Detection of Inter-Turn Fault in Power Transformers Using Fuzzy Logic

J.K. Arthur, IAENG, Member, J. Ohene-Akoto, IAENG, Member, D. A. Narkah, O-N. K. Dokyi, E. Twumasi

ABSTRACT—This work presents the use of Fuzzy Logic to detect inter-turn faults in transformers. One of the key causes of power transformer failures is due to inter-turn faults. This is a very challenging problem since it is very difficult spotting these faults at an early stage. Inter-turn faults also develop into more severe faults and may result in the impairment of the transformer. In this paper, existing inter-turn fault detection techniques are reviewed and their advantages and disadvantages stated. Based on the strengths and weaknesses of the reviews, Negative Sequence currents and Wavelets analysis are used as techniques to show variation of transformer parameters during faulted conditions and Fuzzy Logic used to monitor the condition and also improve sensitivity of the proposed approach. It is envisaged that; the extant study will convey an innovative awareness to the research community and practicing engineers.

Index Terms: Transformers, Fuzzy Logic, Inter-turn faults, Negative Sequence Currents, Wavelet Analysis

I. INTRODUCTION

Transformers play a vital role in power generation, transmission and distribution of electrical energy. It is one of the most essential and expensive devices within electrical systems that are vital links between the generating stations and consumers. Transformers can be affected by different kinds of bizarre conditions and faults. It is expensive and takes a lot of time to make unplanned repairs such as to fix or replace a faulty transformer. The insulation system of the transformer is one its most essential parts and it can be exposed by electrical, mechanical and thermal stresses and moisture. When this system is degraded, there is a breakdown in the insulation leading to the development of the inter-turn short circuits. The most difficult types of faults to detect within the transformers are the internal turn-to-turn faults. These faults can evolve into more unfavorable and pricier to repair faults if not rapidly detected. Examples of such faults are the phase to phase or phase to ground faults. It is therefore crucial that these faults are quickly detected in cost that would have been used for repairs.

Among the numerous causes of transformer breakdown, 70 to 80% are due to internal faults [1]. With internal winding faults too, inter-turn (turn-to-turn) faults are the most difficult types of faults to detect. They are mainly caused by impulse voltage due to lightning surge on transmission lines [2] external short circuits leading to mechanical force on winding and overloading conditions mechanical. Failure to detect these faults leads to development of hot spots in the transformer windings, winding deformation, oil heating, and damage to the transformer core and clamping structures. In certain cases, the transformer may explode making it completely useless.

In power systems, transformers are needed in good condition to prevent unplanned outages, instability and loss of electrical utility. It is therefore necessary to protect the transformer by monitoring its operations to avoid costly replacement and repairs which are also time consuming. These inter-turn faults need to be rapidly detected with considerable accuracy. Sensitive Fault diagnosis methods have to be put in place to identify inter-turn faults as early as possible. Detection of inter-turn faults while the transformer is online will be economical and improve the system reliability. With increasing demands in providing reliable power and maintaining large-scale power plants, an increasing effort has been put in inter-turn fault detection over the years.

Conventional Methods such as Magnetic Balance Test, Buchholz Relay, No-load test, and Ratiometer test have been applied to the power transformer to ascertain it integrity. However, these techniques require the engineer to be abreast with some rules of thumb. Ref. [2], Dissolved Gas Analysis method was used to monitor a power transformer. The methodology involves collecting oil sample from the transformer. After that, the gas samples are then extracted by a method which is not specified. Gas Chromatograph was used to quantify the concentrations of the respective gases and then the data was analyzed with Rogers Ratio. Rogers Ratio makes use of four gas ratios (H2/CH4, C2H6/CH4, C2H4/CH4, C2H2/C2H4). Each ratio is assigned a number code and a distinct combination of four codes signifies one out of 12 distinct fault diagnosis based on the Rogers Table. The Fuzzy Model responsible for the inference makes use of the four gas ratios as inputs. For the Fuzzy Inference System, the Mamdani based Fuzzy Inference System (FIS) in MATLAB/Simulink was used. The output of the Fuzzy Model has 12 membership functions which stand for the state of the transformer depending upon the value of different gas ratios as per Rogers Ratio Method. DGA has the ability of identifying faults at their initial stages. It can also provide information about how quickly faults are growing if the samples are taken at regular time intervals.
Its combination with fuzzy logic gives it a precise inference. However, the main drawback of this technique is that, it is an offline method and can only be used on oil-filled transformers. Also, it is not suitable for air forced naturally cooled and dry type transformers.

