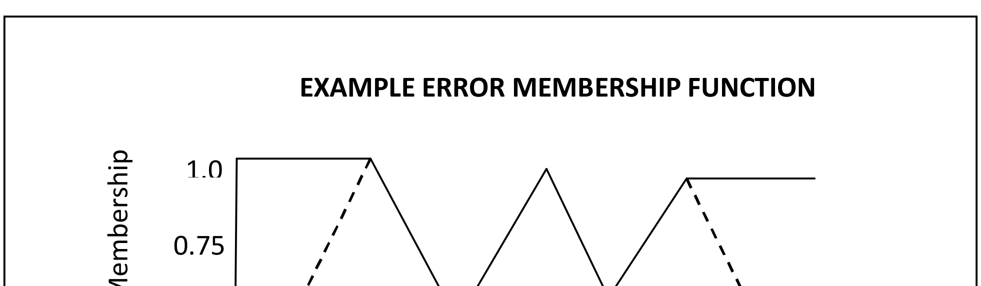


Figure 3.4 Example Error & Error-dot Membership Function

ERROR & ERROR-DOT MEMBERSHIP FUNCTION

Consider an ñerrorò of -1.0 and an ñerror-dotò of +2.5. These particular input conditions indicate that the feedback has exceeded the command and is still increasing.

The degree of membership for an ñerrorò of -1.0 projects up to the middle of the overlapping part of the ñnegativeò and ñzeroò function so the result is ñnegativeò membership = 0.5 and ñzeroò membership = 0.5. Only rules associated with ñnegativeò & ñzeroò error will actually apply to the output response. This selects only the left and middle columns of the rule matrix.

For an ñerror-dotò of +2.5, a ñzeroò and ñpositiveò membership of 0.5 is indicated. This selects the middle and bottom rows of the rule matrix. By overlaying the two regions of the rule matrix, it can be seen that only the rules in the 2-by-2 square in the lower left corner (rules 4, 5, 7, 8) in page 48 of the rules matrix will generate non-zero output conclusions. The other has a zero weighting due to the logical AND in the rules.

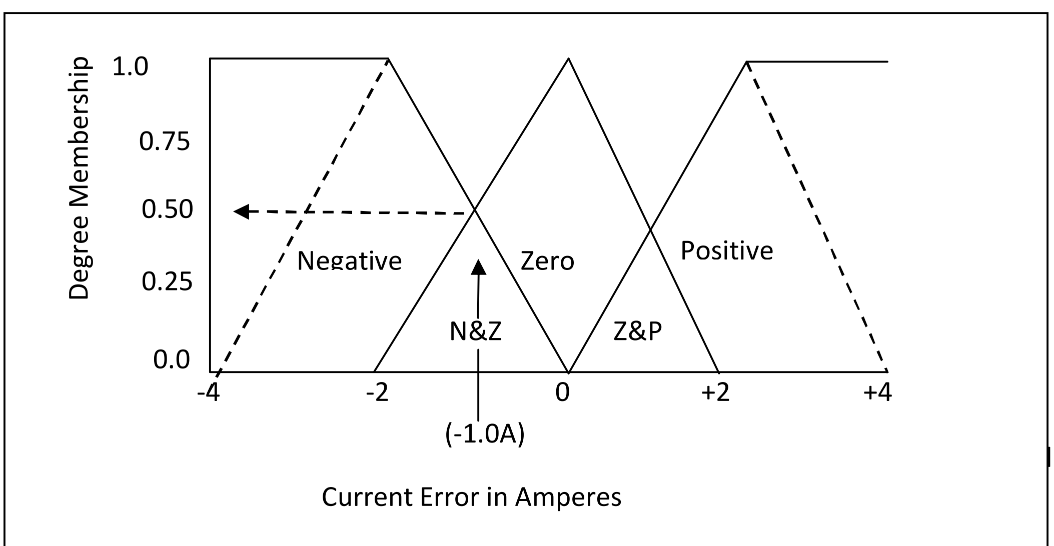
There is a unique membership function associated with each input parameter. The membership functions associate a weighting factor with values of each input and the effective rules. These weighting factors determine the degree of influence or degree of membership (DOM) each active rule has. By computing the logical product of the membership weights for each active rule, a set of fuzzy output response magnitudes are produced. All that remains is to combine and defuzzify these output responses.

3.5 FUZZIFICATION

As inputs are received by the system, the rule base is evaluated. The antecedent (IF X AND Y) blocks test the inputs and produce conclusions. The consequent (THEN Z) blocks of some rules are satisfied while others are not. The conclusions are combined to form logical sums. These conclusions feed into the inference process where each response output member functionôs firing strength (0 to 1) is determined.

Fig 3.6 shows the application on how the antecedent (IF X AND Y) blocks test the inputs and produce conclusions.

ERROR MEMBERSHIP FUNCTION



ERROR-DOT MEMBERSHIP FUNCTION

Current Error-Dot in Amperes/min

Fig 3.5: Examples of Error and Error-Dot membership function

Figure 3.5: Examples of Error and Error-Dot Membership Function

3.5.1 INPUT DEGREE OF MEMBERSHIP

ñerrorò = -1.0: ñnegativeò = 0.5 and ñzeroò = 0.5

ñerror-dotò = +2.5; ñzeroò = 0.5 and ñpositiveò = 0.5

3.5.2 ANTECEDENT & CONSEQUENT BLOCKS (e = error, er = error-dot)

Now referring back to the rules, plug in the membership function weights from above. ñErrorò selects rules 1, 2, 4, 5, 7, 8 while ñerror-dotò selects rules 4 through 9. ñErrorò and ñerror-dotò for all rules are combined to a logical product (LP or AND, that is the minimum of either term). Of the nine rules selected, only four (rules 4, 5, 7, 8) fire or have non-zero results. This leaves fuzzy output response magnitudes for only ñLow Currentò and ñNo-Changeò which must be inferred, combined, and defuzzified to return the actual crisp output. In the rule list below, the following definitions apply: (e) = error, (er) = error-dot.

1. If (e < 0) AND (er <0) then Low 0.5 & 0.0 = 0.0
2. If (e = 0) AND (er < 0) then High 0.5 & 0.0 = 0.0
3. If (e > 0) AND (er < 0) then High 0.5 & 0.0 = 0.0
4. If (e < 0) AND (er =0) then Low 0.5 & 0.5= 0.5
5. If (e = 0) AND (er =0) then No-Changes 0.5 & 0.5 = 0.5

6. If (e > 0) AND (er=0) then High 0.5 & 0.0 = 0.0
7. If (e < 0) AND (er >0) then Low 0.5 & 0.5 = 0.5
8. If (e = 0) AND (er >0) then Low 0.5 & 0.5 = 0.5
9. If (e > 0) AND (er >0) then High 0.5 & 0.0 = 0.0

The inputs are combined logically using the AND operator to produce output response values for all expected inputs. The active conclusions are then combined into a logical sum for each membership function. A firing strength for each output membership function is computed. All that remains is to combine these logical sums in a defuzzification process to produce the crisp output.

