Chapter 1 Introduction

1.1 Importance of power transformer incipient fault diagnosis

Power transformers are 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. For example, 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.

Under the deregulation policy of electric systems, each utility is trying to cut its cost, and the prevention of accidental loss is much more important than before. The capital loss of an accidental power transformer outage is often counted in million dollars for output loss only, not to say the costs associated with equipment repair or replacement [Myers98]. Because of this economic incentive, preventive tests and on-line monitoring are of benefit to predict incipient fault conditions, and to schedule outage, maintenance and retirement of the transformers.

1.2 Methodology of incipient fault diagnosis

The major concern of power transformer incipient faults is that they may decrease the electrical and mechanical integrity of the insulation system. This may progress to a point that the insulation cannot withstand transient overstresses caused by through-fault current (mechanical forces on windings) and electrical overvoltages (temporary, switching or lightning). Incipient fault diagnosis is therefore closely related to insulation condition assessment.

1.2.1 Insulation condition assessment test

Insulation condition assessment test refers mainly to off-line routine tests, including measurement of insulation resistance (IR), dielectric loss factor (DLF), interfacial polarization (IP) using anomalous IR and frequency dispersion of capacitance, turns ratio (TR), winding resistance (WR), core ground resistance (CGR), and some excitation tests [C57.125, Darv97]. These tests are applied to the whole transformer and thus are bulk measurements of the insulation condition. They can reveal some severe problems but may not find the incipient ones.

Other tests examine paper or pressboard samples taken from transformers (and which must be replaced if the transformer is to be returned to service). These tests include measurement of the degree of polymerization (DP) and tensile strength (TS). Some relatively new methods, such as high performance liquid chromatography (HPLC) furan analysis, interfacial polarization spectra (IPS) using return voltage (RV) measurement, and analytical chemical techniques [Darv97], are also used for the same purpose. These intrusive techniques are usually not favorable because the sampling process may damage the integrity of the insulation system, but may be necessary for very old transformers.

The most favorable tests for power transformer insulation assessment are on-line types, including partial discharge (PD) monitoring and dissolved gas-in-oil analysis (DGA) [Chu99]. These on-line tests are also the major incipient fault diagnosis methods.

1.2.2 On-line partial discharge monitoring

Partial discharges (PD) are generated due to fault conditions related to moisture, cavities in the solid insulation, metallic particles, and gas bubbles and can eventually cause dielectric breakdown. A significant increase either in the PD level or in the developing rate of PD activity can provide an early indication of an incipient fault condition.

On-line PD monitoring methods generally fall into two categories: the electrical method and the acoustic method. According to the sensors they are using, both of them can be further classified into two sub-categories: non-intrusive monitoring and intrusive monitoring. Non-intrusive monitoring uses sensors installed outside the transformers, such as coupling capacitors, high frequency current transformers (HFCT), piezoelectric type accelerometers [Lund92], etc. Intrusive monitoring must put the PD sensors inside the transformer and the implementation is thus more dangerous and expensive. For safety reasons, optical fiber sensors are more favorable than other types of sensors for intrusive PD monitoring [Zarg96].

In electrical PD monitoring, the impulsive PD current is often measured directly through a capacitive coupling circuit or a high frequency current transformer (HFCT). The coupling capacitor can be a separate high-voltage PD-free capacitor attached to the transformer terminals, or use the bushing capacitance directly. The major problem with electrical PD monitoring is the handling of interferences. This can involve very complicated algorithms [Borsi95, Nag94] and may not always be solved in practical applications.

Acoustic PD monitoring has been the focus of both academic and industrial interest for many years. The motivation is the benefit that may be realized through an accurate PD location. There are numerous papers studying PD location principles [Har76, Deh91, Lund921, Beng95, Meu96] and quite a few systems developed for this purpose [How81, Kawa84, Elef95, Tang96, Chang97]. Application issues are still causing difficulties in the interpretation of the results, and they must be addressed if a meaningful PD location is required. For example, the acoustic velocity is affected by many factors, including the temperature of oil, the gas and water contents of oil, and the frequency content of acoustic signals [Lund921, Lzb82, How84]; using a constant value in the solution of PD location functions may result in a very rough guess [Kemp95].

A big problem with PD monitoring is the result interpretation. There are currently no general rules can correlate the transformer condition with PD activities, or even a clear classification of PD activities. The only useable parameter is an empirical PD level limit value [Chu99]. There seems to be no agreement on this value because it was not given in some important national standards [C57.113, C57.21].

