SMART DISTRIBUTION TRANSFORMERS: NON-INVASIVE SENSING TO ENABLE BUSINESS TRANSFORMATION

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ABSTRACT

The solution presented here addresses the condition monitoring and diagnosis of distribution transformers, with analytics for decision support to investment planning and predictive maintenance throughout the life-span of each and every installed distribution transformer. Automated diagnosis enabled by real-time condition monitoring of transformers paves the way for new ways to manage transformer fleets with operational efficiency improvements and business innovative opportunities.

MOTIVATION AND SCOPE

Always existing in large numbers, spreading throughout the territory, distribution transformers are currently dealt with as ‘abandoned’ infra-structures, whose maintenance, mostly in the hands of contractors, is often overlooked. In order to fight the consequent rapid installation decay, resorting to remote condition monitoring is a key solution, thus providing real-time monitoring, assessment, and remote communication of a number of status conditions, so as to improve maintenance criteria and operational control, yet at reduced cost.

In recent years, significant advances in different technological areas (sensors, wireless networks, etc) are enabling the possibility to instrument Secondary Distribution Substations (SDS) at a reduced cost. The distribution transformer is the critical element in a SDS, therefore real-time monitoring of critical variables enables possibilities of avoiding premature ageing, faster fault location, network reconfiguration as well as real-time coordination among different equipment. Nonetheless, there are economic constraints to consider, especially for an innovative system that aims to be suitable for large scale implementation, so that it will be promptly adopted by electrical utilities. Hence, a decision for a non-invasive, wireless system was made, thus bringing about the following conditions: (i) all physical contact with a transformer is to take place at the outer body surface only, (ii) power supply design has to be based on local energy harvesting and accumulation technologies, so as to avoid periodic battery replacements, and (iii) communication has to be low-power, in order to ensure power supply self-sustainability, and wireless for easy installation.

TRANSFORMER DIAGNOSIS

A Stand-Alone Multi-Sensor

Oil condition is a key factor to assess the transformer as a whole, usually being described by its moisture and gas contents, and operating temperature. Given the paramount non-invasive requirement, moisture and gas contents cannot be measured directly, but only through the consequences as partial discharges (PD), whose detection is based here on the Acoustic Emission (AE) method by receiving ultrasounds generated by electric sparks, here in the 40kHz band.

Thus, the solution comprises an ultrasound sensor coupled to the transformer lid directed at the transformer's interior, so as to detect a combination of acoustic waves originating at every single PD, which may travel through different paths, as depicted in Figure 1. Since such waves are significantly attenuated till reaching the ultrasound sensor, signal amplification has to be provided, appropriate to the size (power rating) of each transformer.

As suggested in Figure 1, the highest oil temperatures occur at the top, as a result of natural convection, but in ageing studies it is customary to contemplate the ageing effects produced by the highest (hottest-spot) temperature [1], which is usually associated with the transformer’s windings. As oil temperature cannot be directly measured, it is derived from the one taken at a transformer’s lid with recourse to three IC temperature sensors that have been arranged in a triple modular redundancy circuit, given the critical importance of temperature for both operation and maintenance purposes.

This multi-sensing device also encompasses the ability to evaluate both the dielectric condition of a transformer’s bushing, by detecting partial discharges with a radio-