3.6 SELECTION OF COMPOSITIONAL RULE OF INFERENCE

Several inference methods exist. They include min-max, max-dot, averaging and the root sum square (RSS) method. The max-min method tests the magnitudes of each rule and selects the highest one. The horizontal coordinate of the ñfuzzy centroidò of the area under that function is taken as the output. This method does combine the effects of all applicable rules but does produce a continuous output function and is easy to implement.

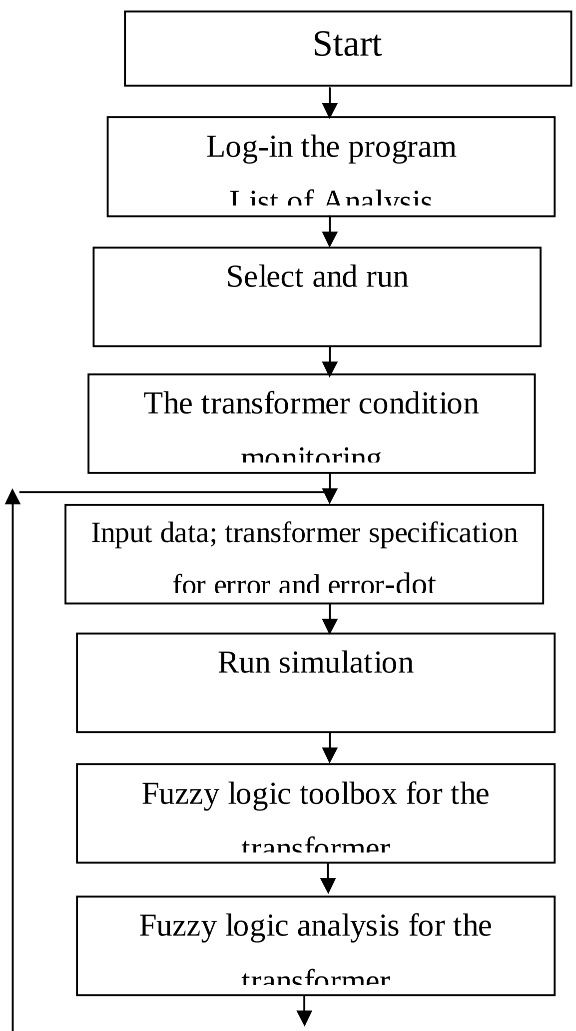
The max-dot or max product method scale each member function to fit under its respective peak value and takes the horizontal coordinate of the ñfuzzyò centroid of the composite area under the function(s) as the output. Essentially, the member function(s) are shrunk so that peak equals the magnitude of the respective function (ñnegativeò ñZeroò and ñpositiveò). This method combines the influences of all active rules and produces a smooth, continuous output.

The AVERAGING method is another approach that works but fails to give increased weighting to more rule votes per output member functions. For example, if three ñnegativeò rules fire, but only one ñzeroò rule does averaging will not reflect this differences since both average will equal 0.5. Each function is clipped at the average and the fuzzyò centroid of the composite area is computed.

The Root-Sum-Square (RSS) method combines the effects of all applicable rules scales. The function at their respective magnitudes, and computes the ñfuzzyò centroid of the composite area. This method is more complicated mathematically than other methods [14].

The approach adopted here in this research is the min-max inference technique/mechanism.

SYSTEM IMPLEMENTATION



CHAPTER FOUR

SIMULATION AND RESULT ANALYSIS

In this chapter, the five steps of evaluating fuzzy algorithms can be performed.

4.1 SIMULATION SOFTWARE USED

The simulation software used in this research is MATLAB Toolbox. This can be achieved by building the system using the graphical user interface (GUI) tools provided by fuzzy logic tool box.

The five primary graphical user interface GUI tools for building, editing and observing fuzzy inference systems in fuzzy logic pool box in is shown in Fig 4.1

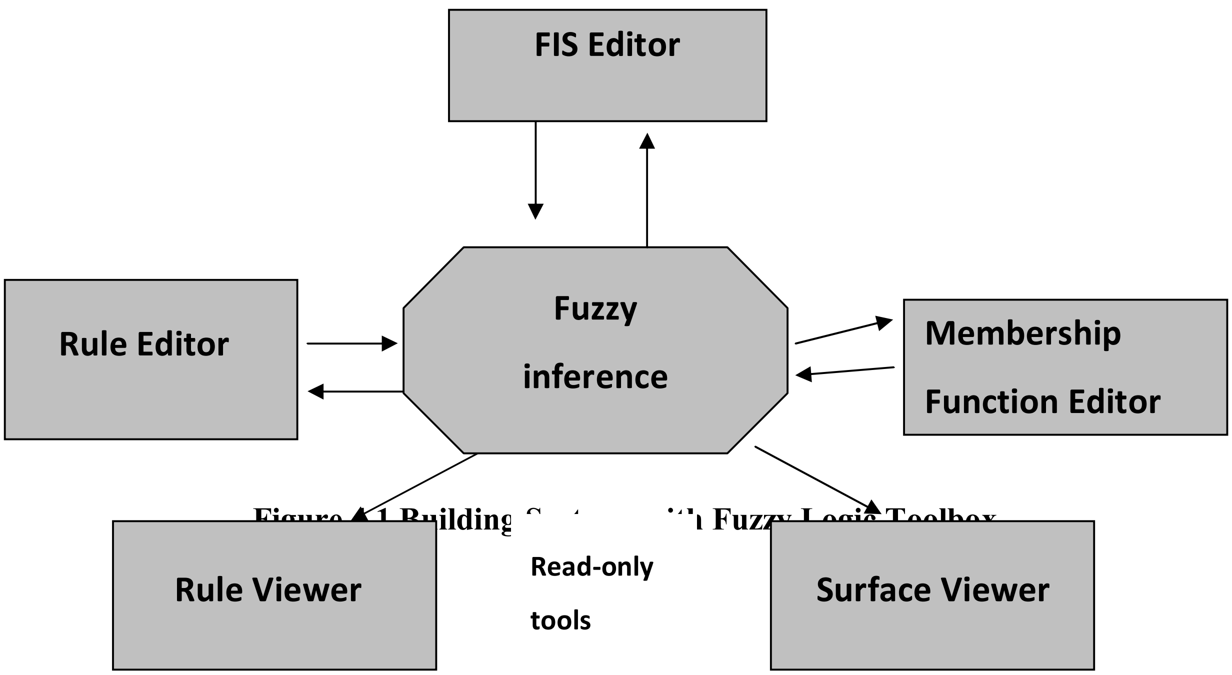


Figure 4.1 Building Systems with Fuzzy Logic Toolbox

The fuzzy Inference System Editor (FIS Editor): Handles the high level issues for the system: How many input and output variables? What are their names?

