CONDITION MONITORING AND FAULT DIAGNOSIS OF SINGLE PHASE TRANSFORMERS

A THESIS

submitted by

POTHULA ABHINAY REDDY

for the award of the degree

of

MASTER OF SCIENCE

(By Research)

SCHOOL OF COMPUTING AND ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY MANDI

March 2016

THESIS CERTIFICATE

This is to certify that the thesis titled **CONDITION MONITORING AND FAULT DIAGNOSIS OF SINGLE PHASE TRANSFORMERS**, submitted by **Pothula Abhinay Reddy**, to the Indian Institute of Technology Mandi, for the award of the degree of **Master of Science By Research**, is a bonafide record of the research work done by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Dr. Anil Kumar Sao **Dr. Bharat Singh Rajpurohit** Date:

DECLARATION BY THE RESEARCH SCHOLAR

This is to certify that the thesis entitled "**CONDITION MONITORING AND FAULT DIAGNOSIS OF SINGLE PHASE TRANSFORMERS**", submitted by me to the Indian Institute of Technology Mandi for the award of the degree of Master of Science by Research is a bonafide record of research work carried out by me under the supervision of **Dr. Anil Kumar Sao** and **Dr. Bharat Singh Rajpurohit.** The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Mandi 175001
Date: Signature of Research Scholar

ACKNOWLEDGEMENTS

On the completion of this work, foremost, I would like to express my deepest gratitude to my advisors, Dr. Anil Kumar Sao and Dr. Bharat Singh Rajpurohit for their excellent guidance, caring, patience, valuable advice, constructive criticism and providing me with an excellent atmosphere for doing research. Dr. Bharat Singh Rajpurohit helped me out of numerous dead end situations with his optimism and ability to think out of the box. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor. I offer my deep sense of reverence and profound indebtedness to him for his deep concern both for my academics and for personal welfare. My association with him has been extremely remarkable and fruitful. Thank you doesn't seem sufficient but it is said with appreciation and respect. I must say, I have pride in working with him.

I am highly obliged to my advisors and Dr. Manoj Thakur who have taught me various courses and provided me with earnest help and support, whenever needed. I would like to thank other faculty members for their support and cooperation. I am also grateful to staff members for assisting me in carrying out various tasks with ease. I would like to thank Gurinderbir, Prateep, Anshul, Lakshmanan, Rajeev, Steela, Srimanta, Anjana, Venky, Ram, Lingeshwar, Narayana, Rajesh, Guru, Gaurav, Archana and Seema for their constant support and for providing a stimulating and fun filled environment.

Achievements in life do not come alone by one's own efforts but by the blessings of parents, masters and the Omniscient. I express my deep sense of reverence and profound gratitude to my mother for everything they have done for me, all the pains and sufferings they have undergone to bring me up to this stage and thus enabling me to devote myself to my studies at IITM without having to worry. I thank Bhagwan Shri Krishna for giving me the strength and resources to complete my academic pursuits.

Pothula Abhinay Reddy

ABSTRACT

KEYWORDS: *Winding parameter identification, real-time measurement, transformer winding deformation, transformer winding temperature*

Transformers are the most critical and capital intensive assets of electrical transmission and distribution system and their reliable operation is necessary for maintaining healthy functioning of power grid. Transformer failures could cause power outages, personal and environmental hazards and expensive rerouting or purchase of power from other suppliers. Transformer failures can occur due to various causes. Transformer in-service interruptions and failures usually result from dielectric breakdown, winding distortion caused by short-circuit withstand, winding and magnetic circuit hot spot, electrical disturbances, deterioration of insulation, lightning, inadequate maintenance, loose connections, overloading, failure of accessories such as OLTCs, bushings, etc. The condition of transformer windings can be gauged by monitoring their equivalent circuit parameters. These parameters are not affected by external faults and change only in the presence of an internal aberration. Changes in the insulation temperature are reflected in winding temperature and can be monitored by observing the winding resistance values. Similarly changes in the short circuit reactance can give information on the condition and structure of windings. Rapid and reliable protection can be implemented by monitoring these parameters since inrush current and over-excitation does not affect these parameters. Presently, there is no accurate measurement method for the transformer winding parameters and generally require the transformer to be disconnected from the power system. A new algorithm for extracting transformer winding parameters which can be implemented online is presented. This method takes only the input currents and voltages as inputs and thereby eliminates the need for the disconnection of the transformer from the power system. In this method, winding parameters are obtained by solving the equivalent circuit equations in real time continuously which allows for interpretation of transformer condition and detection of faults in real-time. The proposed method has been tested and validated by simulations and experiments.

