Analytical Condition Monitoring System for Liquid-immersed Transformers

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***Abstract*—Transformers form an integral part of the electrical power grid are widely employed in a variety of power-system applications inter alia power generation and distribution systems, and arc- and induction-furnace applications. Transformers are among the most expensive components in power systems but the protection and health requirements thereof are still catered for by traditional auxiliary protective devices and cooling control systems. This paper reports the development of an IoT-based condition monitoring system that offers advanced protection and control features. The condition monitoring system is intended to directly contribute to enhancing the lifespan of the transformer by detecting fault conditions at an early stage before catastrophic failure can occur and by ensuring that the quality of the transformer's insulation is preserved for a greater period through improved cooling techniques.**

***Index Terms*—Liquid immersed transformer; condition monitoring system; IoT.**

I. Introduction

There are a wide variety of transformers available in the marketplace and each of these transformers are usually custom designed to operate within a specific section of the electrical power-grid. Most of these transformers are usually large (MVA range) and either of the high voltage- or current types which would almost invariably make use of liquid cooling techniques due to the excellent electrical and thermal properties thereof. These transformers are exposed to all kinds of undesirable system events during their service interval, making them extremely vulnerable which may lead to them failing catastrophically, even shortly after they had been placed in service [1], [2]. Given the fact that transformers are extremely expensive to repair, or even replace, it must be noted that the current auxiliary protective devices installed on transformers do not really offer much protection as these devices do not provide or log data of the transformer itself and therefore leaves the owners of the equipment and manufacturers with little information regarding the protection history and thermal performance of the transformer. These devices include instruments such as the Buchholz relay (shown in figure 1, top-oil and winding temperature indicators (shown in figure 2), and oil-level indicators, all of which are electromechanical devices that are not capable of rapidly detecting and reacting to any low-energy fault conditions that exist within the transformer, irrespective of it being latent defects of fault conditions which originated due to service conditions. Below are a few photographs of the devices that are currently being installed on transformers. However, advancements had been made in other areas such as online gas-monitoring, as presented in [3], [4], and fiber-optic winding temperature and moisture measurement devices, as presented in [5], [6], which have thus far yielded satisfactory results and contributed to the prevention of premature equipment failure. In a smart-grid environment, operational and condition data of equipment needs to be gathered in an automated manner to improve efficiency and reliability [7], [8]. An electronic system needs to be developed which will be able to process the data received from the various associated process variables via the contacts and sensors connected to it, analyse the information, make intelligent decisions based on the information available and log the acquired data onto a cloud-based server where the data can be viewed and permanently stored. This paper reports on the development of analytical condition monitoring (ACM) system to overcome the previously mentioned problems through fulfilling the said requirements.

Figure 1: Typical Buchholz relay with alarm and trip contacts on a liquid-immersed transformer

Figure 2: Typical top-oil and winding temperature indicators with alarm and trip contacts on a liquid-immersed transformer

II. Background

A. System Requirements

Based on the current requirements in industry, the presented ACM system is intended to be able to perform the following functions:

- Human-Machine Interface (HMI) for Displaying System Information.
- Sensing and Processing of Information received from Auxiliary Device Contacts and external Sensors.
- Electronic Top-Oil, Winding and Ambient Temperature Measurement.
- Advanced Cooling Control Capabilities with different modes of control.
- Electronic Notification (SMS, Email, etc) of important system protection and maintenance events and Remote Control via SMS/GPRS commands.
- Detect High-energy, low-energy and sudden fault conditions, as well as ageing / deterioration factors which could in turn be used to Prevent Premature and catastrophic Equipment Failures.
- Measure power-quality and derive information from the signal shape that can be used to detect failure causes related to harmonics, transients, etc.

Figure 3 gives an overview of the system specifications.