In [3], Dhole and Asutikar used Fourier transform (FT) for inter-turn fault detection. The test parameters considered are the current and voltage signals of input and output terminals of the transformer. A physical model of a transformer was simulated in MATLAB/Simulink. Faults conditions were simulated in this model at different step times and analyzed. Fourier transform of the signals were calculated and the harmonic and frequency components of all the faults were extracted from the Fourier transforms plots and were saved as indexes. Fault signals of a real transformer can be compared with the saved indexes in the database and the type and location of fault can be measured. This method can be used on-line after the database is formed.

Thangavelan et al. [4] used Neural Network for inter-turn fault detection. Precisely, a Radial Basis Function Neural Network (RBFNN) was used. This consists of input layer, cryptic layer and an output layer. The inputs to the Neural Network were carefully chosen based on the different procedures used for testing like Core Balance Test, High Voltage (HV) and Low Voltage (LV) Winding Resistance Test, Spill Current Test, Magnetizing Current Test, and Turns Ratio Test. These six networks were combined to form a seventh network where the output indicated the nature of the fault inside the power Transformer. The test data samples gathered were divided into two and part was used for the training of the network. The remaining were fed into the network. The seventh network gave the output of the fault inside the power transformer. To an extent, this approach could tell the location of an internal fault; it was either on the LV winding or the HV winding. Also, lots of tests have to be performed to get data to train the network and make it more accurate. From the test data samples to be gathered, this approach cannot be used on-line.

In [5], Aziz et al. exploited the traditional differential protection of transformers and added a fuzzy logic approach to the whole process to discriminate between magnetizing inrush and internal faults. To improve the sensitivity of fault detection, the inputs to the fuzzy system were flux with differential current derivative curve, second harmonic restraint and percentage differential characteristic curve. To distinguish between faults, transformer inrush currents, external current signals and internal fault signals were simulated by MATLAB and applied to the fuzzy system. The output of the fuzzy system had two membership functions. The parameters used as inputs to the fuzzy logic could be generated due to saturation of Current Transformers (CT)’s, parallel capacitances or disconnected transformers.

Almasoud [6], proposed an inter-turn winding detection technique based on the premise that the relays like the differential, over-current, under-voltage, reverse power were unable to recognize inter-turn faults until they developed into earth faults. By then, more turns would have been involved in the fault. With this method, each winding of the transformer is given one more terminal at the mid-point of each winding during the manufacturing process. This new terminal served as a voltage divider in each winding which enabled a voltage relay to compare voltage of the first half with the voltage of the second half of the same winding. This new terminal could be repeated for the other two windings making the transformer have six terminals in all. To verify the usefulness of this technique, an experiment involving a test transformer with two transformers whose primaries connected across the three terminal test transformer and their secondaries connected in opposite across the voltage relay. The voltage relay is set to one volt, the lowest. Under normal conditions, the voltages across the two halves of the transformer were the same. Under fault conditions, the two voltages varied and their difference was more than the voltage relay setting therefore the relay tripped, notwithstanding where the fault was located on the transformer. This method involves a third terminal and so already manufactured transformers with the usual two terminals on each winding could not be protected. The making of the third terminal meant increased cost of production of transformer. Other fault conditions which produced voltage variations too beside inter-turn faults were going to be detected with no distinction between them.

The remaining of the paper is organised as follows: Section II presents the theory and modelling of the transformer. Section III presents the Fuzzy logic. Section IV presents the methodology and implementation of the approach. Simulation results and discussion are presented in section V. Finally, the paper ends with conclusions in section VI.

