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An expert system for acoustic diagnosis of power circuit breakers and on-load tap changers

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ABSTRACT

Most of the faults on power Circuit Breakers (CBs) and On-Load Tap Changers (OLTCs) on high voltage transformers are of mechanical origin. Mechanical malfunction, mechanical wear and other types of abnormal behaviors can be detected as changes in the acoustic signatures. In this paper, an Expert System (ES) with the addition of a signal processor module and factual database module to the conventional ES has been proposed for the diagnosis of CBs and OLTCs. The feature extraction of the acoustic signatures has been done by decomposing them into voiced and silent portions in time domain and through FFT spectrum analysis in frequency domain. The OLTC's motor current has been decomposed into inrush, steady-state and extended currents to locate the cause of different anomalies in the OLTCs and acoustic-current pair has been used for the synchronization testing. Each extracted feature of the testing signal has been compared to the similar feature of a reference signal to not only identify the health of the testing device but also to locate the cause of each anomaly. Several test signals have been compared against the reference signature and the proposed expert system has proved to be a suitable, effective and reliable system for the acoustic diagnosis of OLTCs and CBs.

1. Introduction

Circuit Breakers (CBs) are very important elements in the power system. Circuit breakers need to be reliable since their mal-operation can cause major issues with power system protection and control (Runde, Aurud, Lundgaard, Ottesen, & Faugstad, 1992). Since CBs are active links in the fault-clearance chain, CBs must be tested and maintained to ensure their proper operation at crucial times (Runde, Ottesen, Skyberg, & Ohlen, 1996). The circuit breakers have to operate within extremely tight tolerances when a disturbance is detected in a network to protect sensitive and costly equipment. They have to be able to operate even after months, or in some cases years, of inactivity (Vilaithong, Tenbohlen, & Stirl, 2007). So it is desirable to do some periodic testing to prevent damaging costly equipment or to prevent outages when the operation of a CB is required.

On-Load Tap Changers (OLTCs) are one of the problematic components of power transformers. Detecting faults in OLTCs is one of the key challenges faced by the power equipment predictive maintenance community (Vilaithong et al., 2007). OLTCs are used to keep the secondary voltage at an acceptable level when the load changes to adjust the transformer phase shift. Tap changer diagnostics are also important to determine when tap changer maintenance is necessary, and to identify the problems in tap changers (Kezunovic, Latisko, & Ved, 2005). Similar to CBs, the condition of OLTCs is also strategic to the reliability of power transformers. OLTC is the only movable part of a transformer and therefore suffers from various aging problems. Over time, the insulation oil inside the tap changer compartment becomes dirty due to switching arcs, thereby weakening its insulation properties. Faults associated with tap changers form up to 40% of catastrophic failures in transformers (Landry & Léonard, 2008).

Between 40% and 50% of failures on high voltage CBs and OLTCs on high voltage transformers are of mechanical origins (CIGRE report) (Landry & Léonard, 2008). Different methods are used to identify the anomalies that occur in CBs and OLTCs. Of these methods, the most common technique is acoustic diagnostics (Fazio & Muzi, 2003; Leung, 2007; Nagata et al., 2009; Paul & Davis, 1985).

By using the acoustic diagnostics technique, contact-wear, arching in diverter and selector, synchronism problems, drive-mechanism problems and brake failures in OLTCs and incipient rupture of the contact plug shaft, incorrectly assembled crank and major lubrication problems all can be detected in CBs. Existing mature techniques used in speech processing can be utilized for the acoustic diagnosis of CBs and OLTCs.

During the operation of a CB and an OLTC, a series of mechanical and electrical events produce distinctive vibration and noise

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patterns. Acoustic monitoring consists of listening to these vibration patterns and detecting any changes in them. These changes can then be compared with the appropriate reference signatures to detect any developing malfunction or possible wear. Acoustic signatures can be recorded by mounting accelerometers onto the mounting base (Landry & Léonard, 2008). The current signal given by the motor driving the OLTC can be captured by an open clamp current sensor. Once the raw data is gathered, it is compared to the reference signature to identify any anomaly in the tested CB or OLTC.

It is necessary to identify the health of CBs and OLTCs for secure and prompt operation (IDA, 2008). There are several causes of abnormal behavior and with an increase in experience in dealing with such abnormalities, our knowledge improves. Several analyses have taken place in order to diagnose the health of CBs and OLTCs by using various methods.

An expert system for acoustic diagnosis of CBs and OLTCs is proposed in this paper. The proposed expert system comprises of a knowledge base, factual data base, signal processor, inference engine and a user interface. The knowledge base and factual data base can be updated as, and when, needed. By using the proposed expert system users cannot only identify the health of testing equipment, they can also locate the cause of the particular abnormality in a broader spectrum. Additionally, a user interface allows the testing crew to simply browse and load the testing and reference signatures.

