CHAPTER 1

INTRODUCTION

1.1 GENERAL

The efficacy of a power system depends mainly on the reliability of the power equipment connected to the system. Power Transformer is one of the critical and expensive components of the power system. As the failures in the power transformer have a crucial impact on the system operation, monitoring and diagnosis of transformer faults are necessary to maintain the dielectric and mechanical integrity of the transformer. Among the survey of various faults, about 19% of failures that occur in transformer are winding faults (Bhide 2010).

Short circuit faults which occur due to the failure of insulation between two conductors are considered as one of the most important defects in power transformers. The fault can either be an inter turn or inter disc fault. Deterioration of the insulation is mainly caused by the combination of electromechanical forces induced by variety of factors such as frequent transformer overloading, mechanical vibrations, high transient voltage stresses, high current stresses particularly in the presence of external short circuits, thermal overloading and contamination (Bartley 2003). In fact, these faults can propagate and result in a complete short circuit fault between the two different phases of transformer or even one phase and ground (Behjat et al. 2011). Hence, detection and localization of winding faults is
indispensable for prevention of damages as the outage may lead to costly, time consuming repair and replacement of the equipment.

Sweep Frequency Response Analysis (SFRA) is a powerful method for the detection and diagnosis of defects in the active part of power transformer which can deliver valuable information about the mechanical as well as the electrical changes in the windings parameters. This method takes into account, the changes in equivalent circuit parameters of the windings due to winding faults.

SFRA consists of measuring the impedance of transformer windings over a wide range of frequencies and compares the measured responses with the reference fingerprints. All the conventional Frequency Response Analysis (FRA) techniques are based on graphical analyses for diagnosis. Graphical analyses require trained experts to interpret the test results to identify both failures and failure tendencies in the transformer. The conclusions would depend on the experience of the personnel interpreting the FRA data (Nirgude 2007).

Attempts have been made to develop an evaluation method that can be applied by inexperienced personnel using statistical indicators. In recent literature, number of numerical diagnostic techniques such as Correlation Coefficient (CC), Root Mean Square Error (RMSE), Comparative Standard Deviation (CSD) etc are employed for interpreting the Sweep Frequency Response (SFR) to judge the extent and location of the fault in the transformer winding (Badgujar 2011). Several features are selected from the obtained signals of SFR to train an Artificial Neural Network (ANN) as the classifier.

As the procedure of application of statistical indicators and training of ANN classifier using the obtained SFR is tedious and complex to
determine the location of fault, a generalised and simplified methodology to detect and locate the short circuit faults due to insulation failures using SFR in different types of transformer windings become essential.

1.2 LITERATURE SURVEY

Surveying the literature helps to gain knowledge about the work done previously and steps to be taken to move forward in a particular field of interest. The literature survey is done under the following broad categories:

- Inter turn and inter disc faults in transformer windings
- Mechanical deformation in transformer windings
- Statistical analysis of faults in transformer windings
- Modelling of transformer windings

1.2.1 Inter turn and Inter disc Faults in Transformer Windings

Farzad Zhalefar & Sanaye Pasand (2007) simulated and studied the effect of fault location and fault resistance on the amplitude of fault current in power transformer. It is found that the change of fault location along the winding and small fault resistance have considerable effect on fault current amplitude. In this work, a real 240/11 kV, 27 MVA transformer is used for simulation studies.

Understanding FRA responses in relation to winding structures by using experimental and simulation results of single continuous, inter shielded, and interleaved disc type windings are developed by Zhongdong Wang et al. (2009). A winding can also be made of two concentric coils, either of the same type or a combination of two different structure types. The effects of such a winding structure on FRA responses are studied through simulation by
using the verified transformer model. For these windings, the factors that
govern the shape and features of their FRA responses are identified.

