SOFT SENSOR FOR DISTRIBUTION TRANSFORMERS: THERMAL AND ELECTRICAL MODELS

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ABSTRACT

This paper presents the characteristics and applications of a soft sensor emulating a coupled thermal and electrical models of MV/LV distribution transformer. This non-intrusive soft sensor is integrated in a smart meter connected on the LV side of the distribution transformer; all the metering data measured on the LV side are necessary and sufficient for an accurate estimation of the primary quantities corresponding to measurement on the MV side of the grid. These embedded new functions allow an accurate supervision of the MV voltages all along the MV feeders and also an accurate balance of energies on the LV side as well as on the MV side.

INTRODUCTION

Power transformers are one of the most expensive components in an electricity system. In order to increase transformer operational efficiency and minimize the probability of an unexpected outage, several on-line and off-line monitoring systems have been developed [1],[2].There are several key factors that determine a transformer lifespan including oil temperature and hot-spot temperature of windings which are directly influenced by the transformer load, ambient temperature and internal losses in the transformer [3]-[5].Transformer temperature is one of the most critical parameters when defining the power transformer thermal conditions and overloading capability beyond the nameplate rating. Knowing this is essential to maximize return on investment and lower the total cost associated with transformer operation. This paper will describe the MV/LV distribution transformer monitoring integrated in a smart meter connected on the LV side of the transformer. In addition to the classical functions of the electricity meter, new options are embedded such as a thermal model to ensure real-time thermal transformer monitoring (top oil temperature, hot-spot temperature, ageing rate) and an inverse electrical model for estimation of the voltages and currents on MV side of the transformer and the internal active and reactive losses, without requiring any other sensors.

DISTRIBUTION STATION METERING

The large scale introduction of renewable energy (RE) generation on the LV and MV networks induces consequences on the stability of the 50Hz voltages and the direction of the energy flow along the LV and MV grid. As a result the Distribution System Operators (DSOs) are more and more interested in monitoring Power Quality (PQ), more specifically voltage patterns (min/max excursion of the voltages all along the MV network). They are also interested in monitoring load coefficients, real time thermal behavior and ageing rate, real time active and reactive losses of the distribution transformers for each transformer.

Meter description

The Itron ACE SL7000 LVRT meter is installed on the low voltage network and is equipped with three independent current sensors connected to the meter. This sensor technology allows the safe commissioning of the meter, live, on an existing installation.

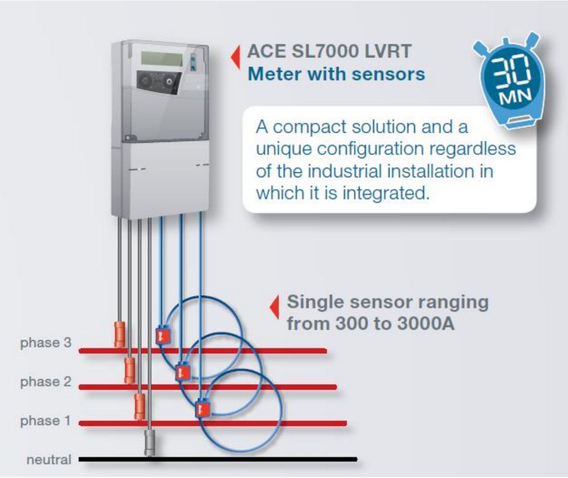

Fig.1 Distribution Transformer Meter (DTM)

This meter provides accuracy over a very wide dynamic range and over a large frequency bandwidth: the global accuracy of the measuring chain is better than 1%, superior to conventional Class 0,5 meters associated with Class 0,5 current transformers (CT). The use of Low Voltage Current Sensors (LVCS) provides also total safety for stakeholders.

TRANSFORMER THERMAL MODEL

Efficient thermal monitoring is based on an accurate thermal model that gives the transformer temperature profile with high precision. The main factors that determine the transformer life are the windings hot-spot temperature and the oil temperature which are directly influenced by transformer load, ambient temperature and active losses in the transformer [6], [7]. Many papers [8]-[11] present the measurements done by specific sensors or by optic fiber. While these solutions give good results, it is however necessary to invest in order to equip transformers with sensors which can be expensive and can introduce fragility points inside the transformer. This paper presents the advantages of using an accurate electricity meter on the LV side of the transformer to implement this thermal model, without requiring any other sensors.