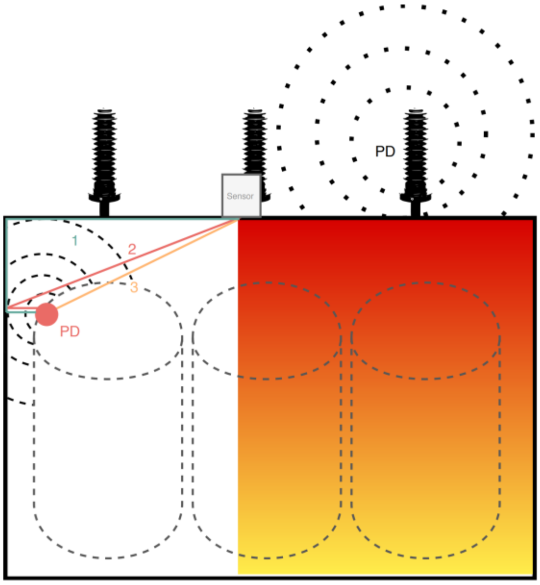

Figure 1- Temperature gradient depiction, representation of bushing partial discharge and acoustic emission different propagation paths: (1) throughout the tank, (2) reflected and (3) direct.

-frequency receiver tuned in the UHF band. This method could not be used previously in order to detect partial discharges inside a transformer given the fundamental non-invasive requirement and the tank being a Faraday cage. Therefore, a sensor placed at the outer layer of the transformer tank would only register PD originated at the outside of the transformer tank, hence enabling an on-line PD detection technique for bushings [2].
The signal captured by the antenna is shown in Figure 2, so a simple way to determine the energy (intensity and duration) of a partial discharge is to associate the antenna to a peak detector, rectifier and integrator circuit, avoiding the need for extensive data processing.

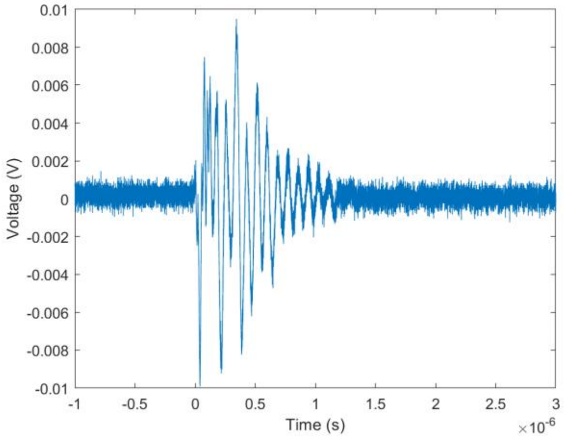

Figure 2- Partial discharge measurement with UHF antenna.

Transformers in standard operation generate a humming or buzzing noise caused by a phenomenon called magnetostriction, in which core laminations are magnetically excited by an alternating voltage and current. Therefore, they are extended and contracted twice during a full cycle, which means that the transformer is vibrating at twice the frequency of supply, as is the fundamental noise frequency [3].

This component of transformer noise is to be expectable, however during longs periods of operation other sources may emerge, such as: (i) defects in core physical structure mechanism, (ii) loose core, (iii) loose grounding plate or (iv) oil level decrease. For instance, when oil level decreases to an extent of core level or below, the temperature increases to very high levels, and may result in core deformation and bushing connector overheating [4]. Moreover, transformers are installed in buildings, and largely closer to the population, and that noise may cause discomfort to nearby communities. It is important to identify units in abnormal conditions, preferably ahead of time so that the appropriate action can be performed before it becomes a problem. Analysing the transformer's humming noise intensity as an indicator of internal faults is prudent and has the additional benefit of preventing potential customer dissatisfaction. Hence, the solution comprises a MEMS microphone in the frequency band of 80 - 500 Hz to monitor humming noise levels.

Computing at the Edge

This multi-sensor is intended to integrate a very short-range (5 m typically) Secondary Distribution Substation network, including a data concentrator/gateway to the cloud as Master node. Bluetooth Low-Energy [5] is adopted for the communications with the data gatherer because of its small communication currents, high market availability and conceivable integration with portable devices.

Such a gateway may easily double as data concentrator, thus allowing other data than the obtained from our multi-sensor to be integrated in order to obtain extra insights concerning the transformer´s exploitation.

The multi-sensor is continuously counting the occurrences of partial discharges, both in oil and in bushings, and periodically sends the resulting sums of detected partial discharges to the gateway. Moreover, the unit collects regular sets of temperature measurements, which are later sent to the data concentrator to be associated with their correspondent load profiles. As an alternative, the unit may only send average temperatures over established time intervals, to reduce overall communication power consumption.

