Wireless Sensor Network Dedicated to Monitoring Noninvasively Power Distribution Transformers

Carlos A. dos Reis Filho
Federal University of ABC – UFABC
São Paulo, SP, Brazil
carlos.reis@ufabc.edu.br

José Francisco Resende
Elektro – Eletricidade e Serviços
Campinas, SP, Brazil
jose.resende@elektro.com.br

Hamilton M. Ferreira,
Marcelo M. Ganzarolli, Carlos A. C.
Altemani and Felipe M. Miranda
State University of Campinas -
UNICAMP,
Campinas, SP, Brazil

***Abstract*— A wireless sensor network is described which provides information about the health status of active transformers in power distribution grids. Transformer diagnosis is performed with basis on the IEEE Standard C57.91 by determining the hot-spot temperature of the winding from measured values of temperatures at the external surface, and the corresponding load current. An alert sign associated with the identification of the transformer is sent from the node that is assigned to the transformer whenever the resulting health status condition so requires. The transformer monitoring node is comprised of a passive linear current sensor; temperature sensors connected to a local I2C network; a microcontroller-based management unit; an 802.15.4 stack based 2.4GHz/+18dBm radio module and a unique power management circuitry that uses the current induced through the passive current sensor to energize the whole unit as well.**

Keywords — Power distribution transformer, smart grid, wireless sensor network, thermal management.

I. INTRODUCTION

The upcoming of electrical power systems typified by the increased use of communications and information technology in the generation, distribution and consumption of electrical energy, the so-called smart grids, calls for the development of techniques and devices that can adequately respond to the new requirements. In some cases, at least in the short term, it will be more convenient to adapt existing components in order to keep them active and in compliance with the new system. The ubiquitous distribution transformer is one of those devices whose adaptation to a smart grid has been discussed and pursued in the last years [1-3].

In the context of a smart grid each and every transformer must be reached both to be controlled and to provide data concerning its on-going status. Thus the above mentioned adaptation, in this case, refers to attaching sensors, actuators and some means of communication to the transformer.

This particular focus on distribution transformers stems from the fact that they are robust, durable, energy efficient and, to date, irreplaceable for the task they serve. When properly sized to the targeted load, installed, maintained and the rated current is not exceeded if not seldom and within predicted short periods of time, the lifetime of these devices surpasses three decades of continuous operation.

Technically feasible solutions have been continuously developed, which can reduce the currently typical 2% of losses [4-5] to less than one half of this by tackling the loss causes. Nevertheless, despite the well-known economic significance of reducing losses in distribution transformers, cost constraints in the transformer fabrication business not always allow those solutions to be adopted.

It is the purpose of this paper to propose a solution for the adaptation of distribution transformers to smart grid technologies with the particular concern that this adaptation can be implemented in existing active transformers and preferably with no interruption of the transformer operation.

II. DISTRIBUTION TRANSFORMERS

The lifetime of a distribution transformer is mainly determined by the lifetime of its insulation components, which deteriorate due to moisture content and oxygen content and at a pace that is accelerated as the internal temperature increases. Thus, the temperature is a critical factor to its health. Since the temperature is not uniformly distributed in the interior of a transformer tank, it is natural to consider that the deterioration rate is higher at the region where the temperature is the highest – the hot-spot. A relationship between the calculated transformer insulation lifetime and the hot-spot temperature is suggested in [6-7]. Figure 1, from [6], shows the curve that relates these two quantities assuming that the insulation material is cellulose. It points out that the transformer will last a normal lifetime as long as the hottest spot in its interior remains at 110°C.

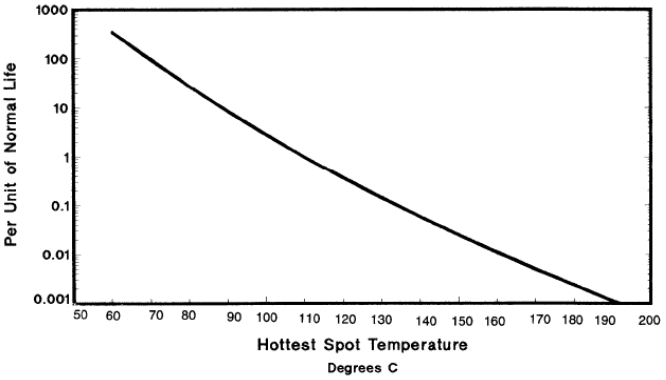

Figure 1: Transformer insulation life [6]

As the hot-spot temperature exceeds this limit, the aging rate increases. Since this estimation method is based on Arrhenius' equation, it is easy to show that an increase of 6 degrees in the hot-spot doubles the aging rate of the transformer insulation during the time it remains in this condition.