IEC 60076-7 model

It is chosen to present the thermal model based on equations given by the IEC60076-7 standard. This method uses heat transfer differential equations applicable for arbitrarily time-varying load factor K and time varying ambient temperature θa.

The corresponding block diagram is shown in Fig. 2, the inputs are : **K** the load factor , **θa** the ambient temperature; the parameters are : $\Delta\theta_{hr}$ the hot spot to top oil gradient at rated current, **y** the winding exponent, $\Delta\theta_{or}$ the top oil temperature rise in steady state at nominal rated losses, **R** the ratio between the internal losses at rated load over the losses without load, **x** the oil exponent, k_{11} k_{21} k_{22} thermal model constants, τ_w and τ_o are the winding time constant and the average oil time constant ; the output is the oil temperature at the top of the tank and the windings hot spot temperature.

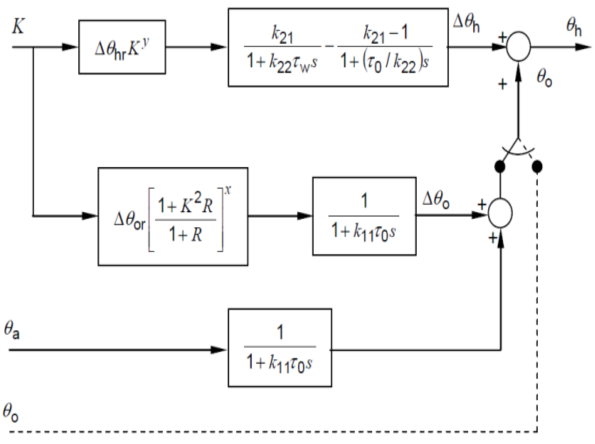

Fig.2 Oil and hot spot temperature block diagram

Table 1: Parameters recommended by IEC60076-7 standard

Parameters	Distribution Transformer ONAN type
x	0.8
R	6.5
τ_o *(min)*	180
τ_w *(min)*	4
$\Delta\theta or$	55
$\Delta\theta hr$	19
y	1.6
k_{11} k_{21} k_{22}	1 1 2

160 to 800kVA experimental set-up

Experimental set up is prepared to test 21000/420V (ONAN) distribution transformers from 160kVA to 800kVA (160, 400 and 800 kVA); all the tests are performed with short circuited LV secondary windings. Each transformer is equipped with a PT100 sensor installed 10cm below the top of the tank which gives the oil temperature. Upstream from the transformer a motorized autotransformer is connected in order to adjust the load factor (K). An electricity meter (Itron ACE SL7000 LVRT) is connected to the transformer measuring the phase current on the LV side (see Fig.4). A computer equipped with Matlab / Simulink is linked to a data acquisition DSpace card. The available measurements are the secondary currents, the three primary voltages, the ambient temperature at a distance of 2m from the transformer tank and the oil temperature given by the PT100 sensor.

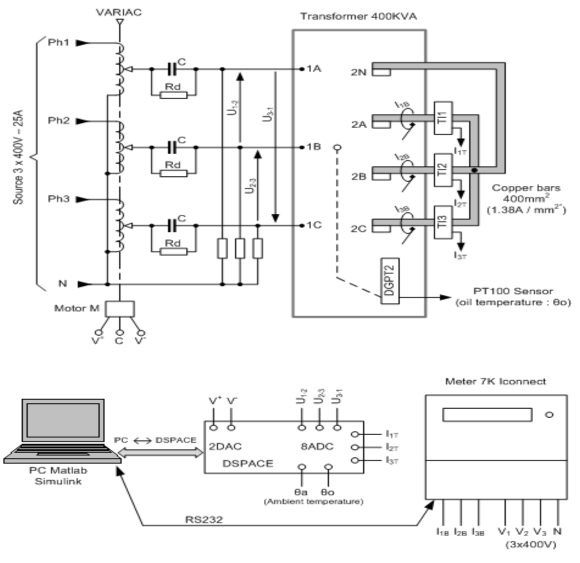

Fig.3 Schematic of the distribution transformer experimental monitoring

Standard IEC parameters

The two inputs (the load factor K and the ambient temperature) and the output (oil temperature measured by a sensor PT100) were acquired via the Itron ACE Vision software. The thermal model presented in Fig.2 was implemented with Matlab/Simulink; enabling the simulated oil temperature and the hot spot temperature to be found using parameters recommended by the standard that considers these parameters to be constant across the ONAN distribution transformer models.