II. TRANSFORMER THEORY AND MODELLING

Before the advent of the transformer, there were direct current (DC) systems where the source of generation of necessity was close to the point of loading. The invention of the power transformer made it possible to develop modern constant voltage alternating current (AC) supply system, where power stations were often located miles from centers of electrical load. The transformer is an AC machine that transfers electrical energy from one electric circuit to another with no change in frequency and this is done by the principle of electromagnetic induction. It has electric circuits that are linked by a common magnetic circuit. It is more economical to transmit electrical energy at high voltages and by the help of transformers, voltages can be stepped up at generating stations for transmission. At the load centers too, transformers step down voltages. Transformers have no moving part and so friction and windage losses are absent, making the transformers efficiency very high.

(a) The Ideal Transformer:

The power transformer is made up of two windings on a core. The action of the transformer is based on the principle that energy may be efficiently transferred by induction from one set of coils to another by means of a varying magnetic flux, provided that both sets of coils are on a common magnetic circuit. A current flow when the primary winding is connected to an AC supply. This generates an alternating flux in the core.
The alternating flux which links both windings induces an emf in each of them. The frequencies of the induced emf in the secondary winding and that of the flux are the same. The induced emf in the primary winding acts as a back emf and limits the primary current in the same way as the back emf in a dc motor limits the armature current. The total voltage induced in each of the windings by the common flux must be proportional to the number of turns due to the fact that there is no difference between the voltage induced in a single turn whether it is part of the primary or the secondary winding. Therefore, the expression:

$$\frac{E_1}{E_2} = \frac{N_1}{N_2}$$  \hspace{1cm} (1)

Where: $N_1$ is the number of turns on the primary coil, $N_2$ is the number of turns on the secondary coil. $E_1$ represent the primary voltage and $E_2$ denotes the voltage on the secondary coil.

The voltage induced in the transformer is given by Equation (2):

$$E = K \Phi_{mf}$$  \hspace{1cm} (2)

Where: $K$ is a constant which is numerically determined from the sinusoidal waveform as 4.44. $\Phi_m$ is the maximum value of the total flux in Weber and $f$ is the frequency.

(b) Transformer Failures and Abnormalities

Transformer failure refers to the situation where a transformer cannot remain in service. This may mean that the transformer can no longer be used or requires certain actions for it to return to service. Among the various factors which cause failure in power transformers are:

- Abnormal system conditions
- Weaknesses in design and manufacturing
- Faults
- Aged condition
- Timescales for fault development

Much concern is given to the abnormal system conditions and the faults which come about in transformers.

(c) Inter-turn Faults

These are short circuits in the windings of a transformer. They are not easily detected at early stages are considered very dangerous because they can develop into more serious faults like core damage and oil overheating. Inter-turn faults are also referred to as incipient faults due to their gradual nature of development. In low voltage transformers, inter-turn faults happen mainly due to mechanical force on the winding due to external short circuits and when insulating oils become contaminated. In high voltage transformers, inter-turn faults may be caused by steep fronted impulse voltages, arising from lightning strikes, and switching operations. A line surge which may be of several times the rated system voltage, will concentrate on the end turns of the winding because of the high equivalent frequency of the surge front. Overloading the transformer has an effect on transformers regarding inter-turn faults.

(d) Characteristics of Inter-turn Faults

In [7], Palmer-Buckle et al. Showed the effects of Inter-turn faults on the current and voltages of a transformer. The primary current increases with increasing number of shorted turns. As the shorted turns increase, the effective number of turns across the primary decrease as is the case of faults on the primary winding. As the primary voltage remains constant at 100V, this causes the magnetizing current, subsequently causing a shoot in the primary current. There is no rapid increase in the primary current when faults occur on the secondary side. The increase is due to the high circulating current in the shorted windings. This current flows in opposition to the normal flow of current in the winding. This reduces the effective flux which is dependent on the primary voltage. More current must therefore be drawn from the primary to bring the flux to the value proportional to the primary voltage. When faults occur on the primary winding, secondary voltages are not significantly affected. For faults on the secondary winding, the voltage decreases with increasing shorted turns. During Inter-turn faults, the insulation between the turns lose their dielectric properties and this also causes localize heating and localized arcing. All these happen inside the transformer and so it is difficult to detect.