In view of these considerations, it is clear that there is an economic motive to monitor the internal temperature of distribution transformers. In the fabrication process of large power transformers, it is customary to include temperature sensors as part of their structures for monitoring purposes. This practice, however, is not usual in the fabrication of distribution transformers mainly due to cost constraints. A secondary but also significant justification to avoid the installation of temperature sensors inside distribution transformers is the risk of leakage in the feed thru hole, thus jeopardizing the life expectancy of three decades.

III. TRANSFORMER TEMPERATURE MODELS

Several models to predict the hot-spot temperature in the interior of a transformer have been proposed in the last decades, showing how important this topic remains [6-12]. A well-done comparison of the three most relevant known models to be applied in on-line monitoring and diagnosis of oil-immersed transformers is presented in [8]. By comparing measured data during unsteady-state condition of load current and ambient temperature from large power transformers with the values predicted by the considered models, it could be concluded that the best results were obtained with the model proposed in [9]. It was further observed that the average error in long term supervision was kept below 2 K showing that the referred model is appropriate for on-line monitoring.

The so-validated model is considered in [8] as an evolution of a model that is proposed in the IEEE Standard C57.91-1995, which in its turn can be regarded as the fundamental model for the prediction of hot-spot temperature of transformers.

According to the model proposed in [9], the top-oil temperature can be obtained from measured values of the ambient temperature and the load current, as long as the values of parameter models K_1, K_2 and K_3 are known. The corresponding equation, assuming natural cooling, is the following:

$$\Theta_{TO}\left[k\right] = K_1\Theta_{TO}[k-1] + \left(1-K_1\right)\Theta_A[k] + K_2\left(I[k]\right)^{1.6} + K_3 \quad (1)$$

The top-oil temperature at instant k, $\Theta_{TO}[k]$, is related with the ambient temperature Θ_A at the same instant, the load current I also at instant [k] and the top-oil temperature at instant k-1. The model parameters K_1-K_3 can be determined from thermal experiments with samples of transformers properly equipped with temperature sensors in the top oil. These parameters are related with measurable variables as follows:

$$K_1 = \left(\frac{T_o}{T_o + \Delta t}\right) \quad (2)$$

$$K_2 = \frac{\Delta t}{T_o + \Delta t}\frac{R}{R+1}\Theta_{fl}\left(\frac{1}{I_{rated}}\right)^{1.6} \quad (3)$$

$$K_3 = \frac{\Delta t}{T_o + \Delta t}\frac{\Theta_{fl}}{R+1} \quad (4)$$

T_o is the transformer thermal time constant, Δt is the measuring period, R is the ratio of load loss at rated load to no-load loss and Θ_{fl} is the full load top-oil temperature rise over ambient temperature.

The long-term variation of the parameter models K_1, K_2 and K_3 due to the aging of the internal components requires a periodic tuning of their values by means of specific thermal measurements. This type of maintenance procedure is technically and economically acceptable in large power transformers but is impracticable in distribution transformers. Hence, some means to tune the values of these parameters that dispense with the thermal characterization procedure turns out to be a necessary condition to use it in on-line monitoring of distribution transformers.

As a part of the work herein described, efforts have been made toward establishing one such mechanism, inasmuch as the proposed transformer adaptation solution must respect the principle of non-invasiveness.

The approach currently under study assumes, in the first place, that the model proposed in [9] is equally valid for transformers with smaller dimensions – the distribution transformers. This assumption was proved to be correct in laboratory tests with two different transformers. Temperature measurements of selected points at the surface and inside of two transformers, one of 25 KVA (single phase) and the other of 75 KVA (three phase) were obtained from 12 - 24 hours warming-up tests.

Upon determining the values of parameters K_1-K_3 using standard linear least squares techniques, the temperature at the top of the winding was calculated and compared with the actual (measured) value. In Figure 2 is a graph showing the obtained results for the single phase transformer. The stair plot shows the measured temperature and the continuous plot, the calculated values. An excellent agreement was found.