Membership Function Editor: Used to define the shapes of the membership functions associated with each variable.

Rule Editor: For editing the list of rules that defines the behaviour of the system.

Rule Viewer and the surface Viewer: Used for looking at, as opposed to editing, the FIS. They are strictly read-only tools. It can show (for example) which rules are active, or how individual membership function shapes are influencing the results. The Surface Viewer is used to display the dependency of one of the outputs on any one or two of the inputs that is, it generates and plots an output surface map for the system. Though it is possible to use fuzzy logic tool box by working strictly from the command line, in general it is much easier to build a system graphically. There are five primary GUI tools for building, editing, and observing fuzzy inference systems in fuzzy logic tool box.

- Fuzzify the inputs
- Application of fuzzy operator
- Application of an implication operation
- Aggregate the outputs
- Defuzzify the output

4.2 FUZZIFICATION

Input variable are assigned degree of membership (u) confidence (CF) or degree of fulfillment in various classes.

The fuzzy parameter of Current (error) is modified by the adjectives negative big (nb), negative small (ns), zero (z), positive small (ps) and positive big (pb). This is done by the source code below. Error = [-1.5 1.5]; See appendix A.

The simulation result of input error (Current) is shown in Fig 4.2.

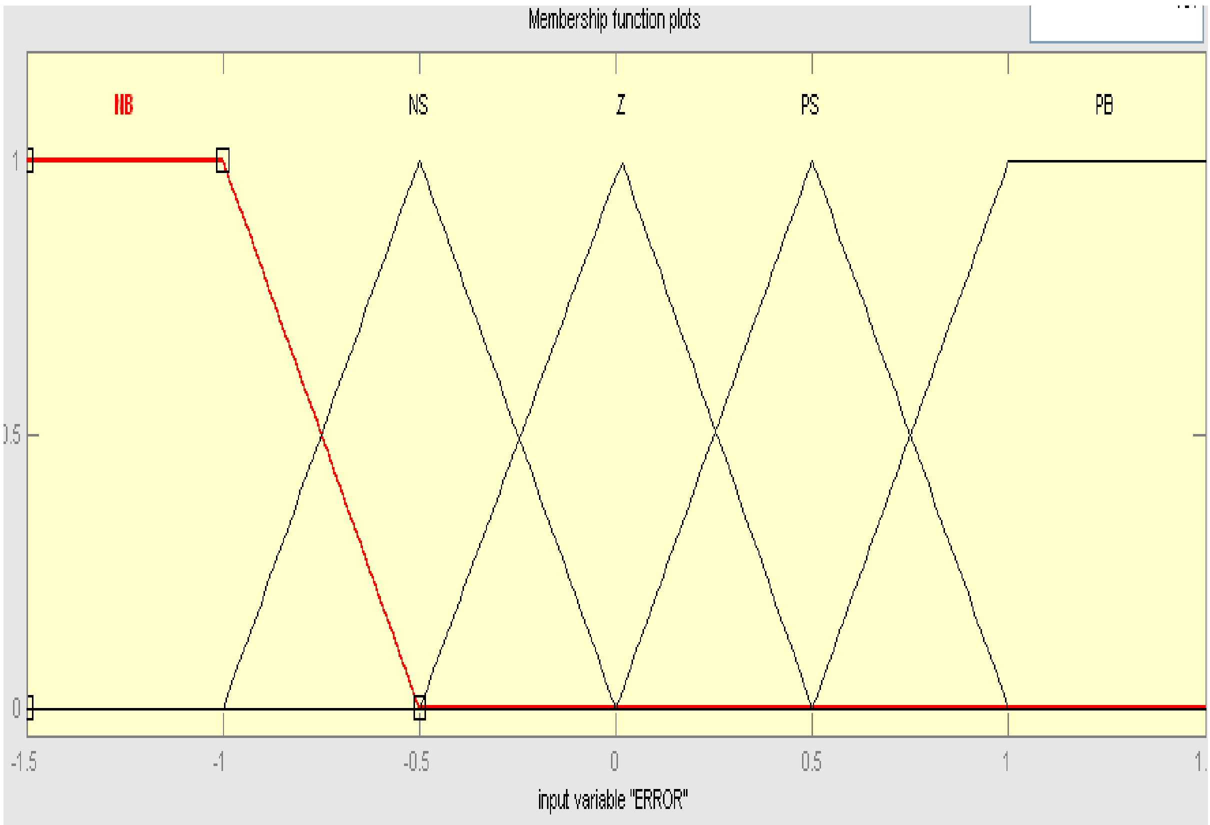


Figure 4.2 Error Membership Function

The second fuzzy input parameter of the rate of change of error (dele-error) is modified by the linguistic variables positive (p), zero (ze) and negative (n). To perform this, computer simulation using the source code in appendix B.

Del- error = [-10, 10]

The simulation result of rate of change of Current Error-dot is shown in Fig 4.3.

