ARTIFICIAL INTELLIGENCE TECHNIQUES FOR DIAGNOSING POWER TRANSFORMERS' FAULTS

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Abstract – The paper is structured in five parts. The first part includes the importance of the power transformers' in the power system. The second part presents the type of incipient faults which may decrease the electrical and mechanical integrity of the insulation system. The third part presents the methods for detecting the incipient faults of power transformers. In the fourth part it is introduced a diagnosis program which identifies different types of faults using artificial intelligence and dissolved gas analysis.

Keywords: diagnosis, dissolved gas analysis, fault, artificial intelligence.

1. INTRODUCTION

Power transformers are major power system equipment. The major concern of power transformers' incipient faults is that they may decrease the electrical and mechanical integrity of the insulation system. Transformer faults can have a significant economic impact due to long lead times in procurement, manufacturing and installation in addition to high equipment cost. Extending the useful life of the power transformers is the single most important strategy for increasing life of power transmission and distribution infrastructures.

The fault of a power 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.

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

It is important to know about transformer failures because:

- Largest financial losses due to failures of power transformer;
- The main responsible for failure of power transformer is insulation;
- The cost of insulation failures alone accounts for more than half of all failure costs.

The purpose of this article is to develop a diagnosis system using artificial intelligence techniques.

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 circuits 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 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 insulation 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 tapchanger;
- 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].

Table 1. Correlation between power transformer internal faults and causes

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

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.

3. METHODOLOGY OF INCIPIENT FAULT DIAGNOSIS

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 [2,3,4,6] 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.

Table 2. The relationship between fault types and key gases

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

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.

Table 3. Diagnostic criteria of 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.

In conclusion, the transformer oil analysis can give

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very important information about the state of the transformer and its electrical insulation, like:

- Internal fault: there can be detected electrical or thermal faults and their type (partial discharge, hot spots, arcing);
- Transformer aging: the actual ageing of the transformer is given by the state of the winding insulation;
- Quality of the oil: it must be verified if it achieves the insulating and cooling functions.

It can be added that the advantages of the oil analyses:

- The cost is very small in comparison wih the cost of a transformer failure;
- No need to interrupt the production process.

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. ARTIFICIAL INTELLIGENCE TECHNIQUES

The most achievements of diagnosis systems are incorporated using expert systems, in which the methods based on analytical models are combined with those based on qualitative models. This reasoning stays at the base of drawing up the architecture of such a system, which combines the heuristic knowledge obtained through experience with the qualitative and quantitative knowledge about the model.

The ordering and diagnosis unit constitutes the central part of the system, which incorporates both the method based on analytical model with the one that uses heuristic information, and the method based on knowledge about the system. The analytical and heuristic knowledge from the knowledge base results after a generating process of symptoms. The analytical knowledge is used to obtain analytical information, quantized through the measured variables processing of the process and a set of characteristic values is obtained which allow:

- the control of the admissible bound values of the directly measured signals;

- the directly measured signals analysis through the utilization of analysis methods;
- the process analysis through the utilization of the mathematical models of the process with the estimation methods of parameters, state and the method of parity equations. Beside the symptoms with quantized information, the heuristic symptoms can be obtained through the utilization of the information supplied by the human operators:
- based on the observations and technical inspections (reviews), the values of the heuristic characteristics are obtained (noise, color, smell, vibration, wear);
- a set of statistical data obtained on the basis of experience in process use or another similar processes and the operations of maintenance, repair, life time.

In the case of complex systems, with the help of heuristic knowledge stated as heuristic models (qualitative models), the causality fault-symptom can be established and it can be done a balance of different diagnosis strategy. In this way, fault trees or IF – THEN reasoning can be used, so the abnormal working and failures, that appear in a system, can be determined.

Figure 1 represents a block diagram showing the steps that are taken for the knowledge-based.