In thesis, a novel method is presented for the extraction of winding parameters of a single-phase transformer. The primary and secondary currents and voltages are taken as inputs, which are used to solve the discretized equivalent parameter equations online to find the winding parameters which allow monitoring of the condition while the transformer is in operation. Moreover it requires minimal computations. The proposed algorithm has been tested for various cases is found to be sufficiently accurate to monitor significant changes in the equivalent parameter values.

Further the interpretation of variation observed in the winding parameters is explained with reference to the possible fault occurrence. It is shown how the parameters will vary when an inter-turn fault, insulation quality compromise and mechanical integrity compromise possibly occur. It was shown that inter-turn faults can be identified by decrease in resistive loss component, insulation quality can be monitored via winding resistance monitoring and mechanical integrity monitored by observing the variation in leakage flux losses.

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NOTATIONS

I_f	Fault current
I_{oc}	No-load current
I_{sc}	Full-load primary current
I_μ	Magnetizing component of no-load current
I_w	Active component of no-load current
i_p	Primary current of the transformer
i_s	Secondary current of the transformer
i_s'	Secondary current, referred to primary
k	Turns ratio of transformer
L_c	Magnetizing inductance
L_{eq}	Equivalent inductance referred to primary
L_p, L_{lp}	Primary leakage inductance of the transformer
L_s, L_{ls}	Secondary leakage inductance of the transformer
L_s', L_{ls}'	Secondary leakage inductance, referred to primary
L_{pp}	Self inductance of primary winding
L_{ss}	Self inductance of secondary winding
L_{ps}, L_{sp}	Mutual inductances between the windings
$L_{mutualp}$	Primary magnetizing inductance

R_c	Core resistance
R_{eq}	Equivalent resistance referred to primary
R_s	Secondary winding resistance of the transformer
R_s'	Secondary winding resistance, referred to primary
R_{lp}	Primary winding reluctance
R_{ls}	Secondary winding reluctance
R_{mutual}	Reluctance experienced by mutual flux
R_L	Load resistance
R_L'	Load resistance referred to primary
T_n	nth time instant
V_{oc}	Primary rated voltage
V_{sc}	Short circuit voltage
v_p	Primary voltage of the transformer
v_s	Secondary voltage of the transformer
v_s'	Secondary voltage, referred to primary
W_{oc}	No-load core loss
W_{sc}	Full-load copper loss
X_{eq}	Equivalent reactance referred to primary
Z_{eq}	Equivalent impedance referred to primary
Z_f	Fault impedance

ϕ_0	Phase angle
Φ_p	Primary flux
ΦS	Secondary flux
Φ_{lp}	Primary leakage flux
Φ_{ls}	Secondary leakage flux
Φ_{mutual}	Mutual flux
$\Phi_{mutualp}$	Mutual flux due to i_p
$\Phi_{mutuals}$	Mutual flux due to i_s
λ_p	Flux linkage of primary winding
λ_s	Flux linkage of secondary winding
θ_{HST}	Hottest spot temperature

CHAPTER 1

Overview

1.1 Introduction

The use of transformers is widespread throughout modern interconnected power systems. The transmission and sub-transmission network comprises of a few hundred to over one thousand transformers in a large public power utility ranging in capacity from 69 kV to 500 kV while not including the lower voltage distribution network. These transformers range in size from a few kVA to several hundred MVA costing from a few hundred dollars to millions of dollars to replace.

Power transformers are usually very reliable within their 20-35 year design life. With proper maintenance, a transformer can remain in service as long as 60 years. However, the catastrophic in-service failure of a transformer is potentially dangerous to utility personnel and the public through explosion and fire, while slow oil leakages from transformers may damage the environment. Failed transformers are costly to repair or replace, and may result in significant loss of revenue through outages [1].