After several heating tests, a two week test was selected to be presented. The load factor K increases and decreases with a step of +/-10% at nominal load.

Results are shown in Fig 4; it compares the real oil temperature measured by the sensor with the oil temperature simulated by the soft sensor of the thermal model.

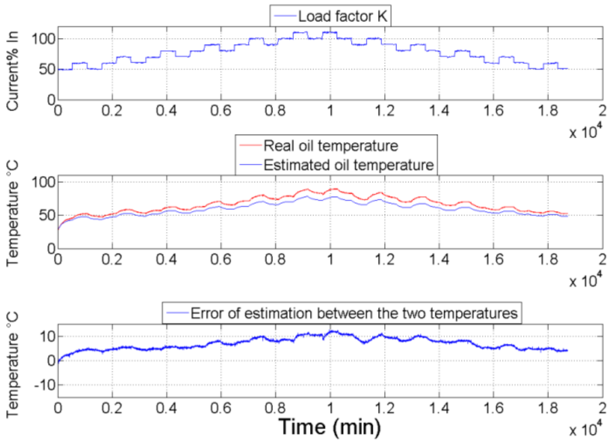

Fig.4 Measured and the estimated oil temperature (400 kVA transformer) using the standard IEC parameters.

This figure shows that there is significant error between the two temperatures (error between ± 12°C). This error can be explained by the fact that the thermal parameters of the transformer used in this model, as recommended by the IEC standard, are not reliable enough. In order to reduce this error, some critical parameters must be estimated for each transformer model using an identification algorithm.

Parameters identification with the Levenberg-Marquardt algorithm

The Levenberg-Marquardt (LM) algorithm is the best solution to identify the critical transformer parameters as there is a measure of two inputs (load factor K; the ambient temperature) and the output (the oil temperature). This algorithm has become a standard technique for non-linear least-squares problems [12]. It is an iterative technique that locates the minimum of a multivariate function that is expressed as the sum of squares of non-linear real-valued functions [13], [14]. Table II shows the values of the critical parameters which were chosen to be identified using the program of LM algorithm.

Table 2: Parameters identified by the LM algorithm

Parameters	Distribution Transformer ONAN type
x	0.61
R	8.89
τ_o (min)	140
$\Delta\theta or$	56.82

The estimated parameters were replaced in the thermal model and a new simulation was launched to determine the oil temperature of the transformer.

The same test described in the previous paragraph will be presented. The aim is to compare both results and show the effect of the parametric identification on the error.

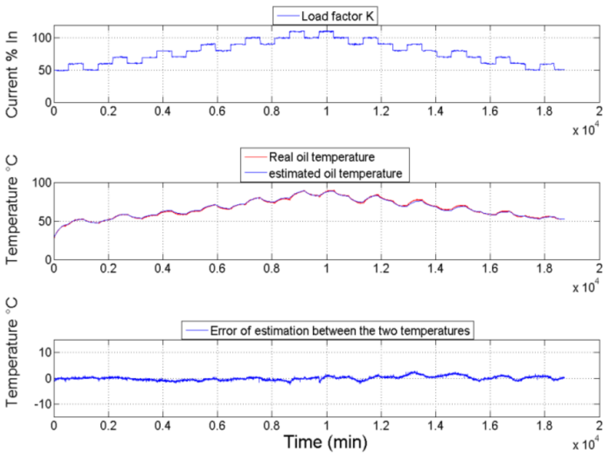

Fig.5 Measured and the estimated oil temperature (400 kVA transformer) using the LM identified parameters.

It can be seen that with the L.M identification, the error between the measured oil temperature and the estimated oil temperature can be reduced in a remarkable way. In this test, the error was reduced from ± 12 ° C to ± 3 ° C.