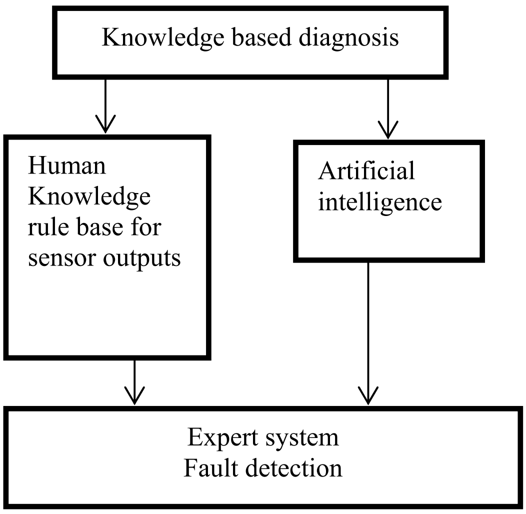

Fig.1. Approach to fault diagnosis

In the beginning, most attempts in transformer diagnostic focused on analytic models. Analytic models attempt to represent the system through mathematical equations. Depending on the complexity of the system and the desired model accuracy, both linear and nonlinear models have been developed. These models attempt to use physical principals to model a system.

For transformers, many different types of models have been developed to try to identify the system and detect failures. The transformer system is very complex. It contains thermal, mechanical, electrical and fluid systems.

For protection against overloading, transformer thermal models have also been developed, which use two exponential equations and non-linear time constants determined from transformer data. These models are used to predict top-oil rise over ambient temperature, hottest-spot conductor over top-oil temperature, and hottest-spot winding temperature given a specific load.

Many models have been formed that combine temperature measurements with current, voltage and other transformer measurements. State estimation methods were used to provide accurate estimates using oil, tank and ambient temperatures in addition to the voltages and currents on all the phases.

In addition to the thermal models, many mechanical, electrical and even fluid models have been developed for the transformer. On the mechanical side, a mathematical model has been derived to express the mechanical stresses due to forces on the transformer windings. This model provides critical information on the possible damage that is caused from radial short circuit forces and gives an assessment of the possibility that a catastrophic fault from a winding short circuit could occur.

Likewise, diagnostics of the electrical system have been developed using the transfer function method. Though the method uses ratios of the transformers electrical voltages and currents, the method actually detects defects in the mechanical system. The transfer function method is a quotient of the Fourier transformed input and output signals. These quotients are used to model the system electrically, and through comparison with previous fingerprints, can detect developing defects.

The artificial intelligence trains itself to the system and provides diagnostic information based on a set of inputs and outputs. The actual mapping that the artificial intelligence develops or how this relationship relates to any physical principles is usually not defined.

The most common forms of artificial intelligence used for transformer diagnosis are neural networks and fuzzy logic. Due to the complexity of the numerous phenomena, it is difficult to formulate a precise relationship relating the different contributing factors. This uncertainty naturally lends itself to fuzzy set theory. It has been developed a transformer diagnostic system that utilized both an expert system and a neural network to detect failures in a transformer.

The knowledge of the expert system has many uncertainties, and therefore fuzzy logic is employed. The two techniques are integrated by comparing the expert system conclusion with the neural network reasoning using a consultative mechanism. A block diagram for this type of hybrid system is presented below.

There was also developed a comprehensive system that included fuzzy logic, expert system and an artificial neural network to detect faults in the insulation system. In this case, fuzzy logic is implemented in coordination with the neural network. The outputs of the neural network are numerical values between 0 and 1, which are placed in membership functions based on a set of fuzzy rules.

The combination of an expert system with neuro-fuzzy techniques is not the only diagnostic tool used in transformer systems. An integration of an artificial neural network and an expert system has been developed for power equipment diagnosis. The system uses the neural network to form implicit diagnostic rules and has the added benefit of logic regression analysis for fault location.

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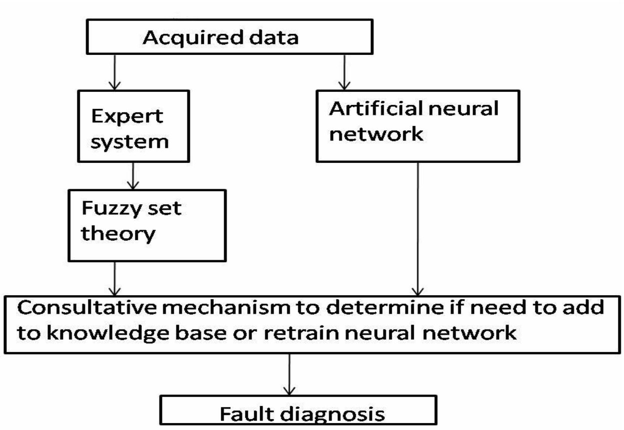

Fig. 2. Strategy for combined fuzzy logic, expert system and neural network

Though many methods have employed some combination of fuzzy logic, artificial neural networks and expert systems, this is not always the case. A highly accurate two-step artificial neural network has been used for transformer fault diagnosis using dissolved gas data.