B. Previous Systems

An extensive review of the literature shows that have been proposed systems similar to the ACM system. The first of which is the called the Transformer Management System (TMS) developed by the Niroo Research Institute (NRI) in Iran for a 230KV Kan substation in Tehran [9]. Although this system shares many of the same features as that of the proposed ACM System, there are some key differences. TMS was developed to improve asset management and maintenance activities in order to offer superior system reliability and at the same time extend the service life of the transformer, and there is no emphasis on the interconnectivity of monitoring systems to a wider network. The ACM system aims to provide this feature as it is a requirement for modern grid components integration. Another similar system is the transformer condition monitoring system proposed in [10] that provides remote measurement, protection and condition reporting of the transformer. Although this system does not make provisions for gas and partial discharge protection control and reporting. More recently, an IoT-based system with the same drawbacks as the monitoring system in [10] has been proposed [12]. However, this system does feature the necessary IoT-based provisions.

III. Methodology

A. Human-Machine Interface

An LCD display module (touch-screen) implemented on the ACM system and a software application was developed specifically for the system which is capable of displaying the information acquired from the various external input contacts and sensors, along with the pre-set protection and control settings. The on-board diagnostic functions of the system enables it to make intelligent protection and control decisions and in turn also display the processed information in text, number and graphical format. Figure 4 shows the LCD Display with its software application.

B. Sensing and Processing

The feedback signals obtained from the auxiliary devices such as the Buchholz relay, pressure relief valve etc., provides critical information which can be used to protect the transformer. However, it is also important to consider that a history of the transformer's performance, protection and control events can also provide critical information related to the transformer which could be used to either remove the transformer from service or to ensure continuity of supply. The information from the various sensors is processed and stored locally on the ACM using a data logging device and can also be transferred to a remote server for further processing and analysis.

C. Top oil and winding temperatures

Using electronic measurement techniques, such as described in [11], it is possible to log and trend the thermal performance of the transformer and to enable and allow advanced cooling control activities to take effect. The measurement and processing of the top-oil and ambient temperatures are measured by using two LM35 Temperature sensors (for prototype testing purposes) and is therefore a direct measuring technique. However, the measurement of the winding temperature is somewhat more complicated and is not a direct measurement technique but a thermal image which is created based on the load current of the transformer. Here a WTI current-transformer (CT) is normally installed on the transformer and scaled according to the load current, where the secondary CT current is then supplied to the measuring device to display a value greater than that of the OTI device, with the offset value being the