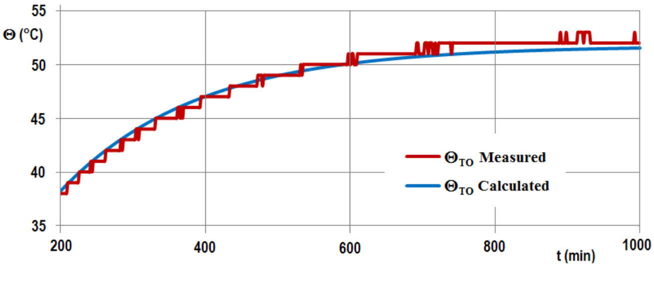

Figure 2: Top-oil temperature of single-phase 25 KVA: Measured and calculated values

Another important result from the experiments was to verify that the model is also applicable to predicting the temperature of points at the external surface of the transformer. Using the corresponding model parameters K_1-K_3 for this point, which are different from the values that apply to the top-oil, the temperature values of a point at the external surface of the transformer could be calculated and compared with the measured values. The considered point, in this case, is at the same ordinate of the oil level, however, at the outside of the tank.

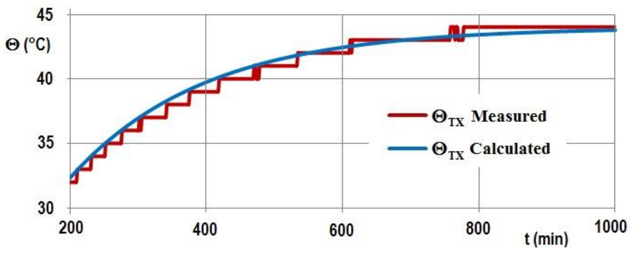

Figure 3: Temperature at the external surface of a single-phase 25 KVA: Measured and calculated values

From this and other gathered experimental data it could be observed good correlations between the top-oil temperature and each one of the measured temperatures at the external surface of the transformer. Figure 4 shows the measured temperatures at various points (internal and external) of a three phase 75 KVA transformer with balanced line currents during a warm-up laboratory test.

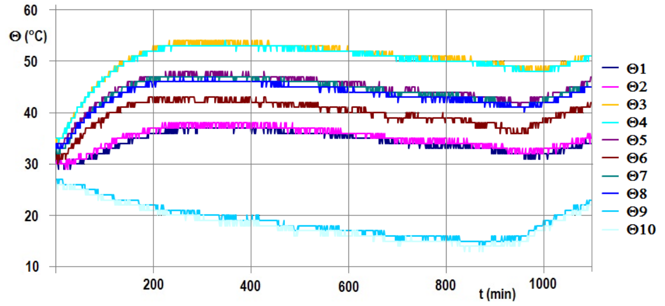

Figure 4: Thermal characterization of a three-phase 75 KVA transformer. Θ3 and Θ4 are top-oil temperatures; Θ9 and Θ10 are ambient temperatures.

With basis on the obtained results it is currently being assumed that each one of the model parameters K_1-K_3 associated with a point in the external surface is a function of the corresponding parameter associated with the top-oil. Furthermore, given the complexity of the system, these functions are being pursued by means of an heuristic approach.

That is to say, that the temperature Θ_1 at an external point can be predicted by (1) replacing the model parameters K_1-K_3 with the parameters K_{11}, K_{21} and K_{31}, to which are related:

$$K_{11}=h_{11}(K_1) \qquad K_{21}=h_{21}(K_2) \qquad K_{31}=h_{31}(K_3) \tag{5}$$

h_{11}, h_{21} *and* h_{31} are heuristically determined functions.

To the extent that these relationships holds true, the top-oil temperature can be determined from measured values of temperatures at three different points from the external surface and the ambient temperature. So far, simulations have shown encouraging results.

IV. TEMPERATURE AND CURRENT SENSING

It is a result from the preceding considerations that only two types of variables need to be measured in order to determine the health status of the transformer: temperature and current. Hence, the network sensor node was designed to accommodate sensors for these variables, namely four (smart) temperature sensors and a passive (inductive) current sensor.

As already justified, three temperature sensors are used to detect the temperatures at previously chosen points of the external surface of the transformer, while the fourth temperature sensor is dedicated to detecting the ambient temperature. These sensors are individually attached to the external surface of the transformer by means of magnet rods to ensure direct contact with the metal housing. The sensor that measures the ambient temperature is also attached to the transformer by means of a magnet, however, at a distance of 4 cm from the external surface.