Fuzzy logic has also been used to diagnose the health of a transformer and foresee any developing failures. Fuzzy logic has been used to smooth out some of the problems that can appear when using the cut and dry rules of expert system knowledge. By forming fuzzy membership functions for the different measurements (gases, generation rates, electric current, temperature), it is possible to overlap the individual membership functions into one large fuzzy matrix that can be used for diagnosis. A fuzzy logic diagnostic system has also been developed for the transformer that utilizes evolutionary programming and different shaped membership functions to get a more accurate fuzzy diagnostic system.

Another artificial intelligence based approach utilizes a genetic algorithm in coordination with an artificial neural network. One of the weaknesses of artificial neural network approach is the tendency to find only a local minimum in its training due to improper initial value. The genetic algorithm is used to optimize the initial value and thus increase the accuracy of the neural network training. Likewise, genetic algorithms have been used in the training of a fuzzy controller that forms diagnostic rules based on dissolved gas data. In this case, the fuzziness helps define diagnostic operating conditions and the genetic algorithm decreases the amount of rules needed.

For a diagnosis system of transformers, it is needed to obtain some rules. For guidance there can be use IEC or IEEE. These are revised from time to time and need a correct interpretation of the rules.

Figure 3 represents a part of a power transformer diagnosis engine using the IEEE conditions and ratio method. The rules are represented in IF-THEN structure.

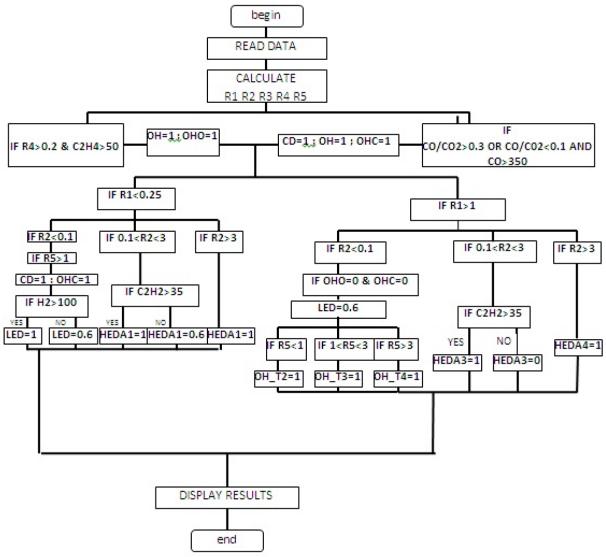

Fig. 3. Power transformer fault diagnosis engine

The ratio CO/CO2 is used as a main factor to diagnose the degradation of cellulose.

5. CONCLUSION

To manage the life of transformers, to reduce failures and to extend the life of the transformer, some tests must be taken. The tests are carried out to prove that the transformers are ready to operate or to find the faults.

Equipment failures do occur even with the best equipment designs available and using the best utility practices. In order to operate a power system reliably, transformer failures must be anticipated.

Dissolved gas analysis is very important to determine the condition of a transformer, it can identify a problem such as: deteriorating insulation oil, overheating, partial discharge and arcing.

The transformers have different gassing characteristics because of their size, structure, manufacture, loading and maintenance history.

The new diagnosis systems have expert systems incorporated, in which the methods based on analytical models are combined with those based on qualitative models.

Expert systems and artificial intelligence techniques have already been proposed to understand the obvious and non-obvious relationships between transformer failures and the causes of failures. Preliminary results, obtained from the application of these techniques, are encouraging, however some limitations exist. Knowledge acquisition, knowledge representation and maintenance of a great number of rules in the expert systems require plenty of efforts.

Artificial intelligence techniques were studied. These techniques include expert system, fuzzy logic, evolutionary algorithm and artificial neural network.

The effectiveness of the expert system and fuzzy logic depends on the precision and completeness of human knowledge accumulated over the years. Both methods need a large knowledge base that must be constructed manually and cannot adjust their diagnostic rules automatically thus cannot acquire knowledge from the new data samples through a self-learning process. The quality of the data is especially important as poor data can lead to a poor diagnosis or misdiagnosis.

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