POWER TRANSFORMER INCIPIENT FAULTS MONITORING

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Abstract: **Power transformers are important and expensive components in the electric power system. The knowledge of the actual status of the transformer insulation behavior, load tap changer performance, temperature, and load condition is necessary in order to evaluate the service performance concerning reliability, availability and safety. Systems abnormalities, loading, switching and ambient condition normally contribute towards accelerated aging and sudden failure. The paper presents the causes which lead to the internal faults appearance in the power transformer. The production mechanisms of the faults and the on-line monitoring are also analyzed. A monitoring procedure is proposed for the diagnosis and forecasting strategy of the functioning state of the power transformer.**

Keywords: *power transformer, monitoring, fault, failure, procedure*.

1. INTRODUCTION

Power transformers are ones of the most important components of electric networks. The majority of these devices have been in service for many years under different environmental, electrical and mechanical conditions.

The fault of a distribution transformer may leave thousands of homes without heat and light, and the fault of a step-up transformer in a power generation plant may cause the shutdown of the attached generation unit.

These devices are very expensive and therefore monitoring systems will be valuable for preventing damage to the transformers.

Generally speaking, monitoring is the observation of transformer conditions. The difference between offline monitoring and online monitoring is that the transformer should be switched off in order to measure data for the offline monitoring, and for the online monitoring the data can be acquired while the transformer is operating [1] - [4].

Starting from the new research outcomes that the incipient fault diagnosis in power transformers can assure information to foretell failures ahead of time, the needed corrective maintenance should be taken in account to stop outages and reduce down time.

The purpose of this paper is to study different methodologies of incipient fault monitoring and to develop a new monitoring procedure for power transformer.

2. TYPES OF FAULTS

The faults that occur within the transformer protection zone are internal faults.

Transformer internal faults can be divided into two classifications: internal short circuit faults and internal incipient faults. Internal short circuit faults are generally turn-to-turn short circuits or turn to earth short circuits in transformer windings.

Internal incipient transformer faults usually develop slowly, often in the form of a gradual deterioration of the insulation due to some causes.

Statistics show that winding failures most frequently cause transformer faults (ANSI/IEEE 1985). Insulation deterioration, often the result of moisture, overheating, vibration, voltage surges, mechanical stress created during transformer through faults, are the major reason for winding failure.

Voltage regulating load tap changers, when supplied, rank as the second most likely cause of a transformer fault. Tap changer failures can be caused by a malfunction of the mechanical switching mechanism, high resistance load contacts, insulation tracking, overheating, or contamination of the insulating oil.

Transformer bushings are the third most likely cause of failure. General aging, contamination, cracking, internal moisture and loss of oil can all cause a bushing to fail.

Two other possible reasons are vandalism and animals that externally flash over the bushing.

Transformer core problems have been attributed to core insulation failure, an open ground strap, or shorted laminators.

Other miscellaneous failures have been caused by current transformers, oil leakage due to inadequate tank welds, oil contamination from metal particles, overloads and over voltage.

The factors responsible for failures and accelerated deterioration can be categorized as:

- operating environment (electrical): load current, short circuits, lightening and switching surges;

- operating environment (physical): temperature, wind, rain, pollution;
- operating time: time in service and time under abnormal conditions;
- number of operations of tap changer;
- vibration effect: sound and material fatigue;
- contaminants: moisture, presence of oxygen and particles in oil.

A correlation between the causes and the effects produced at the flaw is presented in Table 1 [2], [4-16].

Usually, one fault type may have more than one cause. Example: arching and/or overheating of solid insulation may have as cause winding turn-to-turn short-circuit; arching and corona discharges may have as cause free water or excessive moisture in oil, etc. This makes fault location very difficult.

Nevertheless, fault diagnosis is good enough to provide information to a maintenance program, and serve as the basis of a preventive maintenance strategy.

Causes	Faults			
	Arcing	Corona	Overheating of cellulose	Overheating of oil
Winding turn-to-turn short-circuit	X		X	
Winding open circuit	X		X	
Operation of build-in LTC	X			
Winding distortion or displacement		X	X	
Lead distortion or displacement		X	X	
Loose connection to bushing terminals, tap leads, terminal boards	X	X	X	
Free water or excessive moisture in oil	X	X		
Floating metal particles	X	X		
Loose connection to corona shields		X		
Loose collars, spacers, core ground straps, core hold down angle (Braces)		X		
Through fault			X	
Overloading			X	X
Damaged yoke bolt insulation				X
Rust or other damage on core				X
Damaged shunt packs of tank				X
Jammed oil circulating path				X
Cooling system malfunction				X

Table 1: Correlation between power transformer internal faults and causes.

3. METHODOLOGY OF INCIPIENT FAULT MONITORING

Dissolved gas analysis has become a very popular technique for monitoring the overall health of a transformer. As various faults develop, it is known that different gases are generated. By taking samples of the mineral oil inside a transformer, one can determine what gases are present and their concentration levels.

Researches have been done to connect theoretically the gaseous hydrocarbon formation mechanism with the thermodynamic equilibrium.