Ebrahim Hormatollah Firoozi et al. (2009) presented a novel
method for diagnosing and localizing of turn to turn faults simulated at
several different locations in HV winding of a power transformer using both
transfer function method and neural network technique. Various turn to turn
faults have been simulated on a laboratory HV winding of power transformer
and corresponding transfer functions have been measured. A method has been
proposed to identify the location of occurred fault using an ANN with Back
Propagation learning algorithm.

Barzegaran et al. (2009) used electromagnetic quasi static analysis
for achieving accurate simulation. Parameters of transformer are estimated by
means of finite element analysis and utilized in circuit based model and the
input impedance is calculated in wide band frequency. In addition to
classifying and analyzing main types of short circuit, frequency response of
disc to disc short circuit state is investigated in several points of the HV
winding. According to the simulation results, for determining the position of
short circuit in the winding, investigation of the first resonance of the input
impedance is suggested. In addition, deviation of resonances along
frequencies due to disc to disc short circuit is less than disc to ground and
disc-disc to ground short circuits.

Bhide et al. (2010) reviewed and compared the fault diagnostics
methods based on their advantages and limitations. In addition, simple
analytical models of three and five legged transformers are developed based
on their electrical and magnetic equivalent circuits, which can be easily
implemented in the analysis of inter turn fault. Various results obtained from
the analytical models are validated with the help of Finite Element (FE)
modelling using ANSYS Parametric Design Language (APDL).
To characterize and justify the complex physical behaviour of power transformers in the presence of inter turn winding faults, Behjat & Vahedi (2010) developed a transient circuit coupled FEM as well an experimental set up, consisting of the same transformer used with the FEM simulation. The results of the experiments on the transformer demonstrate the remarkable ability of the developed FEM to reproduce the real behaviour of the transformer in both healthy and faulty conditions of the transformer. Extensive simulations and experimental tests in a whole variety of the fault and operating conditions revealed that there is a clear pattern in the electromagnetic characteristics of the transformer damaged by the inter turn faults.

Mohsen Faridi (2010) proposed a turn to turn fault localization method based on neural network. This network uses the features extracted from both transfer voltage and transfer admittance functions to localize the fault. The feasibility of fault localization of trained ANN is tested using the experimental data which are obtained from measurements on artificial turn to turn defects simulated on a specially manufactured winding. Results approve the ability of proposed method.

Luis Oliveira & Marques Cardoso (2010) presented a detailed characterization of the transformer behaviour under the influence of inrush currents and/or incipient winding faults. Also suggested a promising new method to detect low level turn to turn faults and, also, to distinguish them from magnetizing inrush current transients. Experimental and simulation results are presented and discussed.

Vahid Behjat et al. (2012) developed a Finite Element Model (FEM) of the tested transformer to assist in justifying the modifications of the winding frequency response as a result of fault occurrence. Successful operation of SFRA method in precisely detecting inter turn winding faults
with a sensitivity of better than 0.2% of turns along the winding, is described on a real distribution transformer. The usage of correlation coefficient and spectrum deviation for comparison of the frequency responses obtained through SFRA measurements provides quantitative indicators of the fault presence on the transformer windings and also the fault severity level in the shorted turns.

Vahid Behjat & Abolfazl Vahedi (2012) studied the experimental investigation of inter turn faults in power transformers. The results obtained with a 100kVA distribution transformer are provided to show that terminal values of the transformer convey information which would be useful in detecting inter turn faults. The transformer has been tested in several fault and operating conditions aiming to account for the different device characteristics. Exhaustive experiments on different fault scenarios revealed that in spite of the inter turn short circuit fault being of little consequence on the terminal value of the transformer as a whole, there is a clear pattern in the trend of terminal behaviour under all of the operating and fault conditions.