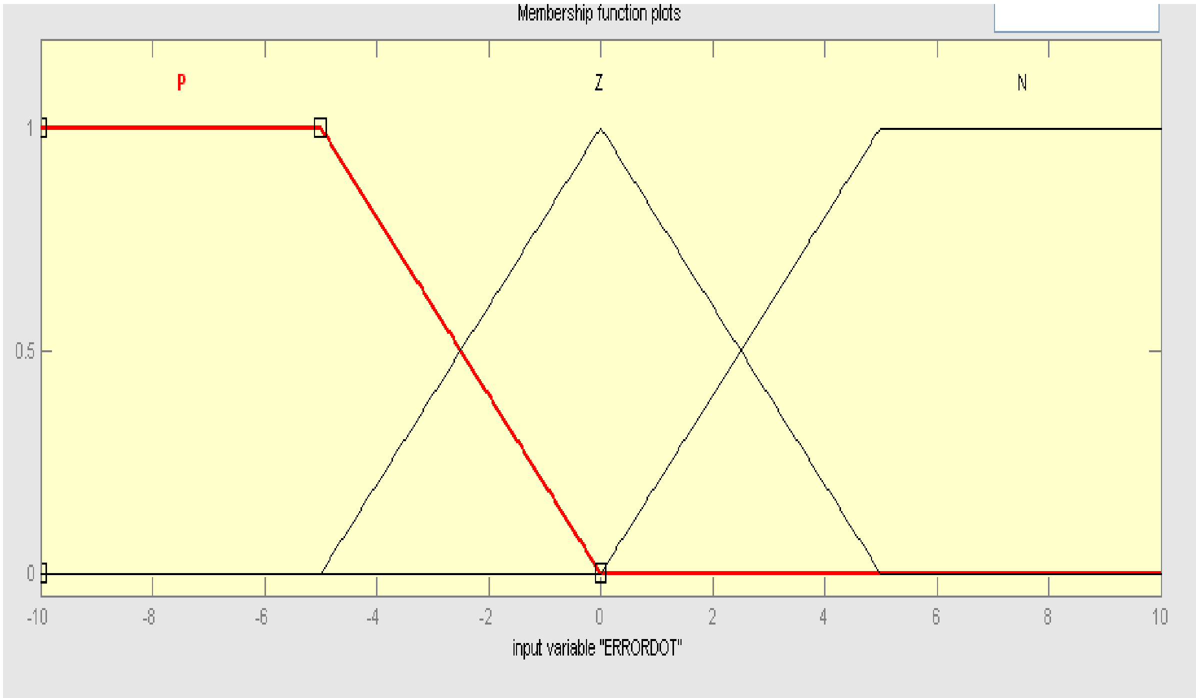


Figure 4.3 Error-Dot membership functions

The fuzzy Output (ócontrol temperatureô) is modified by the linguistic variables;

ñHò = ñHighò Output response.

ñ NCò = ñNo changeò to current output.

ñCò = ñLowò Output response.

The computer simulation can be performed using the source code in Appendix C.

The simulation result of the consequent of the degree of membership with which the antecedents Error and Error-dot are calculated and shown in Fig. 4.4

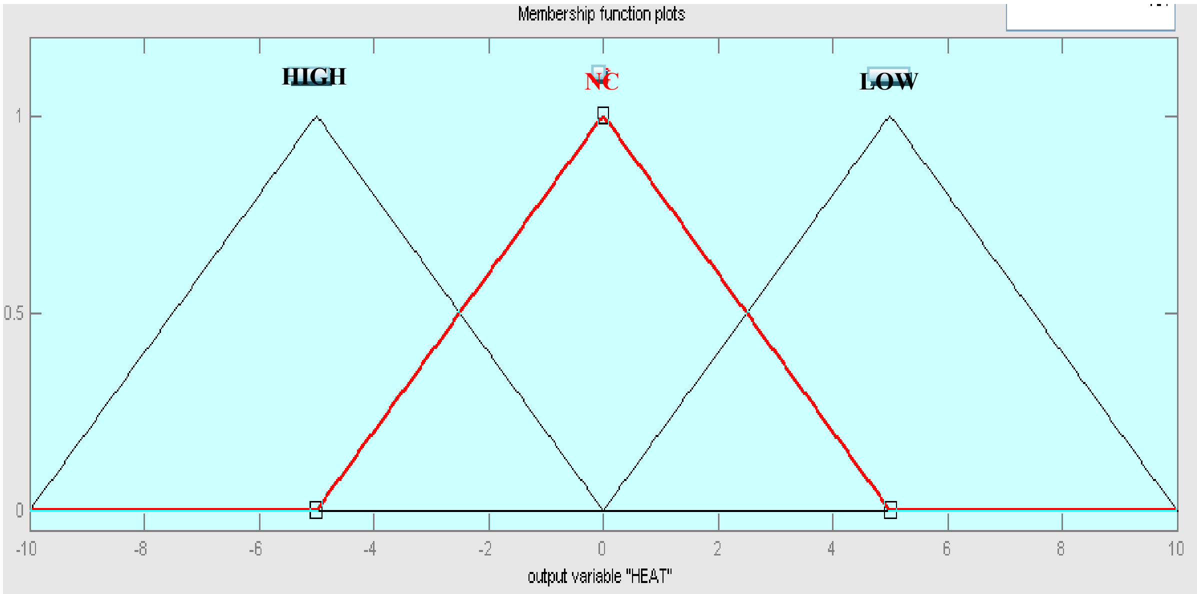


Figure 4.4 Consequent of Fuzzy rules

4.3 RULE NUMBER DETERMINATION

If we have N input variables and K fuzzy sets for each input variable, we should have K^N possible fuzzy rules and 2^N active fuzzy rules.

In this research, N=2 (error and error-dot) and K=3; High Current (H), No change (-), Low Current (L)). So the possible rules are as shown on the rule table overleaf.

4.4 RULES

The inputs are applied to a set of IF then control rules. Next, the fuzzy relation operations inherent in the fifteen rules are performed by same simulation. See Appendix D.

4.5 INFERENCE ENGINE

It processes the rule and data by using the min-max inference technique to calculate numerical conclusion to the linguistic rules and data on system input values. It consist of determining the smallest (Minimum) rule antecedent which is taken to be the truth value of the rule, then applying this truth value to all consequents of the rule.

4.6 RULE FIRING

The degree of membership with which the data match the antecedent is calculated. If this antecedent with the degree of membership (which usually ranges from (0-1) [12] is at least equal to a specific threshold value, (say 0.5) the rule is said to be fireable. When a rule is fired, the consequent action (THENé é é) is carried out. The rule is fireable if the data yields an antecedent confidence which is above the rule firing threshold. The confidence (DOM) with which these action are taken depends on both the antecedent confidence and the confidence in the fuzzy AND (minimum) of the antecedent [15].

The computer program which selects the rule for firing and executes the consequent action is called the inference engine [16]

To fire actually the rule must be tuned on for firing, in default condition, the rule must be picked for firing and the program must be in RUN mode [16].

Data can be fuzzy set (FZ set) low, moderate and high. The confidences are stored as Cf;

For instance

RULE: IF Current<= 30 then declared low

IF Current>=40 then declare moderate (no change)

If Current > = 60 then declare high

Entering data for this subject:

Current, 45; clearly it satisfies rule no. 2 antecedent on the left hand side (LHS). It means that the consequent or right hand side (RHS) can be executed, but does not necessarily mean that the consequent of that rule will be immediately carried out, but the data meets the rules LHS criteria and consequently, the rule s ready to fire, that is to carry out the RHS action, the actual firing is a dynamic process [12].

It is possible for one fuzzy output to be a consequent of more than one rule. When this happens, that fuzzy output is set to the highest (maximum) truth-value of all the rules that include it as a consequent. The result of rule evaluation is a complete set of fuzzy output values, which reflect the effect of all rules whose truth-value is greater than zero [16]

4.7 DEFUZZIFICATION

This is the process of resolving fuzzy output into unique composite output. The output of the detection circuit then serves as input to the protection circuit, which determines the final output to trip or not to trip signal used to control power supply to the circuit breaker relay.