Utilities must prevent these failures and maintain their valuable inventory of transformers in good operating condition. Traditionally, routine preventive maintenance programs have been used combined with regular testing [2]. As the utility industry is gradually deregulated, increasing efforts are being made to achieve maximum possible reduction in maintenance costs and equipment inventories [3]. This has sparked a practice with reduced regular maintenance, reduced spare transformer capacity and increased average loading. These changes are occurring at a time when the average age of transformers in service is increasing and approaching the end of nominal design life [4].

The life of a transformer is directly related to the condition of the insulation within and around the windings. The number one cause of degradation of insulation is heat generated by power losses in the windings [5]. The estimated lifetime of a distribution transformer is based on the amount of heat generated by a constant loading at the rated current. However, many transformers that are in use do not have to be constantly loaded at rated current. Thus, the transformer does not heat up as much, and the process of degradation may be slowed. On the other hand, smart grid operation may require transformers to handle overload over a short period of time which would causing accelerated degradation. Hence, there has been a push towards a condition-based replacement approach instead of a time-based replacement approach for distribution transformers. The transformer maintenance, instead of doing at regular, pre-determined intervals, is expected to be carried out only if the equipment is suspected to be deteriorating and in order to do so, there is an acute need of better non-intrusive diagnostic and monitoring tools to assess the internal condition of transformers. If a problem is found during the course of monitoring, the transformer can then be repaired or replaced before it fails.

1.2 Transformer Failure

Consequences

Transformers are critical, capital intensive assets for the utility industry and their failure can cause large disruptions in power supply. Substantial amount of cost and time are required to repair or replace a power transformer. Normally the time taken for repair and replacement of a 345/138 kV transformer is about 12 to 15 months [3]. The in-service failure of a transformer can prove catastrophic. The explosion and fire occurring during the failure is potentially dangerous to utility personnel and the public, while slow oil leakages from transformers may damage the environment. Failed transformers are costly to repair or replace, and result in significant loss of revenue through outages.

Causes

Commonly, any forced outage due to defective or faulty state of transformer (e.g. insulation degradation, damaged winding, failure of tap-changer), any problem requiring removal of the transformer to repair facility or any problem that requires extensive field repair needing the transformer to be disconnected from the grid (e.g. excessive gas production, high moisture levels), can be defined as transformer failure [36]. The causes of failure can be basically categorized as electrical, thermal, chemical or mechanical. The failure can be caused by internal or external factors or a combination of both. The typical causes of failures are listed in Table 1.1. In addition to failures in the main tank, failures can also occur in the bushings, in the tap changers or in the transformer accessories. Many of the failure effects will increase in probability at a steep rate with aging of the machine. Table 1.2 gives the common causes, the stresses they produce, the agents responsible and their end effects.

Table 1.1: Typical causes of transformer failure

Internal Causes	**External Causes**
Insulation degradation	Lightning strikes
Winding displacement	System switching operations
Overheating	System overload
Hydrocarbons in the oil	System faults (short circuit)
Moisture in oil	
Solid contamination in the insulating oil	
Partial discharges	
Design & manufacture defects	
Internal winding resonance, etc.	

Table 1.2: Agents of transformer internal deterioration

Causes	1. Voltage 2. High electric field	1. Cooling Defect 2. Dielectric Losses 3. Bad Joint	1. Contamination 2. Poor drying 3. Leakage	1. Transit shocks 2. Short circuit 3. Inrush current 4. Vibration
Stresses	Electrical	Thermal	Chemical	Mechanical
Agents	1. PD 2. Tracking 3. Treeing 4. Electrolysis	1. Temperature	1. Moisture 2. Acids 3. Oxygen 4. Sulphur Particles	1. EM forces 2. Shocks
Effects	Arcing decomposition of oil, produce gases & acids, depolymerisation of cellulose, lower mechanical & electrical strengths			1. Winding deformations
Finally insulation or mechanical failure of winding				

The following problems were reported as the main causes of transformer failures (51 % of transformer failures over a five-year period) from a survey [5]:

1) Decreased internal dielectric strength (aging), presence of moisture and solid contaminants
2) Decompression, displacement and deterioration of winding due to the short circuit forces
3) Damaged internal insulation causing deterioration of the transformer bushings.