Vahid Behjat & Abolfazl Vahedi (2013) used the transient circuit coupled Finite Element Model to understand the complex behaviour of a transformer under internal winding short circuit faults. The model is validated with the data provided by the manufacturer, which represented good accuracy in the estimation of the transformer real behaviour. The finite element model of the faulty transformer is constructed. The local and global effects of the faults on the transformer behaviour are discussed. It is found that the effect of an inter turn short circuit fault will be of little consequence on the terminal behaviour of the transformer, but it will be quantifiable in the electromagnetic flux distribution and fault current.

Yousof et al. (2013) proposed a methodology for locating the inter disc fault in the interleaved transformer winding using the SFRA. All faults
and normal condition of the winding are measured using FRA equipment to obtain the corresponding winding responses. It is found that faults located at the top and bottom half of winding at a similar distance from center have almost identical responses. The correlation coefficient and the response sensitivity table are successfully used to identify winding deformation or movement. A new method is proposed by employing the vector fitting algorithm and Nyquist diagram. A methodology based on trend of the variation of the minimum imaginary value of Nyquist plot is used to identify the fault location. A general equation is computed which can also be applied for locating both top and bottom winding faults.

Ramesh & Sushama (2014) presented a new, simple and incipient fault detection technique, which is based on symmetrical component approach. Using this protection technique, it is possible to detect minor turn to turn faults in power transformers. This protection technique is being studied via an extensive simulation study using MATLAB/SIMULINK software in three phase power system.

1.2.2 Mechanical Deformation in Transformer Windings

Dick & Erven (1978) suggested that the FRA is inherently a powerful diagnostic method for detecting mechanical deterioration in power transformers.

Ryder (2003) presented three different case studies showing the application of different comparison methods to the diagnosis of real and simulated faults on transformers. The correlation coefficients calculated in decade bands are compared.

Wang, Vandermaar & Srivastava (2004) performed experiments to study the factors that influence the FRA measurements. The effect of shunt
resistance, high voltage bushing, transformer neutral connection, measurement leads, and winding movement on FRA measurement are discussed.

Jayasinghe et al. (2006) presented a comparison of three FRA measurement connections, namely end to end voltage ratio, input admittance and transfer voltage ratio measurements. Investigations are carried out on the sensitivity of these connections to three types of winding displacement/deformation, namely: axial displacement, forced buckling and axial bending. A simulation based approach is adopted to produce the FRA results and winding movement is presented as a change of electric parameters in the transformer simulation model. The proposed work helps to gain a better understanding of how to identify features of winding movement from the measured FRA responses and choose the best test connections.

Rahimpour & Danial Gorzin (2006) presented a method for correct and proper comparison of Transfer Function (TF) based on weight functions which is more reliable than the other methods. Capability of the new method is proven by calculating the proposed weight functions on the measured TFs at the different axial displacements of a LV winding with respect to HV winding.

Nirgude et al. (2008) conducted experimental studies on two test transformers to study the variation of numerical parameter values for axial and radial displacements. In addition, two sets of identical substation transformers are used to study the applicability of the techniques for interpretation of frequency response without reference fingerprints. The criteria for diagnosing winding displacement/deformation are discussed in this work.
Based on measured data, localization of discrete faults (i.e. short circuit of turns and addition of capacitances) in a real transformer winding is successfully demonstrated by Satish & Subrat Sahoo (2009). The method employed an iterative circuit synthesis approach, and is aimed at constructing a coupled ladder network, whose short circuit and open circuit natural frequencies match the corresponding measured values within a tolerance of 2%. A mapping between the synthesized circuit and the actual winding has been established.

Dahlina Sofian et al. (2010) addressed the issue of coupling between windings and its effect on the features of FRA responses. Using a 1000 MVA 400/275 kV autotransformer as an example, a double peak feature is distinctively observed in the frequency band between 2 and 20 kHz on the series and common windings of FRA responses. Through transformer modelling and simulation sensitivity studies, it is found that the coupling through the delta tertiary connection affects the first resonance of the double peak feature while the coupling between windings of the same phase, especially between the series and the common winding, influences the anti resonance and the second resonance of the double peak feature.