2. Literature review and novelty of proposed algorithm

Contact force monitoring based testing methodology for CBs has been proposed by (Tang, Shisong, Xie, & Cheng, 2015), while a genetic algorithm with support vector machine based algorithm for identifying mechanical faults in CBs has been presented by (Huang, Hu, & Yang, 2011) and a rough set theory based algorithm was suggested by (Yan, Haiguang, & Liang, 2013). Partial discharge detection in CBs, along with diagnostic methods, has been presented by (Nakaoka, Tai, & Kamarol, 2014) and a research for extracting mechanical state parameters by using travel-time waveform has been carried out by (Tianxu & Xiaoguang, 2013). A unique hybrid method of electrical and chemical techniques for the fault diagnosis of gas-insulated switchgears has been analyzed by (Li, Tang, & Liu, 2015). An acoustic signal processing based on blind-source separation through fast independent component analysis has been discussed in (Zhao & Cheng, 2014) while acoustic signal processing based on wavelet transform has been presented by (Charbkaew, 2012; Mingliang & Keqi, 2014). A comprehensive survey of the testing methodologies used by power engineers for analyzing CBs and disconnectors in the last decade has been reviewed by (Westerlund & Hilber, 2014).

A Ph.D. thesis has been presented in Adelaide University by analyzing the vibro-acoustics of transformers and their application in the condition monitoring of power transformers (Wang, Eng, & Eng, 2015). A study for mathematically modeling the acoustic signal of OLTCs has been presented in Cichon, Borucki, and Wotzka (2014) and methods for extracting characteristics of the acoustic signals generated by OLTCs during operation have been analyzed by Cichoń and Frącz (2012). A method for analyzing the arching process in OLTCs based on acoustic signals has been discussed in Bhuyan and Mor (2014). Acoustic Emission Method (AEM) based fault detection in OLTCs has been presented by Cichoń and Berger (2014). The effect of measuring transducers on the acoustic signatures based on AEM has been analyzed by Faria, Costa, and Olivas (2015) and the possibility of using AEM for testing of OLTCs during normal operation has been presented by Cichoń and Borucki (2012). A review of monitoring methods used in power transformers for predictive maintenance has been presented by Bhattacharya and Dan (2014) and recent trends of condition monitoring for fault diagnosis of equipment has been reviewed by Wang et al. (2015). Fuzzy logic based auto-diagnosis of OLTCs has been suggested by Henriquez and Alonso (2014) and Hu, Duan, and Yong (2015). An acoustic diagnosis system based on Dynamic Time Wrapping (DTW) is discussed in the paper presented by Landry and Léonard (2008), where envelopes of testing and reference signals are compared by the testing engineers. The decisions on the health of CBs or OLTCs are made by the testing crew by checking both sets of signatures. This process becomes more difficult if a new case arises.

Firstly, most of the research available in the literature and referenced in this paper focuses on a single problem associated with the CBs or OLTCs. However, the original nature and potential causes of faults in this equipment are enormous. Secondly, all the possible faults in the OLTCs and CBs are not known. Our knowledge about the nature of faults improves with our increasing experience and the occurrence of non-trivial abnormalities. Thirdly, most of the diagnostic techniques available in the literature are based on a 'YES' and 'NO' approach. The testing equipment is only categorized as normal or abnormal without knowing the possible cause for each particular abnormal behavior. Keeping all this in mind, an expert system is an appropriate solution for this diagnostic problem. Expert systems use human knowledge to solve problems by using rules and data, which can be called upon and updated as and when necessary (Taniar, Gervasi, Murgante, Pardede, & Apduhan, 2010). The proposed artificial intelligence based systems in the literature uses only one domain (time or frequency) analysis, which results in loopholes in the diagnosis process.

The developed expert system caters for various possible known causes of CBs and OLTCs failures available in the literature, in contrast to the single problem targeting approaches. It provides a dynamic testing environment by making use of the knowledge base, which allows the field experts to add new cases as and when required without impacting the rest of the testing system, which is opposite to the static testing strategies. It provides an interactive environment to the testing crew through the developed user interface and inference engine. In contrast to the conventional procedural code based systems, it provides a rule-based system with a detailed view of the possible causes for each anomaly in testing CB or OLTC. The uniqueness of the proposed expert system in comparison with other artificial intelligence based systems is the use of well-known speech processing techniques and signal analysis in both the time and frequency domains. With these major advantages and several other minor benefits (computationally inexpensiveness, analysis of motor current along with acoustic signature of OLTCs, visualization of testing and reference signatures and easy to change usage), the proposed expert system can be categorized as a novel, reliable, effective and robust method for the testing of OLTCs and CBs.

3. Feature extraction and comparison

The proposed feature extraction and comparison algorithm requires only acoustic signals for the diagnosis of CBs, and it requires the acoustic signal as well as the current signal of the motor, which allows the tap-changer to move from one position to another, for complete diagnosis of an OLTC. Acoustic signals can be recorded by using a piezo-electric accelerometer, and the current signals can be measured through an open-clamp current sensor. The sampling frequency for both the signals is 100 kHz (Landry & Léonard, 2008). The acoustic signal processing is the same for both OLTCs and CBs. The acoustic signal is processed and analyzed in both the time and frequency domains; however, the current signal used for OLTC's testing is processed only in the time domain. After extracting the features, the corresponding components of the testing signal are compared with those of a reference signal. The testing device is regarded as normal if, and only if, all the differences are within some specified thresholds. This feature extraction and comparison task is achieved through the signal processor module incorporated in the developed