Integrated temperature sensors with I2C interface [13] were chosen to be used in the implementation of the sensing nodes because of their intrinsic higher immunity to interferences, reduced cable wiring and ease of expansion. In operation, the adopted sensor consumes 920uW, has a nominal resolution of 9 bits and accuracy of ±3K (max) over the range of -55°C to 125°C.

Each temperature sensor has been encapsulated together with a magnetic rod and the I2C wiring cable into a resin-filled monolithic block, as depicted in Figure 5.

Figure 5: Resin-encapsulated 80mmX30mm temperature sensor module

The current sensor is a passive toroid transformer with cross section area of 200 mm^2 and internal diameter of 55 mm, built with OG Silicon-Steel. The core is cut in two semicircles to allow embracing the line cable and the coil is wound around one half of the core, as depicted in Figure 6.

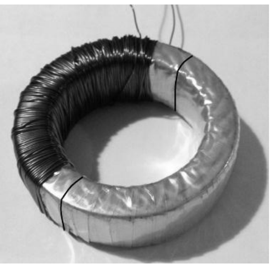

Figure 6: Toroidal transformer used to both sense current and harvest energy by magnetic induction

The measured nonlinearity of the current sensor up to 250 A is less than 0.1%.

V. INDUCTIVE ENERGY HARVESTER

Energy harvesting is used in wireless sensor networks mostly to overcome the lifetime limitation imposed by the use of batteries, but also to avoid the use of batteries for simple convenience or for safety reasons. The motivation for using an energy harvester in the present work, in which energy is abundant and reachable, stems, however, from two fundamental requirements: ease of deployment and installation without energy interruption. The sensor node comes into action and is connected to the network as soon as the current clamp sensor is attached to the power line, since the induced sensor current is concomitantly used to energize the node circuits. The induced energy harvester and the current sensor are actually the same device, which can also be regarded as a current transformer that has been designed for a current gain of 0,003. With such gain, the toroidal transformer provides enough current to energize the associated node (90 mA_{RMS}) when the minimum load current in the measured line is 30A.

Measured values of the induced current as a function of the number of turns for three different values of primary currents (load currents) are plot in Figure 7. The obtained inverse dependence is in perfect agreement with theoretical predictions.

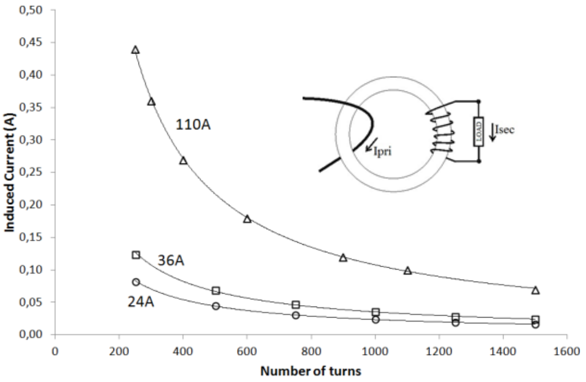

Figure 7: Measured induced current for different number of coil turns and primary current

The magnetic energy harvester was designed to comply with the characteristics of three-phase delta-wye connected 75 KVA transformers, which is predominant in the site where the sensor network is to be deployed. Assuming that each transformer provides power to balanced loads, the rated current per-line is approximately 196 A. Hence, the sensor node will remain functional insofar as the load current in the line to which the harvesting coil is attached does not drop below 15% of its rated current. Given that this extreme condition seldom occurs, the proposed solution is satisfactory. Furthermore, operating at such low percentage of the rated power, the transformer is less prone to thermal related problems.

