Online Ageing Detection in Transformer Oil

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Transformers play an essential role in power networks, ensuring that generated power gets to consumers at the safest voltage level. However, they are prone to insulation failure from ageing, which has fatal and economic consequences if left undetected or unattended. Traditional detection methods are based on scheduled maintenance practices that often involve taking samples from in situ transformers and analysing them in laboratories using several techniques. This conventional method exposes the engineer performing the test to hazards, requires specialised training, and does not guarantee reliable results because samples can be contaminated during collection and transportation. Researchers review the transformer oil types and some traditional ageing detection methods, including breakdown voltage (BDV), spectroscopy, dissolved gas analysis, total acid number, interfacial tension, and corresponding regulating standards. In addition, a review of sensors, technologies to improve the reliability of online ageing detection, and related online transformer ageing systems. A non-destructive online ageing detection method for in situ transformer oil is a better alternative to the traditional offline detection method. Moreover, when combined with the Internet of Things (IoT) and artificial intelligence, a prescriptive maintenance solution emerges, offering more advantages and robustness than offline preventive maintenance approaches

ageing high voltage insulator Internet of Things

1. Introduction

The sole aim of power generation is to meet the electricity needs of consumers spread across homes and industries. This generated power meets different consumers at different voltage levels, and transformers are generally the equipment designed to supply the needed voltage to consumers. Transformers are expensive essential components of high voltage (HV) stations. They have an extended mean time to repair (MTTR) and enormous maintenance costs. Transformer failure can amount to the shutdown of a power station, which has serious economic consequences. Other consequences could include the loss of lives, damage to substation equipment, and environmental (ecological) effects.

A detailed qualitative and quantitative failure mode effect and criticality analysis (FMECA) of power transformers revealed that insulation failure is a significant cause of transformer failure [1][2][3]. The transformer insulators comprise oil and paper. The transformers in most power substations require oil as a medium for cooling, arc extinction and insulation. Additionally, transformer oil acts like an information carrier, providing information on the health of the paper insulator through depolymerisation [4].

Like most HV materials, transformer oil is subject to ageing upon usage [5][6]. Insulation ageing is the gradual decrease in the dielectric strength of an insulator in operation to a complete insulation breakdown from electrical and environmental stresses. While in use, transformer oil is subject to degradation that depends on the transformer loading condition/thermal stress [7][8]. The thermal stress originates from either the windings' copper or core iron losses. This further decomposes the oil, jointly provoking the partial discharge formation and yielding the formation of transformer oil ageing by-products (ABPs), such as moisture-dissolved gases (carbon dioxide, methane, ethane, ethylene, acetylene, propane, propylene, methanol and ethanol), acids and sludge [7][9][10][11][12]. As shown in **Figure 1**, Partial discharges are incipient faults that can culminate in insulation breakdown [13] with a cyclic cause and effect relationship with ageing [14]. Other partial discharge sources include voids in the pressboard, moving bubbles, and surface discharge on winding [15]. ABPs negatively impact the oil's dielectric strength property. In addition, ageing significantly affects transformer oil's chemical and electrical properties, such as dielectric strength (decrease), dielectric dissipation factor, DDF (increase), flashpoint (decrease) and colour (shading) [7][16][17]. The significant chemical properties altered due to ageing include acidity and turbidity, while the significant electrical properties altered include dielectric strength, the dielectric dissipation factor and resistivity [7].

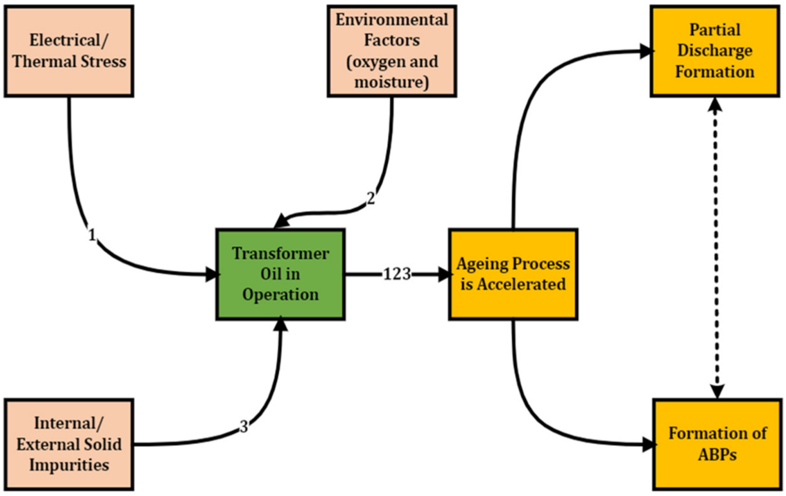

Figure 1. Degradation Mechanism of Transformer Oil.