In the protection circuit, the signals are combined into discrete values needed to heat the bimetallic strip to perform the switching.

The tripping decision depends on multi-criteria evolution of the status of the protection element (sound vs. faulty) [16].

In this application fuzzy logic simulation is used for the defuzzification. This method computes a crisp output as a weighted mean of the term membership maxima, weighted by the inference result [15]

A mamdami fuzzy system that uses centroid defuzzification was created. Test result show that the fuzzy system performs superior to the conventional fault detection and protection scheme, even that of PID controller. There was practically no overshoot, and the speed of response was very superb.

The aggregation of fuzzy rule outputs and the crisp output value for Current is shown in figures 4.5a, 4.5b and 4.5c.

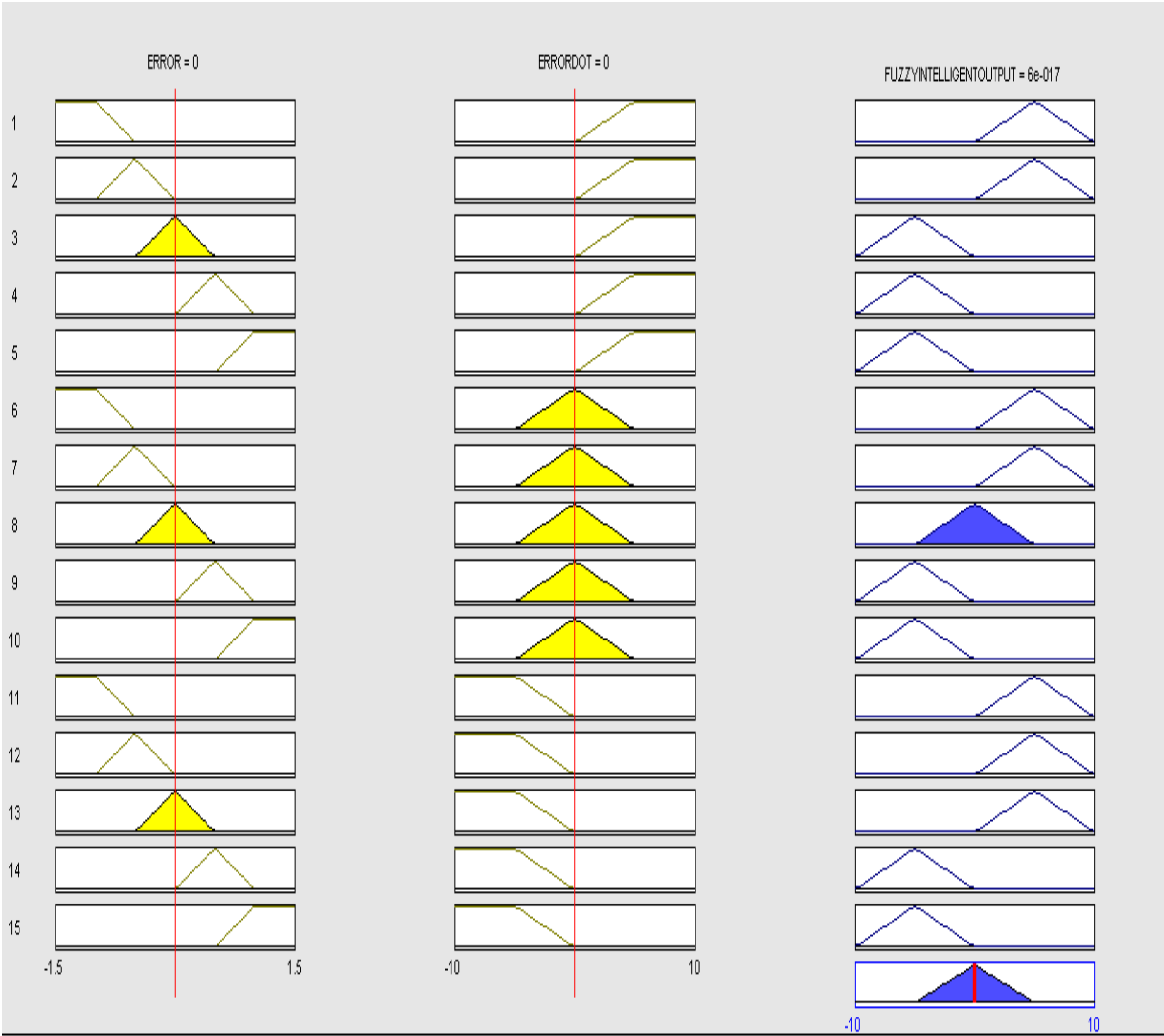


Figure 4.5a Aggregate of Fuzzy for "NO CHANGE" Output Response

At input ñErrorò of [0] and ñError-Dotò of [0], the fuzzy output sets are aggregated to form a single fuzzy output set. These conditions of error and error-dot occur when the Current of the transformer is within the tolerable limit; hence, the system sees no input data and thereby works with zero as input data. The output fuzzy set is defuzzified under this condition to find the crisp output value for the transformer Current to be ñ6e^{-017}ò, which implies that the system is calling for ñNO CHANGEò Output response,hence the system is running at a normal current level.

The fuzzy output sets are aggregated to form a single fuzzy output set.

The output fuzzy set is defuzzified to find the crisp output temperature output = centroid (control, aggregation). If ordinary analysis is used instead of the simulation procedure, which is used in this research work, the centre ï of-max method should be applied. Here each fuzzy output is taken as the strength or weight at y axis position of the corresponding output membership function. During de-fuzzifcCiation, each fuzzy output is multiplied by its corresponding maxima of the output membership functions. The sum of these products is divided by the sum of all fuzzy output to obtain the x-axis position [13].