Tang et al. (2010) presented a simplified distributed parameter model for minor winding deformation fault analysis of power transformers on the basis of FRA. The FRA data of an experimental transformer is employed as a reference trace, which are compared with the simulations of the simplified distributed parameter model concerning minor winding deformation faults. In order to perform quantitative analysis when a deformation fault occurs, three statistical indicators are used to analyze the FRA simulation data. It is suggested that the minor winding deformation faults can be detected at the frequency range above 1 MHz.
Andrey Reykherdt & Valery Davydov (2012) carried out an extensive investigation of FRA measurement circuits to explain differences between FRA signatures obtained for the same transformer windings under different measurement setups. In particular, the effects of the layout of measurement cables, the layout of ground extensions across high voltage bushings, grounding resistance and the shape of ground extensions are considered.

Mehdi Bagheri et al. (2012) concentrated on self inductance variation recognition due to an internal short circuit in transformer using FRA signature. In this work, the effects of turn to turn and disc to disc short circuit faults in transformer, as one of the main mechanical defects, are highlighted on inductance variations. Flux division theory is discussed in order to gain a clear understanding and interpretation of frequency response traces. A single phase 11/0.25 kV, 25 kVA transformer has been taken as test object to perform frequency response analysis. Mathematical calculation at fundamental frequency revealed that self inductance of HV winding when LV winding is open circuit is significantly higher than that of shortened LV. In addition, the effect of grounded internal short circuit on frequency response trace and its interpretation are presented in detail. Self inductance of the HV winding remains intact for isolated and grounded internal short circuits.

Naser Hashemnia et al. (2012) presented a comprehensive simulation analysis to explore the impact of various transformer mechanical faults on its FRA signature. The effects of short circuit fault, inter disc fault, leakage fault, high voltage bushing fault, axial and radial faults are analysed. A comprehensive table highlighting transformer FRA sensitivities to mechanical faults is generated and can be used to establish standard codes for power transformer FRA signature interpretation.
Bigdeli, Vakilian & Rahimpour (2012) presented an intelligent fault classification method for identification of transformer winding fault through TF analysis using Support Vector Machine (SVM). The proposed method is able to accurately distinguish different fault types, such as Axial Deformation (AD), Radial Deformation, Disc Space Variation (DSV) and Short Circuit (SC).

Mehdi Bagheri et al. (2013b) discussed the mechanical defects and transformer frequency response measurement of the winding. The influence of shunt capacitance on frequency response spectrum oscillations in Bode diagram and impact on low, mid and high frequency bands of FRA spectrum are discussed. A practical study on a single phase air core glassy model transformer is carried out to explore the influence of shunt capacitances of HV and LV windings with respect to the transformer tank on FRA spectrum. In addition, a single phase 11/0.25 kV, 25 kVA core type distribution transformer is also tested to evaluate the shunt capacitance impacts on FRA fluctuations.

Tang et al. (2014) presented a simplified distributed parameter model of transformer winding for FRA. The model is used to simulate minor winding distortion faults for a single phase transformer. Two types of faults are simulated, i.e. minor axial displacements of discs and minor radial deformations of discs. Quantitative results using statistical analysis indicators are presented with discussions on the effect of minor winding faults on frequency responses. The study on minor winding movements shows that these winding conditions are generally detectable at frequencies above 1 MHz.

Ghanizadeh & Gharehpetian (2014) presented a method for simultaneous detection and location of electrical Short Circuit (SC) faults and mechanical defects. The detailed model of a real 1.2 MVA transformer
winding is developed considering its geometrical dimensions and characteristics. The parameters of the detailed model are calculated for intact and defected windings. The effect of the disc to disc SC faults is directly inserted to the model. The frequency responses are obtained for each case using EMTP/ATP and a dataset is formed. Using Artificial Neural Network (ANN) as the classifier in the new approach, it is possible to simultaneously detect the defect type and also locate Axial Displacement (AD), Radial Deformation (RD) and disc to disc SC faults in the transformer winding with a good accuracy.