Transformer oil insulation failure has rippling consequences on the primary purpose of power generation, the safety of personnel and the work environment, as well as enormous economic consequences. Consequently, their volume, purity, and reliability cannot be compromised. Ageing in transformer oil is primarily evidenced by interfacial tension and acidity.

The transformer ageing detection method is classified as either intrusive or non-intrusive, destructive or non-destructive, and offline or online. Intrusive detection techniques make contact with the transformer oil as opposed to non-intrusive methods. Destructive methods alter (in the short or long run) the transformer oil properties being measured as opposed to non-destructive methods. The online detection method involves live ageing detection of the transformer oil while operating as opposed to offline ageing detection, which only involves sample collection for laboratory analysis and interpretation.

2. Types of Transformer Oil

Mineral oil and ester oil are two common examples of transformer insulating liquids, with mineral oil having enjoyed over a century of use (compared to ester oil) and made by the fractional distillation of crude petroleum. Mineral oil is a popular insulating liquid for high-voltage transformers, jointly serving the purpose of cooling and insulation. It is low-cost and readily available [18]. However, mineral oil is toxic, non-biodegradable and potentially flammable, thus a hazard to the environment [19]. Additionally, transformer mineral oil produces more water content during use/ageing than ester oil [4].

Natural esters (from animal/vegetable products) and synthetic esters are the two types of ester oil currently in use [4]. Natural ester oils are more environmentally friendly and renewable, gaining increasing usage [19][20][21] at cost expense. Furthermore, ester oil resists oxidation and preserves the paper insulator better than mineral oil [22] as proved by the experiment conducted by Martins and Gomes [4]. This is because water is more soluble in natural esters than mineral oil. In addition, ester oils have better electrical characteristics (BDV) than traditional mineral oil [23].

When unique properties (pour point, partial discharge resistance, flammability, oxidative stability) are sought, synthetic ester oils are often used [24]. As shown in **Figure 2** [25], Synthetic esters are formed from the reversible reaction of carboxylic acids and alcohol to form esters and water (esterification). The building block for synthetic esters is unlimited as there are hundreds of potential acid and alcohol building block combinations to form them [25]. Although not natural, synthetic esters have the eco-friendly properties of natural esters.

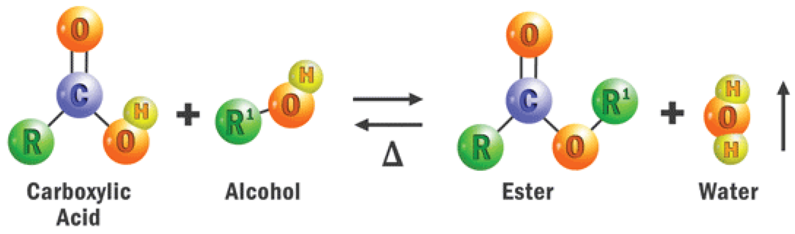

Figure 2. Reversible esterification reaction [25].

Other alternative oils include edible coconut oil, Karanji oil [26], silicon oil, castor oil and sesame oil, which showed acceptable limits in terms of pour point, acidity, DDF and BDV, and which can be further improved by purification [27].

3. IoT and Online Ageing Detection

The Internet of Things (IoT) refers to the technology of interconnection of human assets (also known as things) via the internet using sensors to make informed decisions, minimising human intervention [28]. For example, online ageing detection can be advanced when integrated with IoT technology. The IoT helps prevent considerable person-hour loss to collect and centralise online instrument readings. The IoT provides a more straightforward solution to this challenge, including an extra layer for advanced data analysis and reporting. The things within an IoT network must stay connected regardless of their movements. Some IoT enabling technologies include low-cost/low-power sensor technology, cloud computing platforms, artificial intelligence technologies, etc.

According to Li et al. [28], an IoT service-oriented architecture (SOA) comprises a sensing layer, network layer, service layer and interface layer. The sensing layer primarily consists of the sensors (RFID tags, barcodes, etc.) [29], data acquisition devices and protocols (NI DAQ); the network layer consists of wired or wireless connections (Bluetooth, WIFI, loraWAN, GSM&Sigfox, Satellite); the service layer meets the user's demands; and the interface layer allows for the interaction between the user and the application. Therefore, it is recommended that IoT systems be designed to provide for the extensibility, scalability, modularity, interoperability and reliability of the implemented AI models. An IoT platform (ThingSpeak, ThingWorx, Google Cloud, Oracle IoT, Microsoft Azure IoT, etc.) integrates these sensor data from different devices through appropriate security channels and includes an extra analytics layer for real-time interpretation and implementation.