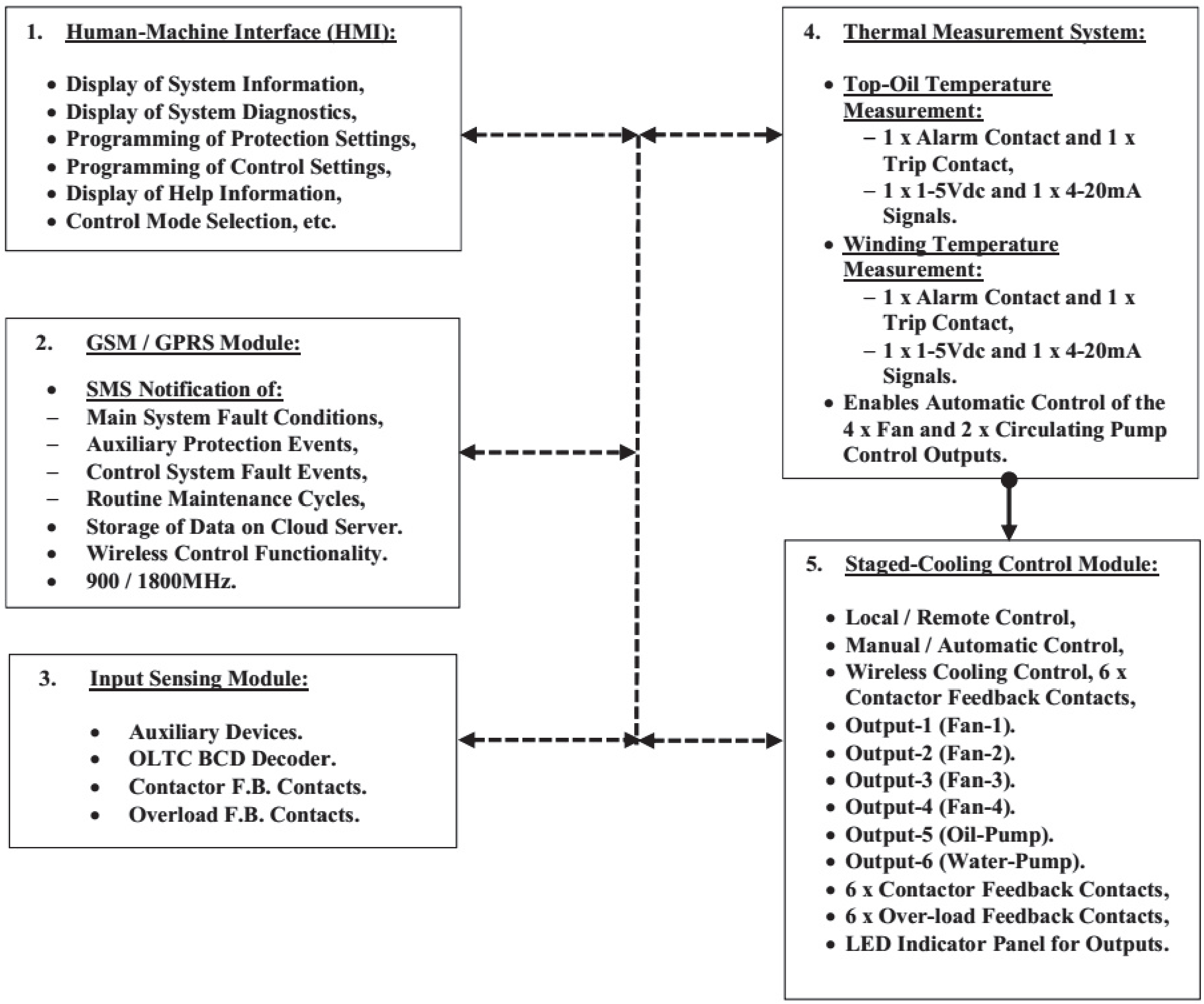

Figure 3: Overview of system specifications

transformer's specific thermal gradient as determined by a temperature-rise test.

The WTI Circuit will have to measure the secondary CT Current and translate the magnitude of the current into a suitable thermal quantity and this can only be achieved via suitable transducers and electronic signal processing techniques. A 10 kΩ potentiometer was used to control the WTI reference value and ultimately control the automatic, staged-cooling control operations. The sensors used for testing temperature measurement and processing capabilities of the ACM are shown in figure 5. The system also gives an indication of the measurements versus the pre-configure temperature limits (as shown in figure 6).

D. Advanced Cooling Control

The cooling subsystem of the ACM system is designed to operate under manual, automatic, substation Remote and wireless remote control. The WTI circuit was used to control the automatic operation of the system and accurate stage-cooling techniques (with strategic combinations) could be successfully executed. The physical ACM housing showing the manual part of the cooling control is shown in figure 7.

E. GSM-GPRS Modem

This remote reporting and control module was programmed and implemented in the design of the ACM System. The purpose of this module is to send SMS Notification messages to the equipment owners when an important protection event or maintenance interval had been reached, log the acquired information via its GPRS link on a cloud-based platform and to permit the equipment owner to take control of the system's wireless control functionality. This system can utilise standard cellular networks available to serve the remote function and is secured via a preprogrammed access rights routine with