1.2.3 Statistical Analysis of Faults in Transformer Windings

To deal with wideband frequency responses of each transformer phase, Jong Wook Kim (2005) proposed a synthetic spectral analysis, which augments low and medium frequency components and equalizes the frequency intervals of a resulting combined curve by a log frequency interpolation. Furthermore, for discriminating a defective phase through computing overall amounts of deviation with other phases, two well known criteria and three proposed criteria are examined with experiment data. The overall diagnosis results show that the proposed criterion discriminates a defective phase with the highest average hit ratio among all of the provided criteria for selected faults.

Ebrahim Rahimpour et al. (2010) investigated the mechanical faults like Disc Space Variation (DSV), Radial Deformation (RD) and Axial Displacement (AD) using Transfer Function (TF) method. Mathematical methods with exact calculations consisting of a standardized difference area, correlation factor, index of frequency deviation, index of amplitude deviation, frequency weight function, and amplitude weight function are also studied to compare TFs and determine the type, location and level of fault.
Kennedy et al. (2007) presented an approach using cross correlation coefficients with an understanding of traditional SFRA techniques for assessing mechanical damage to a transformer winding.

Badgujar (2011) studied the commonly used statistical parameters in SFRA diagnostics. The work reported in this paper has made three contributions to the subject of the statistical diagnosis of deviations, viz. renaming of a statistical parameter as Root Mean Square Error (RMSE), coining a new parameter Comparative Standard Deviation (CSD) and application of the well known t-test in statistics to SFRA diagnostics for the first time. A new parameter called the t-test has been proposed, which gives a binary output 0/1 and can still be used for data analysis if the sample size and/or the spot frequencies of the two SFRA data sets are different in a frequency interval.

Mehdi Bagheri et al. (2013a) concentrated on mid frequency oscillations of transformer winding frequency response spectrum presented in Bode diagram. To explore frequency response trace behaviour, mathematical approach using travelling wave theory is employed. Practical studies on a prepared glassy transformer as well as two 66 kV, 25 MVA continuous and interleaved disc windings have been performed to validate mathematical calculation. In addition, two 245 kV, 45 MVA and 66 MVA power transformers have been examined to study mid frequency oscillations.

Vahid Behjat & Mojtaba Mahvi (2014) dealt with statistical criteria for interpretation of the FRA results and presented a number of statistical and mathematical indicators that have not been used so far. A measurement setup accompanied by a transformer as a test object, on which winding faults are imposed, completes the test setup for performing the FRA measurements. The parameters are applied to the experimental FRA measurements and the results are compared by a simple normalizing equation. SFRA is used in this study
because of its efficiency and simplicity. It is found that F-test, which is introduced in the study, has higher sensitivity and the differences between the normal and faulty responses of the transformers’ windings are more reflected in this parameter compared with the other ones.

1.2.4 Modelling of Transformer Windings

Ragavan & Satish (2007) demonstrated how discrete changes made in a model winding could be correctly located based on terminal measurements. From knowledge of its measured short circuit and open circuit natural frequencies and pertinent winding data, an equivalent circuit is synthesized (called reference circuit). Corresponding to every new set of measured natural frequencies based on the introduced changes at different locations in the model winding, a new circuit is synthesized (with topology remaining unchanged). A comparison of these circuits with the reference circuit revealed that a mapping could be established between changes introduced in the model winding and those predicted by the synthesized circuits.