Transformer winding resonance is an important factor to be considered when evaluating the possibility of a failure. Four single-phase extra high voltage (EHV) autotransformer failures were attributed to winding resonance by an American utility [6]. Also, three 25/765 kV, 500 MVA generator step-up transformer failures and two 765 kV, 80 MVA reserve auxiliary transformer failures were experienced by the same utility. It was observed that immediately after the transmission system was energized, breakdown of the no-load tap changers occurred in all the failures involved and all the failures were dielectric in nature.

In large power transformers, it was found that about 41% of failures were due to on-load tap changers (OLTCs) and about 19% were due to the windings. The failure origins were 53% mechanical and 31 % dielectric. On transformers without on-load tap changers, 26.6% of failures were due to the windings, 6.4% were due to the magnetic circuit, 33.3% were due to terminals, 17.4% were due to the tank and dielectric fluid, 11% were due to other accessories and 4.6% were due to the tap changer [7]. It can be observed that a considerable portion of the failures may be associated to defect related to changes in the transformer windings, such as loss of clamping pressure.

From these surveys and research results, it can be inferred that the key sources of transformer failure are load tap changers, windings, insulation ageing and contamination. Winding deformation and insulation aging are very significant contributors to field failures of transformers.

1.3 Processes Involved In Transformer Aging

There primary methods of aging in distribution transformers are electrical stress, mechanical stress, chemical composition changes, and thermal stress. Electrical stress is caused by faults in the windings, coronas, and partial discharges. Mechanical stress in a transformer is a result of vibrations and the expanding and contracting of the windings due to fluctuating temperatures. Thermal stress is caused by overheating of the transformer due to overloading of the machine [5]. Chemical changes occur due to the de-polymerization of the oil and paper insulation occurring naturally as a result of aging, aided and aiding the other primary causes directly. Each of these processes will be discussed in more detail in the sections that follow.

Electrical Stress

Electrical stress occurs inside a distribution transformer due to over-voltages caused mainly by switching surges and lightning strikes. These stresses can be intensified if there is surface contamination in the insulation system of the transformer. Surface contamination causes the electric field inside the windings to distort and in effect reduces its electric strength [8]. One of the weakest parts of the insulation system inside a distribution transformer is the gaps between the paper insulation and the coils. Due to the difference in relative permittivity of the paper insulation and the oil/air, the electric field is concentrated inside these areas. Thus, partial discharges can occur there which degrades the overall insulation system [3].

Mechanical Stress

Mechanical stress in a piece of electrical equipment is primarily caused by the strain inducing forces and movement of parts inside the machine. The mechanical structure of a transformer is continuously subjected to huge stress developed due to the repulsive forces between the wires within the windings. The vibrations inside a transformer are chiefly due to short-circuit currents which arise outside of the transformer. The large currents that flow into the transformer produce an inaudible noise which can damage the windings and insulation [3]. In addition, harmonic currents may also induce vibrations as a result of resonance. The other major cause of mechanical stress in transformers is expansion and contraction of the windings due to fluctuations in temperature.

Thermally Accelerated Aging

The main cause of premature aging in distribution transformers is excessive temperature. Due to the very high demand for electricity, distribution transformers are constantly being run at their maximum capacity or even higher at peak hours of operation. During these periods of high loading, the transformers can become very hot. The extreme temperatures cause the solid insulating material inside the windings of the transformer to deteriorate. The deterioration leads to a shorter time period of useful life. IEEE standard C57.91-1995 describes the method which is commonly used to determine the amount of additional aging that a transformer undergoes because of high operating temperatures [9]. As with other equipment, the temperature inside a transformer is not distributed evenly. The insulation which is subjected to the highest temperature will be subjected to the most deterioration. Hence, the hottest spot temperature (HST) is used to determine the Aging of the transformer.

1.4 Transformer - Life and Maintenance

Transformers are subjected to natural ageing under operating stress and accelerated ageing due to over-stress and internal defects during service. The general condition of a transformer can be precisely gauged by several monitoring techniques in use or under investigation. Traditional routine tests include excitation impedance and loss dissipation factor, transformer ratio measurement, winding resistance, short circuit impedance and loss, capacitance, and applied and induced potential. These tests usually provide information on faults in windings, winding conductor and joint problems, winding deformation, oil moisture and contamination and insulation dielectric problems.