VI. SENSING AND HARVESTING CONTROL CIRCUIT

Shown in Figure 8 is the schematic diagram of the circuit that converts the current from the sensing/harvesting coil into a regulated voltage of 3.3 V that is supplied to other components of the sensor node: a microcontroller and the radio module. The diode bridge D1-D4 rectifies the current from the coil and this current charges capacitor C2 to a voltage, whose level is determined by the impedance at the upper node of C2. By controlling the impedance at that node, the voltage across the capacitor can be maintained at a fixed desirable level and almost independent of the amplitude of the current from the coil. This voltage controlling mechanism is implemented with the shunt regulator formed by transistors Q1-Q6 and the associated resistors R1-R4. The impedance at the upper node of C2 is now determined by the conduction status of Q6: As the current from the coil increases, tending to raise the voltage across the C2, the amplifier Q1-Q5 drives transistor Q6, making it act as a bypass for the excess current, thus avoiding the amplitude of Vout from changing. In the opposite direction, as the current from the coil decreases, the shunt regulator will not be able to control Vout from the moment Q6 is driven into cutoff. When this happens, Vout decreases without any control. Nevertheless, even when Vout is no longer maintained at the desired amplitude, the voltage that is supplied to the voltage sensitive devices, the microcontroller and radio module, will remain at the proper level, 3.3 V, as long as Vout exceeds the dropout level of the LDO regulator.

At the upper extreme of induced currents, the highest tolerable current from the coil is determined by the current and power dissipating capacity of transistor Q6.

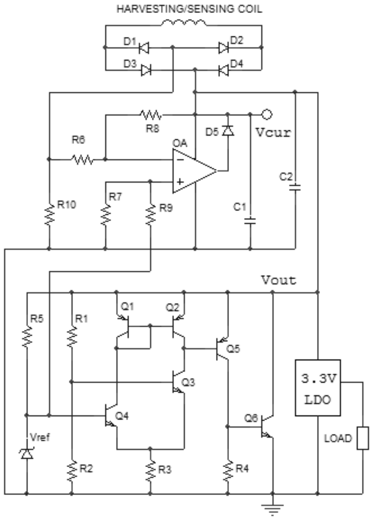

Figure 8: Current sensing and energy harvesting circuit

Still referring to Figure 8, in order to measure the current from the coil, a shunt resistance, R10, is included in the return path of the circuit seen by the diode bridge. The voltage drop across this resistance is amplified by the rail-to-rail op-amp OA and the peak value is held in capacitor C1. A fraction of the return current is deviated from the shunt resistance due to R6 and R8, thus introducing an error in the measured current.

The maximum amplitude of this error, however, is less than 0.3% of the minimum measured current.

VII. DATA COLLECTING AND NETWORK COMMUNICATION

An 8-bit microcontroller collects data from the temperature sensors through the I2C interface while the amplitude of the load current is acquired through one of the channels of its ADC. Measurements are taken every 5 minutes and with basis on the acquired data and the aging status criteria as established by IEEE Standard C57.91 [6], the microcontroller determines whether the momentary condition of the transformer is adequate or not. When an abnormal condition is found, the microcontroller commands the radio module to send an alert to the central, adding a diagnostic report to the message. The occurrences of accelerated aging and uncorrelated values of load current and top-oil temperature are defined as abnormal conditions.

Whenever the diagnostic indicates that the momentary operating status is acceptable, no message is sent to the central. Each one of the network nodes sends a compulsory message in time intervals of six hours reporting the current status of the transformer as a policy to detect faulty nodes.

The network communication was implemented with radio modules that operate in the 2.4GHz band, IEEE 802.15.4 standard mesh network protocol and feature an output power of +18dBm to accomplish a range of approximately 100 m (exceeds this distance in case of line of sight) [14]. Radio modules with such power were adopted to avoid the use of sensorless routing nodes, which would be necessary if less powerful radios were used. The adopted solution not only reduces the installation effort as it also circumvents the increased throughput loss that is expected as the number of hops increases.

VIII. EXPERIMENTAL RESULTS

A field test installation with ten transformers has been in operation and continuously evaluated for the last three months. So far, no communication failures were observed. One of the monitored transformers has been equipped with a temperature sensor placed in its interior at the top of the winding, in addition to sensors that are attached to the external surfaces. This setup is intended to compare the measured internal temperature with the corresponding (off-line) calculated value. Heuristic relationships between external temperatures and the top-oil temperature are currently being pursued.

IX. CONCLUSIONS

A wireless sensor network has been developed for on-line monitoring of distribution transformers as a solution to adapt these devices to smart grid technologies. Each monitored transformer is assigned a sensing node that comprises temperature sensors and a current sensor along with a microcontrolled-based management unit and a radio module. All components of the sensing node can be installed in an active transformer with no interruption in the power delivery. In the so-proposed solution it is novel the concept of determining the transformer top-oil temperature from temperatures measured at the external surface and the use of an inductive energy harvester to energize the whole node circuitry.

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