The formula for centre-of-maximum method (COM) is as follows:

$$\text{Crisp output (y)} = \sum \frac{\left(\text{fuzzy output}\right) \text{ x } \left(\text{maxima of output membership function}\right)}{\sum_{;} \left(\text{fuzzy output}_{;}\right)}$$

If there is change between the error membership and error-dot membership, then, there exists change at output as shown below in the Figure 4.5b

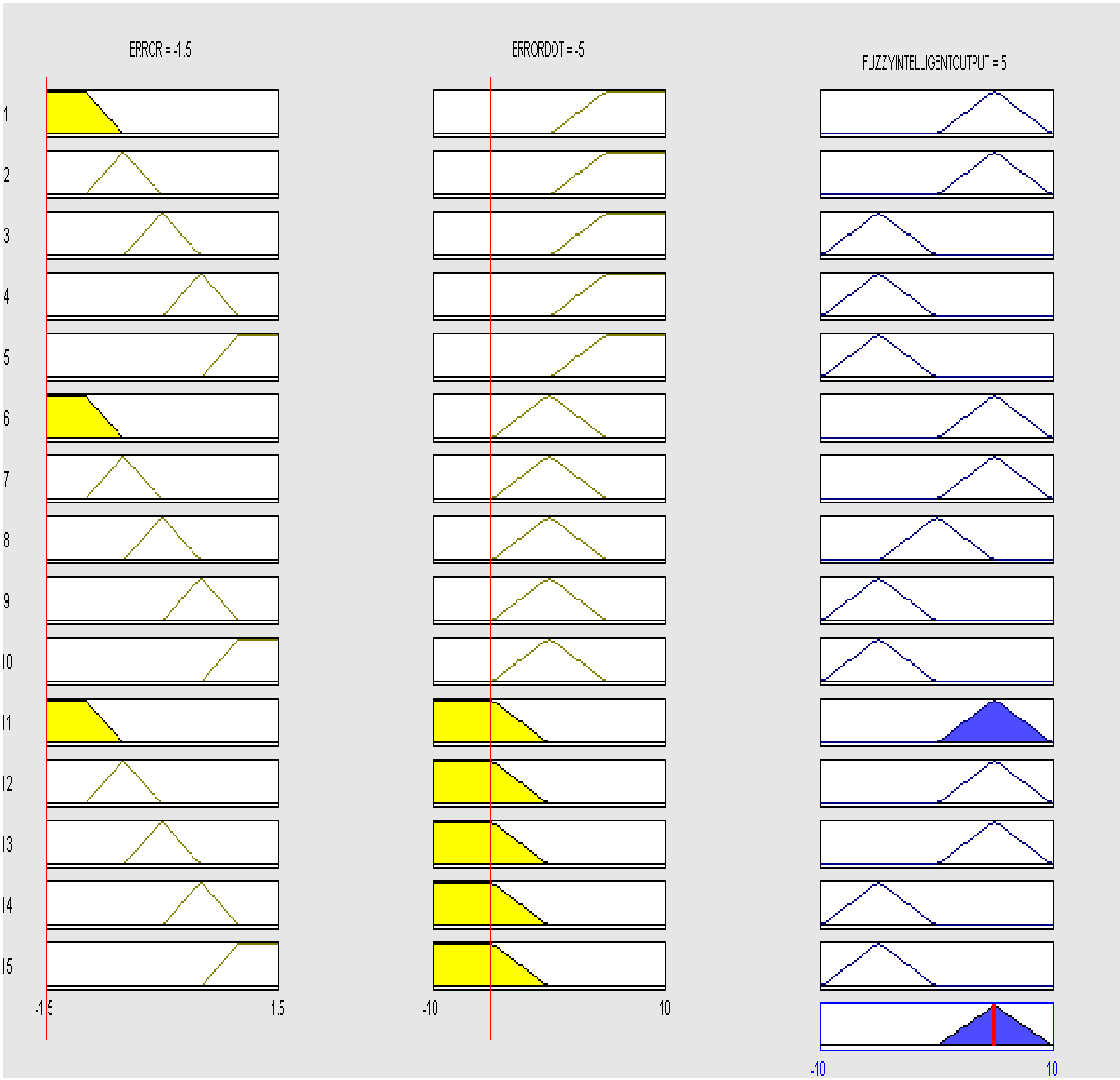


Figure 4.5b Aggregate of Fuzzy for "High Current" Output Response

In this result analysis, input ñerrorò = [-1.5] and ñerror-dotò= [-5], after defuzzification, we have a crisp output = ñ5ò, which implies that the system is alerting the protection scheme since the Current may be too high.