Some studies indicated that the hydrocarbon gases with the fastest rate of evolution would be methane, ethane, ethylene and acetylene.

Some studies have focused on key gases and what faults they can identify.

In Table 2 the relationship between fault types and the key gases is shown. In the case of key gas analysis, a fault condition is indicated when there is excessive generation of any of these gases.

For this to be effective, much expert experience is still needed.

Key gas	Chemical symbol	Fault type
Hydrogen	H_2	Corona
Carbon monoxide and carbon dioxide	CO CO_2	Cellulose insulation Breakdown
Methane and ethane	CH_4 C_2H_6	Low temperature Oil Breakdown
Acetylene	C_2H_2	Arcing
Ethylene	C_2H_4	High temperature oil breakdown

Table 2: The relationship between fault types and key gases.

For example, acetylene concentrations that exceed the ethylene concentrations indicate that extensive arcing is occurring in the transformer, since arcing produces acetylene.

In addition to gas in the oil, it is an accepted fact that the presence of water is not healthy for power transformers. Water in the oil indicates paper aging, since the cellulose insulation used in power transformers is known to produce water when it degrades. Water and oxygen in the mineral oil further increases the rate at which the insulation will degrade. This means that a high concentration of water in the oil not only indicates that the insulation has been degrading but it will degrade more quickly in the future due to increased presence of water in the oil. Water in the oil is also a sign that the mineral oil itself is deteriorating.

When the mineral oil deteriorates, the dielectric constant of the oil decreases.

The key gas method identifies the key gas for each type of fault and uses the percent of this gas to diagnose the fault. It interprets dissolved gas analysis results based on a simple set of facts. In Table 3 is summarized the diagnostic criteria of the key gas method.

Fault	Key gas	Criteria
Arcing	Acetylene (C_2H_2)	Large amount of H_2 and C_2H_2 and minor quantities of CH_4 and C_2H_4. CO and CO_2 may also exist if cellulose is involved.
Corona (PD)	Hydrogen (H_2)	Large amount of H_2, some CH_4, with small quantities of C_2H_6 and C_2H_4. CO and CO_2 may be comparable if cellulose is involved.
Overheating of oil	Ethylene (C_2H_4)	Large amount of C_2H_4, less amount of C_2H_6, some quantities of CH_4 and H_2. Traces of CO.
Overheating of cellulose	Carbon monoxide (CO)	Large amount of CO and CO_2. Hydrocarbon gases may exist.

Table 3: Diagnostic criteria of key gas method.

Though *moisture and dissolved gas analysis* are helpful in detecting many types of failures that can occur in a transformer, the measurement of *partial discharges* is the most effective method to detect pending failure in the electrical system. As the electrical insulation in a transformer begins to degrade and breakdown, there are localized discharges within the electrical insulation. Every discharge deteriorates the insulation material by the impact of high-energy electrons, thus causing chemical reactions. Partial discharges may occur only right before failure but may also be present for years before any type of failure. A high occurrence of partial discharges can indicate voids, cracking, contamination or abnormal electrical stress in the insulation [2], [4-16].

The most common method for on-line detection of *partial discharges* is the use of *acoustical sensors* mounted external to the transformer. The main difficulty with using acoustical sensors in the field, however, is in distinguishing between internal transformer partial discharges and external partial discharges sources, such as discharges from surrounding power equipment. An alternative method has been proposed recently to differentiate between internal and external partial discharges and is based on the combined use of signals from a capacitive tap and signals from an inductive coil fitted around the base of the bushing.

The advantage of partial discharges sensors is the ability to detect the actual location of insulation deterioration, unlike the dissolved gas sensors. The one disadvantage to partial discharge sensors is that they are greatly affected by the electromagnetic interference in the substation environment.

One of the simplest and most effective ways to monitor a transformer externally is through *temperature sensors*. Abnormal temperature readings almost always indicate some type of failure in a transformer.

It is known that as a transformer begins to heat up, the winding insulation begins to deteriorate and the dielectric constant of the mineral oil begins to degrade.

In order to make on-line monitoring possible, thermocouples are placed externally on the transformer and provide real-time data on the temperature at various locations on the transformer. In many applications, temperature sensors have been placed externally on transformers in order to estimate the internal state of the transformer.

Though the breakdown of the insulation can cause catastrophic failure in a transformer, the life of a transformer is predominantly shortened by the deterioration of its accessories. These accessories include the bushings, load tap changers and cooling system.

Some of the causes of bushing failures include changing dielectric properties with age, oil leaks, design or manufacturing flaws, or the presence of moisture. Sensors have now been created to monitor the health of bushings. Transformer bushings have a finite life.

Overheated load tap changers can result from many different phenomena. These causes include coking, misalignment, and loss of spring pressure. Though the contact temperature cannot easily be measured directly, the overheating will generally result in an increase in the load tap changer oil temperature. By monitoring the load tap changer temperature closely, the flashover between the contacts can be avoided, which usually results in a short circuit of the regulating winding and subsequent failure of the transformer [2].