Nilanga Abeywickrama (2008) presented an advanced model of the frequency response of a three phase power transformer for use in conjunction with diagnostic measurements by the method of FRA. The model includes high frequency behaviour of the laminated core and the insulation. A lumped parameter circuit model is used to simulate the frequency response of open circuit impedance, short circuit impedance and impedance between primary and secondary windings, in which the characteristics of circuit elements are calculated by means of the finite element method. The effect of actual representation of each circuit element on the FRA response is analyzed and discussed in comparison to measurement results on a real transformer.
Marek Florkowski & Jakub Furgał (2009) presented the application of the mathematical model of windings for numerical simulations of the winding admittance which is used for the calculations of the admittance of the winding displacement of the transformers and turn to turn fault detection in the winding coil of a windmill generator. The calculation results of the transfer function performed on the different winding of transformers and electrical machine are presented. The calculation results are compared with the experimental results.

Maximilian Heindl et al. (2010) suggested deriving an electrical equivalent model from measured frequency responses. The model is subdivided into a low and a high frequency part. For the Low Frequency (LF) part, which contains few resonances, equivalent resonance circuits are identified from measured Transfer Function. For High Frequency (HF) part, an electrically equivalent circuit is identified using the analytical expression gained by vector fitting. For the LF and HF model, deviations between measurements are interpreted as changes of the lumped element RLC values and poles and zeros of the analytical TF respectively.

Wilder Herrera Portilla (2014) described a new procedure which facilitates the frequency response curve interpretation in the low frequency bandwidth. The procedure is able to estimate the magnetization inductance and winding capacitance, for each transformer phase by using data from its frequency response only. The described calculation procedure uses RLC electrical equivalent circuit developed to simulate the impedance measured in the frequency response test. The procedure takes into account the magnetic coupling among different phases and allows their analysis separately, enabling the identification of a possible failure.
1.3 SCOPE OF THE PRESENT WORK

Transformer failures in service cost enormous amount of money due to unexpected outages, unscheduled maintenance and have significant safety, environmental and economic impacts. It is therefore extremely valuable to have reliable and efficient testing and diagnostics methods for detecting damage to transformers at an early stage before catastrophic failure occurs.

Frequency response characteristic of a transformer winding is sensitive to inside physical changes which alter the equivalent electrical parameters of the winding (Jayasinghe et al. 2006). The applicability and sensitivity of the SFRA method have been extensively tested by means of fault simulations in laboratory and real case studies of transformers on site. A practical and reliable method of detecting faults in transformer windings is estimated with the accuracy rate upto 95.4% using FRA (Ghanizadeh & Gharehpetian 2014).

In the present study, a generalized methodology with the identification of new diagnostic parameter namely Fault Factor, is proposed to locate the fault using SFRA. Two methods such as SFR of the half winding reference (SFR\(_{50}\%\)) and ground capacitive current methods are proposed to locate whether the fault is in the upper/lower half of the winding.

In general, the mathematical models are used to reduce the complexity and time consumption of the measurement. In the present work, a hyperbolic model using only two reference measurements is proposed to predict the exact fault location for different percentage of inter disc faults using a 22 kV continuous disc winding. The proposed methodology is validated on different types and ratings of transformer windings.
The proposed methodology employing the hyperbolic model is useful for design engineers to prepare a template to identify the location of fault by predicting the fault factor characteristics with the electrical equivalent circuit using only the design data.

1.4 ORGANISATION OF THE THESIS

Chapter 1 deals with introduction to faults of power transformer, location of faults, main objective of the thesis and literature survey.

Chapter 2 briefs about the available standards, test types of SFRA, various factors influencing the SFRA measurements and failure modes in transformer winding.

Chapter 3 deals with the identification of parameter and proposes a simplified methodology for the location of inter disc faults in transformer winding.

Chapter 4 deals with the mathematical model of the proposed methodology for predicting the fault factor characteristics of transformer windings under faulty conditions using SFRA. The applicability of the developed methodology is validated for different types and rating of transformer windings.

Chapter 5 discusses the modelling/simulation of frequency response in transformer windings using electrical equivalent circuit model.

Chapter 6 discusses the applicability of the proposed methodology to locate inter turn fault in the transformer winding.

Chapter 7 provides the conclusion and scope for the future work of the project.