IoT systems suffer from some challenges, mainly sensor and data security challenges. There are three (3) challenges with sensors: sensor accuracy to detect the necessary data, environmental/operational impact on sensor accuracy [30], and sensor ageing. All these affect the fidelity of IoT data.

There is a need to select and locate the best sensor that can detect the unique functional characteristics of an asset. One sensor may not satisfy this condition and thus the need for a combination of sensors at the expense of cost. If possible, sensors should be shielded from operational and environmental conditions affecting their accuracy. Sensor ageing or sensor deterioration is the sensor's sensitivity reduction owing to prolonged usage or/and the impact of external influences on the sensor. The authors suggest the periodic recalibration or retrofitting of sensors to preserve the accuracy of the IoT data. In addition, the authors suggest a predictive algorithm to detect the fidelity of these sensors while idle or in operation. This algorithm should safely notify the user or operator to recalibrate or retrofit the sensor.

Security challenges abound and pose a significant threat, especially when connected to cloud technologies [31]. A feasible solution will include measures to detect cyber attacks in hacking or phishing and alert experts when necessary. Additional layers of security can be added to make different cyberattack activities impossible. Edge computing helps to solve security challenges by allowing computing and data storage to occur at the edge of the internet instead of the cloud.

The IoT can be integrated to track ageing and make proactive decisions to ensure optimal transformer performance for the online ageing detection of transformer oil. Although there has not been significant research output in this area for transformer oil, the authors suggest adopting **Figure 3** as the framework for online ageing detection in transformer oil. An intensitymodulated optical fibre sensor, cross-capacitive sensors, and ageing gas sensors (examples include hydrogen gas sensors and carbon dioxide gas sensors) can be utilised for the sensing layer. National Instrument NI USB 6008/6009, Arduino microcontroller, and Raspberry Pi are some examples of data acquisition devices for ageing data. ThingSpeak, ThingWorx, Google Cloud, Oracle IoT and Microsoft Azure IoT are examples of IoT platforms that can provide the network, services and interface layer.

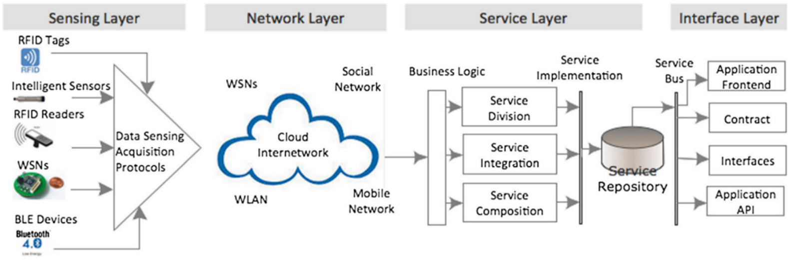

Figure 3. IoT service-oriented architecture [28].

Thingspeak has reportedly succeeded in several IoT applications and can be applied to transformer oil ageing systems. Thingspeak is an open-source IoT platform [32] compatible with MATLAB (for AI capabilities), microcontrollers and DAQs. It has been utilised for real-time room condition monitoring systems, water monitoring systems and analytics, air quality monitoring systems, traffic control systems, and transformer subsystems [32][33][34][35][36][37][38]. When used with MATLAB (for example), the channel ID and API key are inputted to enable sensor data to be read with the help of the ESP8266 WIFI module and Arduino microcontroller. In addition, the MATLAB data analysis toolkit, Simulink and Simscape can be employed for data cleaning, analysis, predictive model development, and the design of frontends and user interfaces.

IoT has applications in healthcare, aviation, intelligent homes, agriculture, food processing, security surveillance, reliability engineering, pharmaceutical, retail and logistics, recycling and entertainment [29][31]. This can be integrated for the online ageing detection of transformer oil.