1.2.3 Dissolved gas-in-oil analysis (DGA)

A more successful technique for on-line incipient fault diagnosis is dissolved gas-in-oil analysis (DGA). By “on-line” we mean the transformer does not need to be de-energized. This type of analysis includes the conventional DGA, which is based on routine oil sampling, and the modern technology of on-line gas monitors.

Conventional DGA has been in practice for about thirty years, and has gained tremendous success compared to other techniques [Kemp95]. The main reason for this success is that the sampling and analyzing procedures are simple and inexpensive, and easy to be standardized. Many experiences have been gained from the process and several DGA standards have been set up [IEC599, IEC599r, C57.104]. Major diagnostic gases have been identified as hydrogen (H_2), ethane (CH_4), methane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), carbon monoxide (CO) and carbon dioxide (CO_2).

An important problem with conventional DGA methods, however, is over reliance on experts. Since transformers of different size, structure, manufacturer, loading and maintenance history may have different gassing characteristic, they need to be considered differently in most cases. DGA is thus often referred to as “art” instead of “science” [Ding95, Zhang96].

On-line gas-in-oil monitors appeared soon after the introduction of the DGA technology [Lyke77]. Several research prototypes and commercial products were introduced later. Some of the monitors concentrated on hydrogen (H_2) only [Gold83, McDe85, Bel85, Inoue90], while others are of multi-gas type [Tsu86, Lind94, Lind95, Ger95, Glodjo98, Liao98, Birlase98].

An advantage of these on-line monitors is the continuous measurement of one or more gases, so that any gassing trend, which is critical information for incipient fault screening, can be easily obtained. Problems with these monitors are related to selectivity and durability of the gas molecule screening membrane, field calibration, measurement range and resolution. Selectivity refers to the membrane allowing certain kinds of gases to pass but preventing the rests. Poor selectivity lowers measurement accuracy. Membranes with poor durability deteriorate faster, especially under field conditions where temperatures vary greatly between summer and winter, or even between day and night. Since the inputs of the monitors are non-electrical quantities, while the readout device of the monitors contains electronic circuits that are subject to offset and characteristic shift due to factors like temperature and humidity, field calibration of the device could be a big problem. Generally the measurement range and resolution of on-line monitors are far behind that of laboratory tests. With the new generation of monitors being developed, the gap is becoming narrower. For all these reasons, on-line monitors are usually used as screening tool to identify possible abnormal units. Detailed fault diagnosis is then left to conventional DGA.

Networking capability and diagnostic intelligence are also important requirements for on-line monitors. The former has been incorporated in some approaches [Glodjo98]. The latter is not yet available, probably because no machine intelligence is yet good enough to replace the work of a human expert, and it is too risky to implement an immature technology.

1.2.4 Combination of DGA and acoustic method

Combining the use of DGA and acoustic methods often leads to successful diagnosis and location of PD type fault [Hayes86, Austin92, Berent95]. The procedure is to identify the PD fault first using DGA, and then find the location of PD using acoustic method.

1.3 The scope of this dissertation

1.3.1 Areas of interest

This dissertation addresses two areas. One involves summarizing human expertise and representing it in machine language. The other is to use machine intelligence to extract expertise directly from raw data.

1.3.2 Contributions through the research

The major contribution of this dissertation is the development of a neural network and expert system tool for power transformer incipient diagnosis, the ANNEPS system [Wang98]. Additional contributions include the development of a knowledge-based fault detection inference engine, the identification of a multi-layer perceptron (MLP) modular neural network for fault diagnosis, procedures for combining the outputs of knowledge-based and neural network-based diagnosis, and fuzzy logic methods for transformer condition assessment and maintenance recommendations. Finally, techniques are presented for power transformer fault location and on-load tap changer (OLTC) coking fault diagnosis.

These contributions can be seen from the contents of the chapters and will be summarized in the final conclusions.

1.3.3 Arrangement of this dissertation

This dissertation has nine chapters. Chapter 1 (this chapter) is an introduction to the problem. Chapter 2 will review the development of DGA technologies and identify what is the state of art and what are likely the future developments. Chapter 3 will concentrate on the development of a knowledge based fault detector. Chapter 4 will study extensively the neural network based fault diagnosis, including neural network selection, input vector and topology optimization, etc. Chapter 5 will introduce the principle and implementation of a hybrid fault diagnosis, - the ANNEPS system. Chapter 6 will discuss fuzzy logic based transformer condition assessment and maintenance recommendations. Chapter 7 will investigate transformer fault location techniques. Chapter 8 will study the techniques for OLTC fault diagnosis. As a conclusion, Chapter 9 will summarize what has been studied and what are the major achievements of this dissertation.