For further insight into the condition of transformer, specialized tests like frequency response analysis, degree of polymerization, vibration analysis, partial discharge measurement, infrared examination and voltage recovery analysis are employed. These tests serve to identify problems such as hot spots on connections, moisture in paper and aging of paper, local partial discharge, winding looseness and displacement, slack winding and mechanical faults and insulation degradation. Oil tests consisting of dissolved gas analysis (DGA) with ratio analysis, furan analysis, water content, resistivity, acidity, interfacial tension (IFT) and dissipation factor (DF) are used extensively. These detect oil incipient faults, overheating, aging of paper, dryness of oil-paper and aging of oil. Large transformers require life assessment analysis in order to [10]:

1) gauge the condition of transformers and obtain warning of faults and defects in advance
2) diagnose issues when transformers exhibit defective symptoms or following the operation of protective equipment
3) determine whether a transformer is in a satisfactory condition to cope with unexpected overloads and unusual operating conditions
4) extract reference results to aid in the interpretation of subsequent tests
5) facilitate in planning an economic replacement strategy for transformers
6) satisfy the insurance coverage requirements

1.5 Monitoring and Diagnostic Methods

The term *monitoring*, broadly describes measurement of a basic parameter which alarms the operator when the parameter varies beyond the allowable threshold limits. The term *diagnostics* refers to the inclusion of sophisticated analysis, such as an expert system capable of providing an assessment of condition of the equipment and suggest appropriate actions. Evaluation of transformer condition can be done by a variety of tools [3]. Some of the traditional diagnostic methods in practice are presented as following:-

1.5.1 Traditional Methods of Diagnosis

a) Oil Testing

State of winding insulating oil is an important indication of transformer condition. Oil degradation is mostly caused by thermal and electrical faults.

Dissolved Gas Analysis

Insulating oils breakdown under abnormal electrical or thermal stresses, liberating small quantities of gases, mostly hydrocarbons, and the composition of these gases is dependent upon the type of fault. Dissolved Gas Analysis (DGA), enables to distinguish faults such as partial discharge (corona), overheating, and arcing in a variety of oil-filled equipment. Over a period of time, by collecting a number of samples it is possible to discern trends and to determine the severity and progression of incipient faults [11]. From DGA obtained data, it is possible to:

1) monitor the condition during overload
2) identify the presence of faults and monitor the rate of fault development
3) provide an advanced warning of incipient and developing faults
4) plan ahead and schedule repair conveniently

At least two consecutive samples are needed to calculate the rates of fault generation. The IEEE Std. C57.104-1991 [12], can be referred for a detailed discussion on the interpretation of gases generated in oil-immersed transformers. A list of key gases and their related faults is shown in Table 1.3 [3].

Table 1.3 - Key gases and related faults [3]

Key Gas	Characteristic Fault
H_2	Partial Discharge
C_2H_6	Thermal Fault < 300°C
C_2H_4	Thermal fault 300°C - 700°C
C_2H_2, C_2H_4	Thermal Fault > 700°C
C_2H_2,H_2	Discharge of Energy

Insulating Oil Quality

The degree of deterioration, extent of contamination of the insulating oil and any change in the oil's electrical properties can be measured by performing a combination of electrical, physical and chemical tests. A number of specific furanic compounds are produced and dissolved in the oil, as paper degrades. The presence of these compounds is related to the strength of the paper, as measured by its degree of polymerization (DP). The condition of paper insulation can be assessed conveniently and non-invasively through measurement of furans and phenols in oil. From the results obtained preventative maintenance procedures are established so as to avoid premature failure of the equipment, costly shutdowns and catastrophic damages in order to extend the service life of the transformer. Threshold levels for these oil tests are specified in ASTM D3487 (for new oils) and IEEE guide 637-1985 (for service oils).

b) Power Factor Testing

Insulation power factor is the ratio of the resistive current component to the total leakage current under an applied voltage. A power factor of less than 1% is generally considered to be good, 1% - 2% is questionable, and a power factor that exceeds 2% requires action to be taken. In practice, the evaluation is based on a single power factor data point along with the history of change in the power factor [3].

c) Winding Resistance

Winding resistance is the measure of resistance of primary and secondary windings of transformer and indicates the condition of the winding conductor and tap change contact. A sensitive ohmmeter capable of accurately measuring resistance in the range of 20 Ω down to fractions of an ohm is required for the test. As the insulating oil temperature varies, it affects