ELECTRICAL TRANSFORMER MODEL

The electrical model used for the computation of the MV side data is the Kapp model and diagram, the magnetizing admittance is on the primary side in parallel on each primary MV winding and the total leakage impedance is on the LV secondary side in series with each secondary winding.

Set-up for leakage impedance monitoring

A particular use of an electricity meter is done in the thermal tests set up. It consists of measuring the currents on the LV secondary side on each phase and the measurement of the voltage at the primary side. The transformer is short circuited at the secondary and a capacitive compensation is introduced in series on each primary phase.

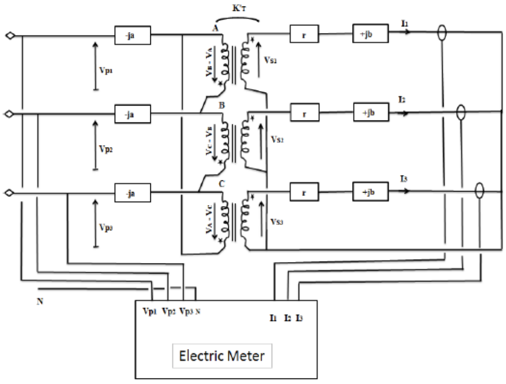

Fig.6 Test set up used for electrical parameters identification

$$r_{1,2,3} = \frac{-1}{2K_T' I_{1,2,3}^2}\left(\sqrt{3}P_{1,2,3} + Q_{1,2,3}\right) \quad (1)$$

$$Ls_{1,2,3} = \frac{1}{2\omega K_T' I_{1,2,3}^2}\left(P_{1,2,3} - \sqrt{3}Q_{1,2,3}\right) + \frac{1}{K_T'^2 C\omega^2} \quad (2)$$

Equations (1) and (2) give the leakage impedance elements: resistive and inductive as functions of active and reactive instantaneous power measured by the meter. Then the variations of these elements can be represented as functions of the oil temperature of the transformer.

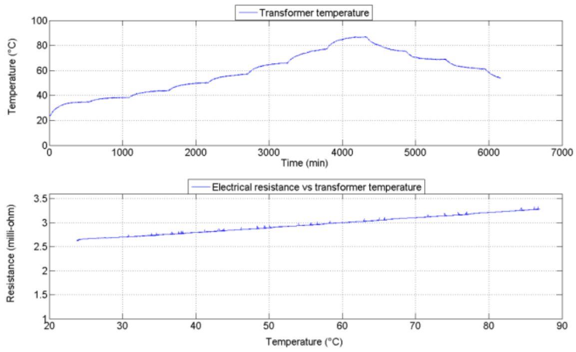

Fig.7 Electrical resistance vs transformer oil temperature

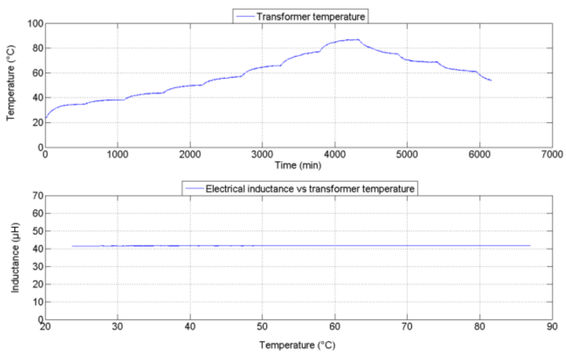

Fig.8 Inductance vs transformer oil temperature

Tests results

As expected, the leakage inductance and the transformer ratio are independent from the oil temperature. The resistive part of the leakage impedance corresponding to total windings resistance is a linear function of the oil temperature, the reference point is known at 75°C.

MODELS COUPLING

The two models are computed simultaneously.

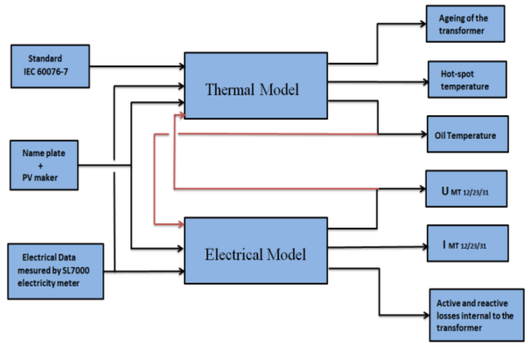

Fig.9 Block diagram of the coupled models

Parameters input are: IEC60076-7 standard, data from the nameplate, data from the routine test report from the manufacturer. Electrical data inputs are measured by the electricity meter on the LV side of the transformer.