Vibration analysis by itself cannot predict many faults associated with transformers, but it is another useful tool to help determine transformer condition. Vibration can result from loose transformer core segments, loose windings, shield problems, loose parts or bad bearings on oil cooling pumps or fans. Every transformer is different, therefore, to detect this, baseline vibration tests should be run and data recorded for comparison with future tests.

Vibration analyzers are used to detect and measure the vibration. Information gained from these tests supplements ultrasonic and sonic fault detection tests and dissolved gas analysis. Information from these tests may indicate maintenance is needed on pumps/fans mounted external to the tank. It may also show when an internal transformer inspection is necessary. If wedging has been displaced due to paper deterioration or through faults, vibration will increase markedly.

4. EXPERT SYSTEMS FOR DIAGNOSIS

An expert system is a software application that uses artificial intelligence techniques to achieve the performances of a human expert in a certain field [17-22].

It is a specific approach in which there is a separation between knowledge (facts, data) and reasoning (decision, search of the solution), so that new knowledge can be added in an incremental way. Often, the expression “expert system” is used alternately with the concept of “knowledge based system”.

Structural , an expert system includes:

- a knowledge base (facts), which represents the essence of the accumulated data in the respective field (the knowledge and the experience of the human expert);
- an inference engine which guarantees the application of the reasoning rules on the data base to find a solution;
- a user interface which rectifies the software ensemble under the operator’s command.

One problem is the representation of the knowledge. A very used way is that of a contraction on the arborescent network. The nodes represent partial solutions and the bows the relations between these solutions. This kind of structure is useful where the problem is explicit defined, which at their turn became new facts.

Another type of structure is the one based on rules like IF-THEN which link data or facts to the partial conclusions, which, at their turn, became new facts [17-22].

Other types of structures are the ones based on the utilization of behavioral models (mathematical models of the system characterization which allow to obtain some answers attending to the simultaneous transformation of lots of factors).

In the last years, the artificial intelligence techniques like neural networks or fuzzy logic guaranteed new possibilities of representing the knowledge with learning facilities, respectively decision ones in situations where YES-NO logic is not adequate.

A second problem is represented by the inference engine, namely the process of facts base cover and the construction of an adequate solution.

Generally, the approach of resolving a problem can be thought as a search process in a multi dimensional space of solutions.

The easiest way in this direction is the control of all the possibilities that is the exhaustive testing of each possibility, to find the best. The method is called generation and control of the solutions.

The most used searching strategies in an arborescent structure are the depth search and the width search, also other combined alternative.

5. MONITORING PROCEDURE PROPOSAL

In creating the expert system, a series of IF/THEN statements must serve to connect the various sensor measurements [17-23].
It is known that a rise in the acetylene concentration with respect to the ethylene concentration indicates arcing occurring in the transformer.
Arcing will also cause a rise in the top oil temperature. To validate the arcing hypothesis, the temperature over reference measurement should also be checked.
There is always the possibility of sensor failure, which could set off a warning but not be indicative of a developing failure.

The goal of monitoring substation equipment is to prevent catastrophic failure, but also eliminate unnecessary maintenance. By creating an expert system, the idea is to prevent incorrect diagnosis by coordinating the thresholds from several different, but related measurements. Through this coordination, incorrect warnings based on one threshold can be validated using other measurements as well.

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IF (Temperature above reference) > admissible value
THEN
    IF (Fan Bank Current) > admissible value
    THEN
        IF (Ethylene Concentration) > admissible value
        THEN
            IF (Moisture Concentration) > admissible value
            THEN
                Transformer Overheating, take off-line to service
            ELSE
                Check DGA and moisture analyzer for proper functioning
        ELSE
            Check thermocouple sensor
    ELSE
        Fan bank not operating properly, have serviced
ELSE
    Transformers operating normally.
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6. CONCLUSIONS

Power transformer is major power system equipment. Their reliability not only affects the electric energy availability of the supplied area, but also affects the economical operation of a utility.

Determining transformer condition is useful for making short-term decisions regarding operation and maintenance.

The major concern of the power transformer incipient faults is that they may decrease the electrical and mechanical integrity of the insulation system.

Incipient faults of power transformers can be classified into the following major categories: electrical arcing, electrical corona, overheating of cellulose, overheating of oil. These faults may be caused due to one or more of the causes.

A monitoring procedure is conceived to take into consideration all the aspects regarding the incipient faults which appear in transformers. This will allow to establish a monitoring strategy regarding the diagnosis of the power transformer faults.

Every expert system that is created consists of numerous set of IF/THEN possibilities. The design of different expert systems will depend on the sensor measurements available and the type of failures being detected. The key to a successful expert system is to utilize all the knowledge known about the system.

Acknowledgments

The research work has been developed in the frame of the project "CEREX – ***Models and Indicators for the Evaluation of Scientific Research in Universities in the Context of Knowledge Based Society"***, No.2-CEx-06-8-85/19.02.2006, within Excellence Research Program granted by Romanian Government.

The article is part of the project "TD-CNCSIS-Diagnosis of electrical equipments of the high and medium power station",139/1.10.2007.

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