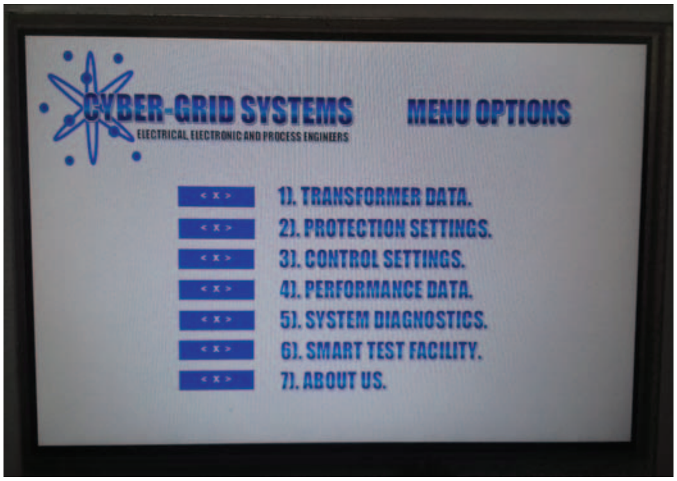

Figure 4: HMI module with software application

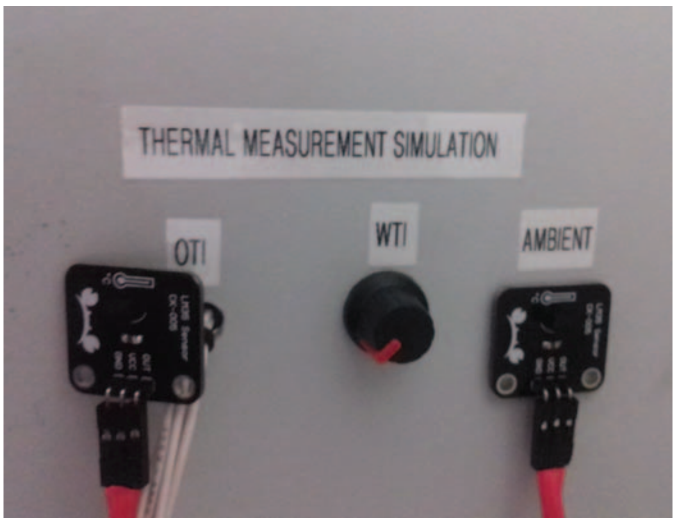

Figure 5: 2 x LM35 Thermal Sensors and 1 x 10 kΩ Potentiometer

configurable user database. The implemented GSM/GPRS Module is shown in figure 8.

F. Voltage and Current Harmonics

The ACM system has the capacity to implement advanced fault detection techniques. The voltage and current harmonics technique basically assesses the shape of the voltage and current signals that are introduced to the transformer at its primary line terminals and the secondary voltage signal produced by the transformer. If any undesirable system disturbances such as harmonics, transients, through-faults, etc are present then the system will be able to detect and log these events. This method is based on comparison of healthy and unhealthy voltage-current loci of the transformer excitation as presented in [13]. In addition, if a fault condition exists within the windings of the transformer then the output signal will be distorted and this will also be detected by the ACM System.

Figure 6: Graphical Display of Thermal Measurements. Black = OTI, Blue = WTI, Green = Ambient and Red = WTI Trip Limit

Figure 7: ACM system's user interface with cooling control panel

G. Partial Discharge

Partial discharge phenomena is typical occurence in transformer equipment. This can have detrimental effects on the transformer's service life and can lead to premature or early equipment failure, which in many cases, results in catastrophic

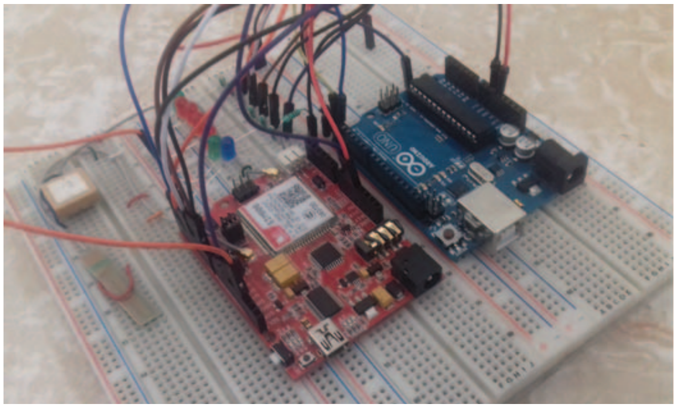

Figure 8: GSM/GPRS/GPS (Simduino) Module of the ACM system tested with an Arduino Uno