(e) Transformer Modelling

For fault study in the transformer, the transformer model plays a key role. How the transformer is modelled has a huge influence on the results. In this project, not only the transformer bad to be modelled, the windings were the main concern. Transformer windings are generally coupled resistance, inductances and capacitance. In view of this, many approaches have been used to model the transformer. In [8][9], a modelled winding in PSPICE was used. With this method, it was difficult obtaining the values of the individual resistances, capacitances and inductances to use. Bacterial swarming algorithms were also used in [10], this method was quite complex. In [11], the BCTRAN subroutine in ATP/EMTP was used to generate the resistance and inducator matrices of a healthy transformer by inputting values from the short circuit and open-circuit tests. From six differential equations developed, the parameters for a short-circuited transformer can be generated as well. In this project, an example of a 2400/600V 225kVA 3-phase transformer magnetically modelled for study of saturation characteristics is edited to suit the purposes of this work. In this model, the 3-phase were built with MATLAB/Simulink blocks [12]. The diagram of the power system used is shown below.

III. FUZZY LOGIC

Zadeh and Klaua in 1965, These are extended version of classical sets for dealing with uncertainty events. The application of fuzzy logic for power system problems was introduced in 1979. Fuzzy logic is a superset of Boolean logic which adds degrees between absolute truth and absolute false. It is a technique that facilitates the control of a complicated system without knowledge of its mathematical description. Fuzzy logic mechanisms can result in higher accuracy and smoother control. Fuzzy systems are very useful in two general
contexts: In situations involving highly complex systems whose behaviors are not well understood and in situations where an approximate but fast solution is warranted. A key part of Fuzzy logic is the membership functions. Membership functions are diagrams which show how the inputs are linked to the outputs. Examples of membership functions are:

![Membership Function Diagrams](image_url)

Figure 1. Different Types of Membership Functions

(a) **Characteristics of Fuzzy Systems**

It is stipulated that fuzzy systems too are robust. They are said to be robust because the uncertainties contained in both the inputs and outputs of the system are used in formulating the system structure itself, unlike conventional systems analysis that first poses a model, based on a collective set of assumptions needed to formulate a mathematical form, then uncertainties in each of the parameters of that mathematical abstraction are considered. Unlike other decision-making approaches like genetic algorithms and neural networks, fuzzy logic has the advantage that the solution to the problem can be cast in terms that human operators can understand, so that their experience can be used in the design of the controller. Fuzzy logic can give various degrees of truth of a situation and therefore emulates the normal human reasoning. Fuzzy logic computations are generally simple. Fuzzy Systems involve three Stages:

i. Fuzzification,

ii. Fuzzy Inference System (FIS) and

iii. Defuzzification

Fuzzification is the first step in the fuzzy process. It involves a domain transformation where crisp inputs are transformed into fuzzy inputs. The fuzzy inference system is a system that uses rules based on antecedents and consequences to map fuzzy inputs unto outputs. Defuzzification is the process of obtaining the crisp output obtained from the fuzzy data.

(b) **Fuzzy Logic and Inter-turn faults detection**

Since fuzzy system is a reasoning and decision-making mechanism based on the expert rules, it can be used to access the severity of inter-turn fault in a transformer. A fuzzy-based detection system will be able to tell the degree of an inter-turn fault rather than just conclude that an inter-turn fault has occurred or not. The inputs to the fuzzy system will be determined by the distinct parameters in a transformer which changes when an inter-turn fault occurs. Based on ideal operations of the transformer, and the effects of inter-turn faults, a concise set of inference rules can be designed. Depending on the range of input data, the output can also be grouped into several membership sets which can tell the degree of the inter-turn fault.