The outputs of the thermal model are:

- Estimated hot-spot temperature,
- Estimated oil temperature,
- Ageing rate.

The outputs from the electrical model are:

- Total active and reactive power dissipated inside the transformer,
- MV voltages and the MV phase currents.

Interactions between the two models

One output of each model is an input for the other one: the MV voltages are inputs of the thermal model and the oil temperature is an input of the electrical model.

APPLICATION IN REAL CONDITIONS

Fig.10 presents an example of reconstructed MV voltages from a 20500/410V transformer of 400kVA over a period of 24 hours. Similar load curves representing MV currents or active energy on MV side can be delivered to DSOs.

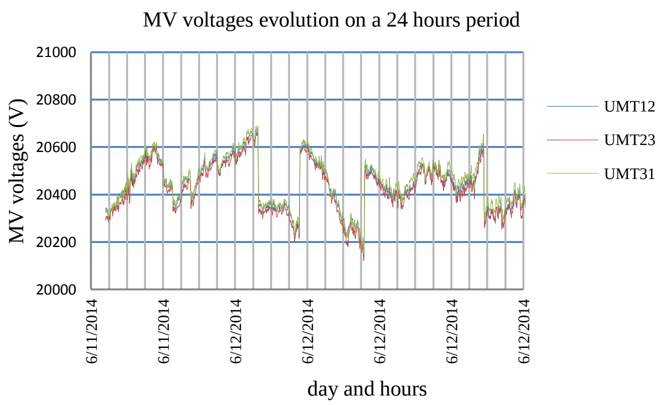

Fig.10 Estimated MV voltages

SOLUTIONS AND BENEFITS FOR DSO

For utilities, the smart meters installed at the LV side of the distribution transformers will not only be meters that can register consumption, they will also provide comprehensive information of downstream and upstream electrical data of the grid.

Monitoring of the MV voltage system

Usually, the DSO adjusts the MV voltage from the HV/MV main substations; such a voltage control imposes a common setting for all MV feeders at the output of the main substation. Now we can have on a MV feeder a voltage rise (instead of a drop), while the other lines of the same MV substation still have a voltage drop. Hence the interest of DSO's to understand the MV voltage level throughout each MV feeder (especially those that receive renewable production); MV/LV distribution transformers are good candidates for this measurement because they are spread all along the MV feeders.

Monitoring of the energy balancing of the LV and MV distribution

In developing regions, huge non-technical losses are often reported - up to 30% of the total distributed energy, and an equivalent share of DSO's revenue is also lost. Today utilities do not know precisely where these losses occur, they know the overall energy that is distributed by the HV/MV main substation, the energy injected by local MV producers and power consumed by local MV customers (including their load curve) and energy consumed by LV customers. Tomorrow, with the generalized introduction of residential smart metering, utilities will know the load curves of all LV customers and producers. With this solution utilities will be able to verify the energy balance of each transformer on the LV side:

Etr (energy output by the transformer on the LV grid) + Ep_LV (energy produced on LV grid) – Ec_LV (energy consumed on LV grid) = LV line losses + **LV fraud**.

Utilities will also be able to conduct similar studies on the MV side, once they have the knowledge of energy distributed by each MV/LV transformer.

The equation of the MV energy balance is:

ET (energy output from the main HV/MV substation) + Ere_MV(MV renewable energy) – Ec_MV(energy consumed by MV customers) – Et_MV(energy distributed by MV/LV transformers) = MV line losses + **MV fraud**.

CONCLUSION

The concept presented in this paper is a new component for smart grids with local intelligence based on standardized models of distribution transformers. It is economically more interesting to install the smart meter on the LV side and make it even smarter by feeding its metering data to the embedded soft sensors. These new soft sensors distributed on the grid will enable the monitoring of the good thermal health of the transformers and the energy balance on LV and MV grids. The reconstructed MV data will be very useful for power flow management, MV energy balance and MV voltage monitoring from the HV/MV substation.

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