failure or expensive repairs. However, various techniques to detect and locate these partial discharges are being considered and will also lead to the prevention of equipment failure in many cases, if these are accurately detected. Some of the key root causes of partial discharges in transformers are as follows [14]:

- Insufficient voltage clearance to earth,
- Poor tracking / creepage distance,
- Poor dielectric properties of the insulation itself,
- Poor dielectric properties of Insulating oil,
- The presence of moisture within the oil,
- Voids in the transformer's insulation,
- Voids in glue of pressboard sheets,
- Insufficient bushing impregnation (bubbles),
- Gas bubbles generated by the partial discharges,
- Bad electro-static shield connections,
- Sludge within the transformer oil that enabling tracking,
- Impurities within transformer and the oil.

The following potential methods can be considered to detect partial discharges, arising from the aforementioned root causes, with the ACM system [14]:

- Electrical energy (physical quantity),
- Mechanical energy (sound/vibration),
- Optical energy (flash/discharge),
- Electro-magnetic energy,
- Dissolved gas in oil.

Further research is still required in this area before the suitable sensing technology can be developed and used to detect and locate the origin of the discharges with the ACM.

IV. Laboratory Results

The ACM system performed at satisfactory levels on all the relevant aspects with reference to the specifications which have been outlined. The HMI along with the intelligent on-board diagnostics enabled the system to supply the user with sufficient information regarding the overall performance of the system. Figure 9 gives an example of the summary information displayed at the local interface of the system.

Figure 9: ACM System with local diagnostics

In addition to this, all the other functions operated correctly as well and adequate accuracies were initially obtained from the sensors and software algorithms. Figure 10 gives another example of the real-time information obtained during testing of the complete system.

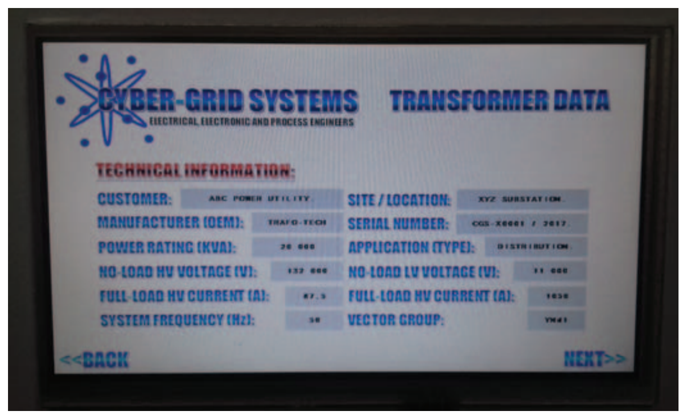

Figure 10: ACM system transformer data

V. Conclusion

The proposed ACM system operates to the originally prescribed specifications and all the desired objectives have been successfully reached. Apart from the professional research which has been conducted, the need to develop this system has also been realised through engagement with people working in the power-engineering industry. There are numerous transformer instrumentation systems such as on-line gas monitors, fiber-optic systems etc., which have already been developed and had since gone into mass production in many parts of the world. The benefits which the ACM system offers is that it can easily integrate easily sensing and protective devices regardless of the manufacturer. It is believed that the use of such a system could have a significant impact on the life of the transformer, as well as present financial benefits to the engineering and insurance industries as this system can assists with the vital operational and performance information. Moreover, there is currently a need for such systems with the advent of the modern electrical grid or smart grid. The next step of this work is to develop a fully functional prototype for field testing.

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