Thus, by bringing together data relating to transformer's loads, in all three phases, as supplied by a meter located at the respective switchboard such as EWS DTVI [6], and of the ambient temperature inside the vault, as well as at the open air, it is easy to cross-correlate all data gathered over the BLE network so as to determine locally the adequacy of the instant load condition.

POWER SUPPLY

As distribution transformers are used in several constructive types of Secondary Distribution Substations such as cabin, vault or pole-type, the selected energy harvesting technique should be related with transformer operation instead of environment conditions which differ between constructive types.

Transformers are naturally at a higher temperature than their environment, resultant to the heat generated by Joule effect in the transformers windings. Hence, a feasible option is to exploit the Seebeck effect, taking advantage of this temperature differential by coupling thermoelectric generators (TEGs) to the transformer tank. Bear in mind that the temperature differential between the transformer tank and the environment will be extensively higher than the one amongst the TEG's opposite surfaces due to heat conduction from the warmer to the cooler side and from the transformer elevating its surrounding's temperature. Therefore, in order to optimize the harvested power, two TEGs combined with bulky heat sinks are used.

The power supply block features LTC3109, a power manager and ultralow voltage step-up converter, ideal for harvesting energy from extremely low input voltage sources — less than ±1°C needed across the TEG to harvest energy [7]. As suggested by Figure 3 the LTC3109 is combined with a supercapacitor, enabling continuous energy storage to ensure availability whenever necessary. With the purpose of running an initial test immediately after installation there is a possibility to charge the unit beforehand.

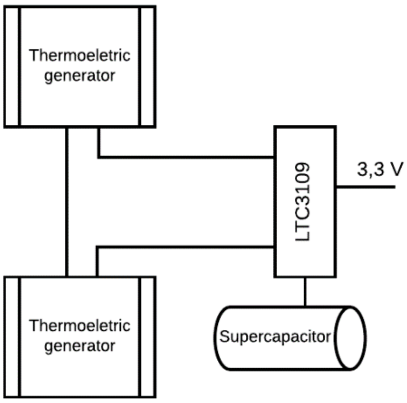

Figure 3- Simplified block diagram of the power supply circuit.

The setup described above led to charging rates as shown in Figure 4. Here, a 0.22F supercapacitor was fully charged to 5.2 V, and, as expected, the charging process is faster at higher temperature differentials: even with temperature differentials of less than 3ºC, charging occurs in less than seven hours' time. This is a decent result and feasibility tests regarding communication rate are being performed.

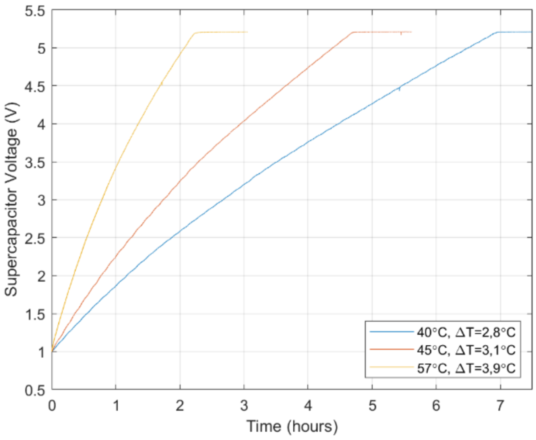

Figure 4- Supercapacitor charging for different transformer tank temperatures.

STRUCTURE AND FORM FACTOR

The product assembly must comply with several guidelines: (i) accommodate the ultrasonic sensor in a manner that secures good coupling to the transformer tank, so as to prevent further reflections; (ii) have high thermal conductivity characteristics, for temperature measurement and energy harvesting purposes; (iii) provide a hot surface for the thermoelectric generators whilst ensuring a minimal thermal differential to its opposite surface; (iv) enclosure suitable for wireless communication, antenna and microphone reception; and (v) magnetic coupling to the tank, for an easy deployment, avoiding thermal adhesives.