**IV. METHODOLOGY AND IMPLEMENTATION**

The extant study adopted the following approach to detect the inter-turn faults in the power transformer.

i. Modelling of the transformer in MATLAB/Simulink based on the information collected. This modeled transformer had its steady state values recorded and then various intensities of inter-turn fault applied by changing the transformer parameters.

ii. Recording terminal currents at steady state and during faulted conditions on both primary and secondary sides of the transformer modeled was carried out in MATLAB/Simulink.

iii. Fuzzy rules based on the ideal operations of a transformer and the effects of inter-turn fault on a transformer was then created.

iv. Testing the Fuzzy System with transformer data collected from other research papers was carried out to ascertain the efficiency of the proposed approach.

(a) **Parameter Selection**

Karen et al. in Characteristics of Transformer Parameters During Internal Winding Faults Based on Experimental Measurements, detailed field experiments were performed on a single-phase distribution transformer to study the behavior of transformer terminal parameters during internal winding faults. Terminal values of voltages and currents were monitored and the results presented. After simulations and field tests, it was noticed that, the primary current increased with increasing number of shorted turns. In the case of faults on the primary winding, the effective number of turns across the primary
decreased as the shorted turns increased. Since the primary voltage does not change, the magnetizing current and hence the primary current increase rapidly [13]. On the secondary side, high circulating current in the shorted windings causes the primary current to increase. The current flows in opposition to the normal flow of current in the winding. This reduces the effective flux which is dependent on the primary voltage therefore, more current is drawn from the primary to bring the flux to the value proportional to the primary voltage. The faults on the primary winding did not greatly affect the secondary voltages. The voltage was slightly reduced with increasing shorted turns when the fault was on the secondary winding. This is because of the reduction in effective number of turns across which the load is connected.

V. SIMULATION RESULTS AND DISCUSSION

Results obtained from the simulation is depicted in table 1.

<table>
<thead>
<tr>
<th>Percentage of Shorted Turns</th>
<th>Primary current after short circuit</th>
<th>Negative Sequence angle after short circuit</th>
<th>Primary current magnitude difference</th>
<th>Angle Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.332</td>
<td>124.1</td>
<td>0.008</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>5.336</td>
<td>124.1</td>
<td>0.012</td>
<td>0.1</td>
</tr>
<tr>
<td>3</td>
<td>5.342</td>
<td>124.1</td>
<td>0.018</td>
<td>0.2</td>
</tr>
<tr>
<td>5</td>
<td>5.354</td>
<td>124.2</td>
<td>0.03</td>
<td>0.4</td>
</tr>
<tr>
<td>10</td>
<td>5.334</td>
<td>124.4</td>
<td>0.01</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>5.37</td>
<td>125</td>
<td>0.046</td>
<td>1.5</td>
</tr>
<tr>
<td>20</td>
<td>5.356</td>
<td>125.5</td>
<td>0.032</td>
<td>2.2</td>
</tr>
<tr>
<td>25</td>
<td>5.401</td>
<td>126.9</td>
<td>0.077</td>
<td>2.9</td>
</tr>
<tr>
<td>30</td>
<td>5.402</td>
<td>127.8</td>
<td>0.078</td>
<td>3.8</td>
</tr>
<tr>
<td>40</td>
<td>5.431</td>
<td>130</td>
<td>0.107</td>
<td>6</td>
</tr>
</tbody>
</table>

The Fuzzification Process

From the table of values, the steadiest varying parameter is the Primary current magnitude difference. This is used as input 1 to the Fuzzy inference System. The Angle Difference is used as input 2 to the Fuzzy Inference System. Figure 2. depicts the diagrams of the Input Membership functions.
VI. CONCLUSION AND RECOMMENDATION

This study has presented a unique method of inter-turn fault detection which makes use of terminal characteristics of the transformer. These characteristics are a fixed parameter of the transformer. The Fuzzy approach added makes the system robust. In future works, more transformer modelling parameters can be exploited. Also, other techniques like the frequency response analysis, wavelets, neural networks and fuzzy logic can be combined to make a much more efficient detection method. Again, study can be made to find techniques of locating exact position of inter-turn fault. Furthermore, a microcontroller can be designed with the detection technique and attached to the transformer control panel to monitor the transformer online.

REFERENCES