4. Example of Related Systems

4.1. A Non-Destructive, Non-Intrusive Design Using an Antenna

Rohit, Sisir and Marley [9] implemented a non-intrusive, non-destructive technique for the condition assessment of transformer oil as shown in **Figure 4**. A horn antenna was placed over an open vessel in an anechoic chamber (a room designed to stop sound reflections or electromagnetic waves) to prevent interference, filled with oil to study its characteristics. The anechoic chamber was maintained at a temperature of 20 °C and 50% humidity using a temperature controller and a dehumidifier; this is because the frequency response of the insulating liquid is sensitive to temperature and humidity variation. The parameters monitored to detect ageing were moisture content (MC) and total acid number (TAN). Laboratory samples were initially used before extensions were made to actual in-service transformer oil samples for validation. Accelerated thermal ageing and oxidation ageing approaches were used to study transformer insulation's early, midlife, and afterlife properties with several ageing samples. The frequency response plot clearly showed the degree of ageing present in the transformer oil. A linear fit was derived from the plot of the reflection coefficient, $|S_{11}|$ against the moisture content and the TAN. Guranteeing constant humidity and temperature for an in situ transformer will involve additional costs to implement new controlled designs. This solution is also limited by the need to significantly re-mechanise existing transformer designs to accommodate the anechoic chamber. An evanescent wave absorption intrusive fibre optic solution offers a better solution in terms of cost, online adaptability, simplistic design and immunity to external interference.

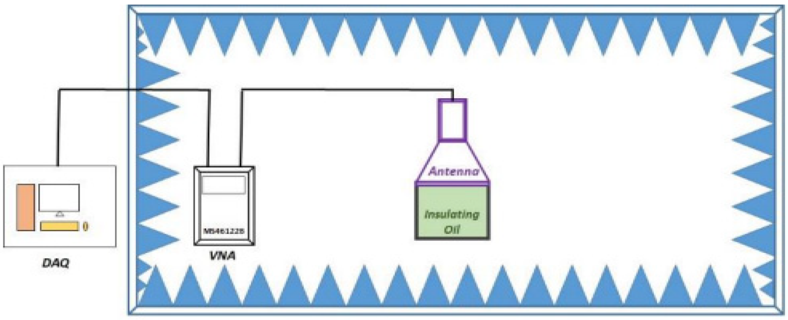

Figure 4. Antenna design setup [9].

4.2. An Intrusive Ageing Detection Design Using a Cross-Capacitance Sensor

Rahman et al. [39] used a cross-capacitive sensor to predict the dielectric constant of a transformer insulating oil with a known contamination level of 2-Fal, and the combination of moisture and 2-FAL, mineral oil, synthetic ester, soybean oil and rapeseed oil. The oil cell measured the dielectric constant of the various solutions. The plot of the dielectric constant against different concentrations for the oil samples shows linear characteristics. The results were reported for the simulated cross-capacitance of various transformer oil concentrations. The sensor was calibrated, and a linear calibration result was reported with a maximum error of 0.86%, 0.33%, 0.91% and 0.64% for mineral oil, synthetic ester oil, soybean oil and rapeseed oil, respectively. The sensor was validated for online ageing detection using cross-capacitance technology. Cross-capacitance intrusive ageing detection technology offers good repeatability but is prone to electromagnetic interference. The moisture content affects the permittivity, making it difficult to discriminate between ageing and moisture content detection when using this solution.

4.3. An Intrusive Ageing Detection Design Using Fibre Optic Technology

The authors of [10] as shown in **Figure 5** used a single-mode–multimode–single-mode (SMS) fibre optic configuration to track the ageing of transformer oil. Four samples of palm-based transformer oil were used (S1, S2, S3, S4), with S1 representing the pure sample and S2 to S4 representing samples of varied age. The lightwave refractive index was used for the calibration; changes in transformer oil's age affect the lightwave refractive index (RI). Two ageing characterisation techniques were used to determine the age of the unknown samples: the breakdown voltage test (BDV, with 25 kV) and the UV–Vis spectrum using appropriate standards.

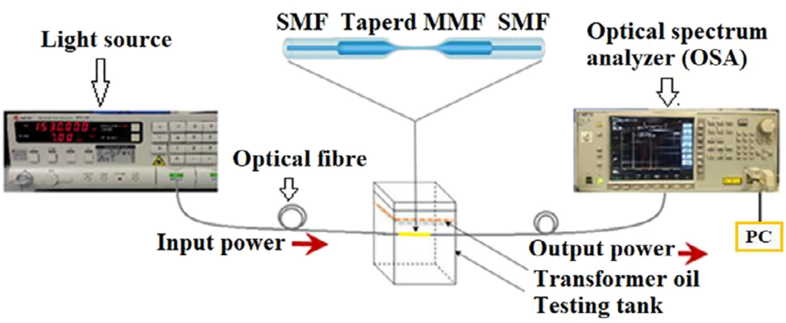

Figure 5. Experimental configuration [10].

A light source (WSL-100) was injected through the SMS fibre optic configuration, and the MS9740A optical spectral analyser was used to display the plots (wavelength, absorption and refractive index). The resonant wavelength shift plot against the refractive index showed linear behaviour.

This configuration can be improved for real-time ageing detection with a photodetector, DAQ device and the IoT.

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