Consequently, the product assembly is composed by two separate modules: an aluminium base and a plastic cover. The aluminium U-shaped base enables the integration of two thermoelectric generators and their respective heat sinks. The base has a cavity to accommodate the ultrasound sensor and an area to fix the temperature sensors with thermal glue. To complete the enclosure, the base is combined with a U-shaped ABS plastic cover to facilitate wireless communication and antenna reception.

Figure 5 – Multi-sensor with U-shaped ABS plastic cover.

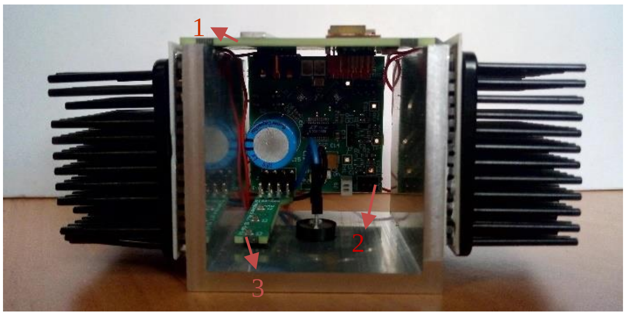

Figure 6 – Unframed multi-sensor.

In order to comply with the previously stated requirements, three printed circuit boards are encapsulated in the small U-shaped aluminium enclosure —5 cm cube—, as shown in Figure 6. PCB-1 comprises the RF detection circuitry, MEMS microphone and CC2650MODA — Bluetooth's communications module and microcontroller. PCB-2 encompasses the power supply system and the ultrasound sensor circuitry. Finally, PCB-3 contains the temperature sensors.

CONCLUSION

Based on the information provided by such device, new business models can be regarded as opportunities for differentiation into business efficiency, in addition to the usual operational efficiency. Thus, automated diagnosis enabled by real-time condition monitoring of transformers paves the way for new ways to manage over long-term economic factors such as TCO (Total Cost of Ownership) and investment planning.

As show in Figure 7, management actions can be conceptually divided in medium and long-term actions, the former is related with the fleet's resource optimization and the latter with investment planning.

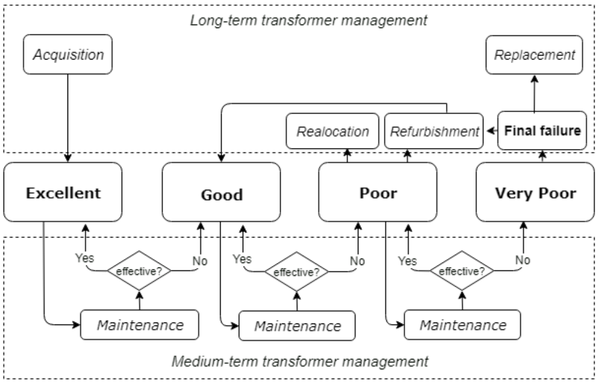

Figure 7- Prospective transformer management during its life-span (adapted from [8]).

Collaborative value can be obtained by bringing together transformer manufacturers, automation manufacturers and integrators, and utilities as end-users, where timely data fuels business models addressing a drastic simplification and risk reduction in network exploitation by utilities. Different approaches can be pursued, which may go as far as a 'Transformer-As-A-Service' business model, where transformers are leased at a competitive cost, instead of sold, under negotiated conditions of overall Quality of Service.

In this manner, by adopting the paradigm of service orientation, with risk sharing amongst partners based on enabling IT technologies, including analytics for decision support to predictive maintenance throughout the life-span of each and every installed distribution transformer, improved operational efficiency can be achieved at a lower cost in the scope of an Equipment Project financing.

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