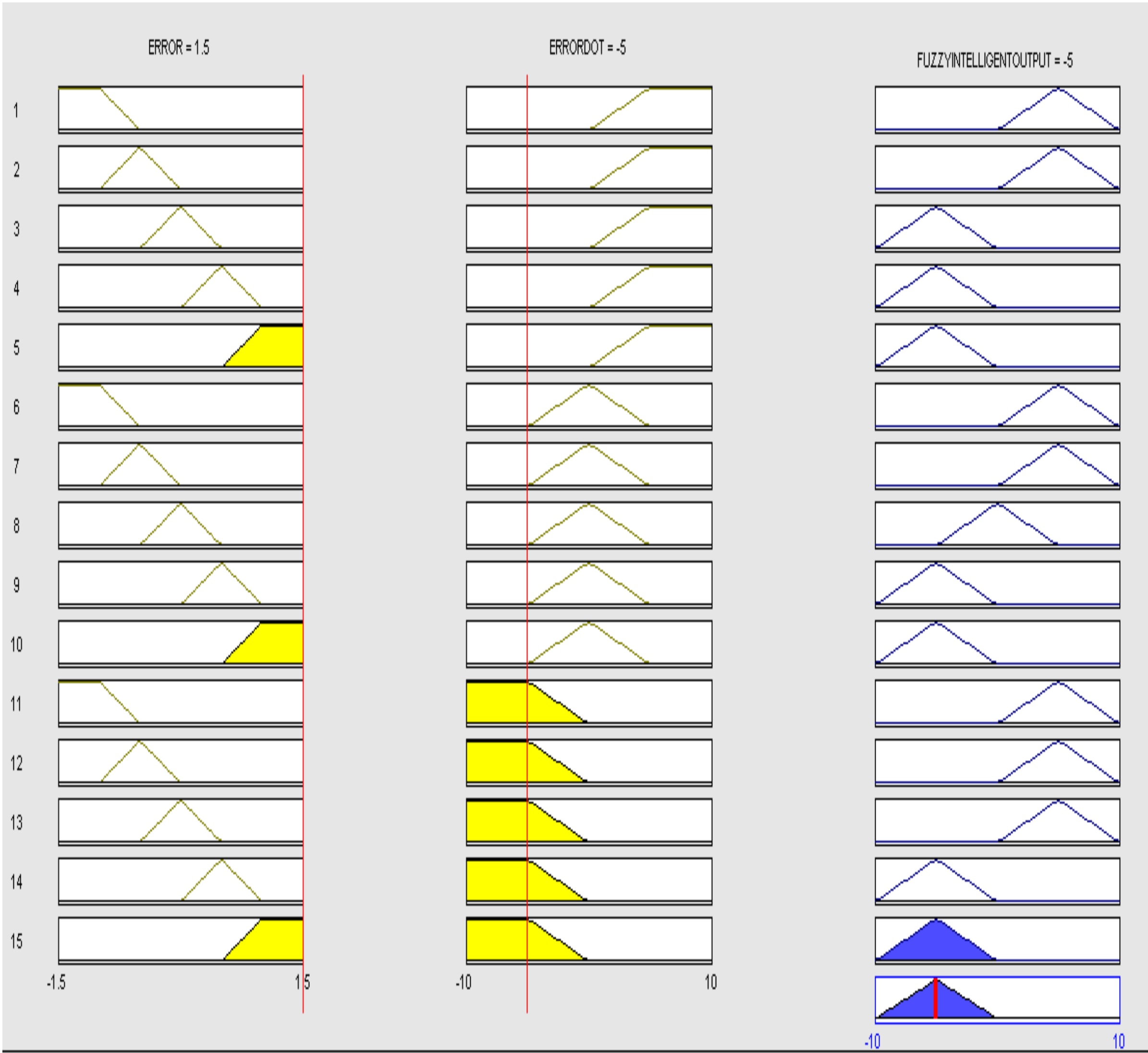


Figure 4.5c Aggregate of Fuzzy for “Low Current” Output Response

The simulation result of the input data ñ1.5ò and ñ-5ò from the analysis = ñ-5ò, which implies that the transformer is having low Current, hence the detector is just notifying the control engineer that the current in the system is low.

4.8 RESULTS ANALYSIS

Fuzzy logic tool in MATLAB workbench is used in the simulation and the results of inputs error (current) and rate of change of current (error-dot).

They have their universe of discourse from -1.5 to 1.5 and from -10 to 10 respectively. The degree of membership is determined by plugging the selected input error and rate of change of input (error-dot) into the horizontal and projecting vertically to the upper boundary of the membership function, then the fuzzy values are found.

Figure 4.5a, 4.5b and 4.5c, displays a roadmap of the whole fuzzy inference process. We see a single figure window with 46 plots nested in it. The three plots across the top of the figure represents the antecedent and consequent of the first rule. Each rule is a row of plots, and each column is a variable. The rule numbers are displayed on the left of each row.

Note that;

1.The first two columns of plots(Error and Error-Dot) show the membership functions represented by the antecedent, or the if-part of each rule.

2.The third column of plots (fuzzy intelligent-output) shows the membership functions referenced by the consequent, or the then-part of each rule.

3.The sixteenth plot in the third column of plots represents the aggregate weighted decision for the given inference system. This decision will depend on the input values for the system. The defuzzified output is displayed as a bold vertical line on these plots. The results from the research show that whenever the output response is zero the transformer current do not need any change. Whereas if the output response is greater than zero it implies that the transformer current is above normal. However, if the response is less than zero then the transformer is current below normal.

The variables and their present values are displayed on top of the columns. For the two input system like this, you can enter specific input values and press enter, or you can adjust these input values by clicking on any of the fifteen plots for each input in order to change the input values, and a new calculation is performed and you can see the whole fuzzy inference process take place.

Where the index line representing Error crosses the membership function line ñError is Negative bigò in the upper left plot determines the degree to which rule one is activated.

A yellow patch of colour under the actual membership curve is used to make the fuzzy membership value usually apparent.

Each of the characterization of each of each of variables is specified with respect to the input index line in this manner; If you follow rule one across the top of the diagram, you can see the consequent ñalerting High Currentò has been truncated to exactly the same degree as the (composite) antecedent ï this is the implication process in action. The aggregation occurs down the third column and the resultant aggregate plot is shown in the single plot appearing in the lower right-corner of the plot field. The defuzzified output value is shown by the thick line passing through the aggregate fuzzy set.

CHAPTER FIVE
CONCLUSION

5.1 SUMMARY

Fuzzy logic was conceived as a better method for sorting and handling data but has proven to be an excellent choice for many control system applications since it mimics human control logic. It can be built into anything from small, hand-held products to large computerized process control system. It uses an imprecise but very descriptive language to deal with input data more like a human operator.

1) Since the fuzzy logic controller processes user-defined rules governing the target control system. It can be modified easily to improve or drastically alter system performance. New sensors can easily be incorporated into the system simply by generating appropriate governing rules.

- Fuzzy logic is not limited to a few feedback inputs and one or two control outputs, nor is it necessary to measure or compute rate of-change parameters in order for it to be implemented. Any sensor data that provides some indication of a systemǿs actions and reactions is sufficient. This allows the sensors to be inexpensive and imprecise thus keeping the overall system cost and complexity low.

2) Because of the rule-based operation, any reasonable number of inputs can be processed (1-8 or more) and numerous output (1-4 or more) generated, although defining the rule base quickly becomes complex if too many inputs and outputs are chosen for a single implementation since rules defining their interrelations must also be defined. It would be better to break the control system into smaller chunks and use several smaller fuzzy logic controller distributed on the system. Each with more limited responsibilities.

3) Fuzzy logic can control nonlinear systems that would be difficult or impossible to model mathematically. Traditionally, computing demands precision to the last ðbitô but since knowledge can be expressed more naturally by using fuzzy sets, many engineering and decision problems can be greatly simplified. Above all we want our machines to talk the way we do, so that translation will be minimized.

5.2 CONCLUSION

A fuzzy logic on transformer fault diagnostic system has been designed with two inputs and a single output variable, each having three membership function detector. The accuracy of the fuzzy logic fault detector and protection can also be improved by choosing the appropriate defuzzification scheme for a given problem.

The two basic requirement that must be fulfilled by a protection scheme which include rapid and automatic disconnection of the faulty equipment and minimizing the disconnection of the healthy section of the system are inherent in fuzzy scheme, therefore this scheme adds prolonged life to the power system, equipment, and a subsequent reduction in the cost of maintenance.

The flexibility offered by the rule paradigm for formalizing thinking is very greater. Comparism between the fuzzy detector and the conventional method reveals the superiority of fuzzy. The fuzzy detector is more sensitive to equipment and the system parameters.

Unlike the convectional control design, which often requires a plant model for designing the controller, fuzzy logic provides alternative approach which allow one to design a controller using a higher level of abstraction without knowing the plant model.

It follows a computation structure which includes fuzzification of the input variables, the inference or rule firing, the defuzzification of the controlled output variable.

Fuzzy system plays an important role in the control and automation technology today. They are used as separate controllers or in combination with conventional control.

Earlier fuzzy logic controller/processor (coprocessor) takes time to compute because of it characteristic trait of converting the binary computing system into the continuous intervals but this problem has been overcome, by the new design hardware acceleration of the coprocessors.

5.3 Contribution to Knowledge

The contributions of this research work to knowledge are as follows;

1. Instead of using only conventional methods like Buchholz relay in detecting and protecting fault such as phase to phase fault, overloading etc. fuzzy logic approach could be incorporated to the protective system to handle all kinds of incipient faults, imprecise, vague or fuzzy information about the transformer to produce correct response analysis for the given fault.

2. Also a computer LABVIEW can be used to connect the user with the transformer for following functions:

- Transformerôs network status monitoring,
- Transformerôs fault logging and fault reporting,
- Transformerôs overall systems network performance reporting.

3. Finally, any sensor that can indicate systemôs actions and reactions is good enough for this work, which makes the sensors to be cheap and imprecise, thus keeping the overall system cost and complexity low.

REFERENCES

[1].O.L. Kagho, ñMaintenance of Electrical Distribution Transformersò, Nigeria Society of Engineers 2002.

[2.] Bogdan Kasztenny, ñImproved Power Transformer protection using numerical relaysò, Texas, A and M University USA 2004.

[3.] A.F. Abbott, ñOrdinary level physics, Heinemann Educational Books London,ò 3rd Ed 1980.

[4.] P.O. Ayaegbu, ñFault section diagnosis in power system using fuzzy logicò, M. Eng. Thesis ESUT, Enugu, Nigeria, pp.377 2003 .

[5]. William silver ñBuilding Fuzzy extent systemsò, Birmingham, USA. 1992

[6.] N.A. Muhamad and S.M.A Ali, ñLabview with Fuzzy Logic Controler Simulation Panel for Condition Monitoring of Oil and Dry type Transformerò, World Academy of Science, Engineering and technology 20 2006.

[7] M.I.S.M. Arshad, ñPower Transformer critical Diagnostic for reliability and life Extensionò CCECEï CCGEI : pp.625-628. 2004.

[8.] B.M. Weedy, ñElectric power systemsò, John Welly and sons New York. 1977.

[9]. S.N. Ndubisi., ñA hand book of Electrical Machine designò. Enugu State University of Science and Technology , Immaculate, Enugu. 2006.

[10]. V.K. MEHTA & ROHIT MEHTA Principle of power system, ï S, CHAND & company Ltd RAM Naggar, New Delhi ï 110 055, 4th Revised Edition 2008.

[11]. L. A. Zadeh; ñFuzzy Sets, Fuzzy genetic system and Out line of a new approach to the analysis of complex systemò. University of California, USA. 1965

[12]. G.J Klir and T.A. Folger; ñFuzzy sets Uncertainty and Informationò Prentice Hall,Englewood Cliffs,N.J.,1988.

[13]. C.C. Lee, ñFuzzy Logic in Control Systemsò IEEE Trans. On Systems, Man, and Cybernetics, SMC, Vol. 20; No. 2; pp.404-35 1990.

[14]. D.K. Steven, ñFuzzy logic an introduction part 2ò (ONLINE) available www. Search Seattle robotics.org 2006, Feb.

15. M. James Siligtot, ñimplementing Fuzzy expert Rules in Hardwareò, A1 expert, April. 1992.

16. Y.H. Song, A.T.J ñApplication of fuzzy logic in power systemò; part 1. ñGeneral introduction to fuzzy logic,ò power engineering journal, Vol.11; No.5; 1997.

17. S.A. Saleh, R.M.A; ñmodeling and protection of a three phase transformer using wavelet packet transformerò. IEEE transaction on power delivery 20(2); pp. 1273-1282. 2005.

18. J.N. KIM, P.B.K; S.C. Jeong; S.W. Kim, P.G. park, fault diagnosis of a power transformer using an improved frequency response analysisò. IEEE transaction on power delivery;.20(1); pp. 169-178. 2005

19. L.B.P Karen, M.J Mausavi, P.B Peter; Experimental Investigation of internal short circuit fault leading to advanced incipient behavior and failure of Distribution Transformer.IEEE Trans., 2004.

APPENDIX A

[System]
Name='ERROR'
Type='mamdani'
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=0
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

[Input1]
Name='error'
Range=[-1.5 1.5]
NumMFs=5
MF1='nb':'trimf',[-1.5 -1 -0.5]
MF2='ns':'trimf',[-1 -0.5 0]
MF3='z':'trimf',[-0.5 0 0.5]
MF4='ps':'trimf',[0 0.5 1]
MF5='pb':'trimf',[0.5 1 1.5]

APPENDIX B

[System]
Name='ERRORDOT'
Type='mamdani'

```
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=0
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

[Input2]
Name='error_dot'
Range=[-10 10]
NumMFs=3
MF1='p':'trapmf',[-10 -10 -5 0]
MF2='z':'trimf',[-5 0 5]
MF3='n':'trapmf',[0 5 10 10]
```

APPENDIX C

[System]
Name='SYSTEM OUTPUT'
Type='mamdani'
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=9
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

[Output1]
Name='heat'
Range=[-10 10]
NumMFs=3
MF1=ôlow current':'trimf',[-10 -5 0]
MF2='NC':'trimf',[-5 0 5]
MF3='high current':'trimf',[0 5 10]

[Rules]
1 1, 1 (1) : 1
2 2, 2 (1) : 1
3 3, 3 (1) : 1
3 2, 2 (1) : 1
1 3, 3 (1) : 1
1 3, 3 (1) : 1
2 1, 1 (1) : 1
5 3, 3 (1) : 1
4 1, 1 (1) : 1

[System]
Name='Rules'
Type='mamdani'
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=9
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

```
[Input1]
Name='error'
Range=[-1.5 1.5]
NumMFs=5
MF1='nb':'trimf',[-1.5 -1 -0.5]
MF2='ns':'trimf',[-1 -0.5 0]
MF3='z':'trimf',[-0.5 0 0.5]
MF4='ps':'trimf',[0 0.5 1]
MF5='pb':'trimf',[0.5 1 1.5]

[Input2]
Name='error_dot'
Range=[-10 10]
NumMFs=3
MF1='p':'trapmf',[-10 -10 -5 0]
MF2='z':'trimf',[-5 0 5]
MF3='n':'trapmf',[0 5 10 10]

[Output1]
Name='current'
Range=[-10 10]
NumMFs=3
MF1='signaling low current':'trimf',[-10 -5 0]
MF2='dont_change':'trimf',[-5 0 5]
MF3='signaling high current':'trimf',[0 5 10]
```

Appendix D
[Rules in Index Format]

```
1 3,3(1):1
2 3,3(1):1
3 3,2(1):1
4 3,2(1):1
5 3,2(1):1
1 2,3(1):1
2 2,3(1):1
3 2,1(1):1
4 2,2(1):1
5 2,2(1):1
1 1,3(1):1
2 1,3(1):1
3 1,3(1):1
4 1,2(1):1
5 1,2(1):1
```