REMOTE MONITORING OF POWER TRANSFORMERS THERMAL IMAGE

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ABSTRACT

This paper presents an original technical solution of device for distributive transformers' thermal image recording. The paper elaborates mathematical model of power transformer's thermal image, applied to estimate its hot-spot temperature. The block-scheme and brief technical description of realized device are presented here. The paper presents both hardware and firmware solution of the system. Developed prototype of such device has been tested during several months, in real conditions, in one substation 10/0.4 kV/kV in serbian capital, Belgrade. Permanent transmission of measured data have been obtained via GPRS. Technical solution of remote monitoring is described in the paper, too.

INTRODUCTION

The single restriction for power transformers loading is the temperature of the hottest part of their windings (so called „hot-spot", abbr. HS), which is determined by windings' insulation class. In the case of oil-immersed power transformer (OIPT) with paper insulation, its value is 140 °C. According to the fact mentioned above, overload protection of OIPTs should be thermal one, with taking into account great thermal inertia of cooling and insulating system (i.e. oil, in this type of power transformers, PT).
Regarding the rate between prices of OIPT itself and its protection system, in distributive substations (SS) 10(20)/0.4 kV/kV in Serbia contact thermometers are used as overload protection devices. They protect OIPTs by monitoring their top-oil temperature. For more loaded OIPTs 35/10 kV/kV and for all PTs 110/10 kV/kV, so called „thermal image" is used, the device which takes into account thermal inertia of colling and insulating system.

Determination of power transformer's optimal operation

Supposing that the price of PT rises with 0.75 degree of its rated power (so called *Wiedmar law*), economic relative load of PT, [1], can be calculated as:

$$x_{opt} = \sqrt{\frac{3}{5} \cdot \frac{p_{aT} \cdot N_T + p_{Fe} \cdot (c_p + T_a \cdot c_e)}{p_{Cun} \cdot o^2 \cdot (j_{T-ca}^2 \cdot c_p + \tau \cdot c_e)}} \quad , \qquad (1)$$

where: x_{opt} – optimal relative load of PT, p_{aT} – relative annual rate of PT, N_T – commision price of PT (in €), p_{Fe} – rated power of permanent losses (i.e. losses in Fe-core of PT, in kW), c_p – specific costs of engaged electrical power (€/kW), T_a = 8760 (h), c_e – specific costs of electrical energy used (€/kWh), p_{Cun} – rated power of variable losses (i.e. losses in Cu-windings of PT, in kW), o – factor of variable peak load, j_{T-ca} – coefficient of PT-consumption area simultaneous load, and τ – equivalent annual duration time of peak losses.
Regarding very low value of average electricity price in Serbia (c_e is cca 0.05 €/kWh) and very significant commision price of OIPT (N_T is cca 9000 € for OIPT of 630 kVA rated power and 12,000 € for OIPT 1000 kVA), calculated value of optimal relative load, x_{opt}, points to loading of OIPTs during peak-load periods towards the extreme thermal limits, as economic, optimal operation, even with faster ageing of OIPT's insulation.

Overloading in pasive distribution networks
To realize such operational regime of OIPTs in a safety manner, it is necessary to apply „thermal image", even to those units with rated power less than 1 MVA. Namely, OIPT's protection with contact thermometer, based on top-oil temperature measuring, is too rough and appropriate only for OIPT used for supplying strictly defined consumption area, with slow annual increase of peak load value. Contact thermometer is able to detect such an increase as the rise of OIPT's top-oil temperature. On the contrary, in the case of instant and significant OIPT's peak load increase, temperature of winding's HS could exceed permitted values, but with top-oil temperature still under prohibited limits, due to thermal inertia of insulating oil. The thermal image should be used then. The price of such device, of course, has to be appropriate to the price of protected distribution network element, i.e. it should be significantly cheaper and with smaller dimensions, compared with thermal images available for OIPTs with middle values of rated power. Concerning prices and abilities of state-of-the-art microprocessors and other elements of power electronics, Power Industry od Serbia supported the reasearch and development work [2], which led to realization of one cheaper thermal image for distributive OIPTs. Beside its basic, protective function, this thermal image would have also the remote monitoring one. This paper presents the essence and results of that research and development process.

Overloading in distribution networks with DG
The fact that thermal image, proposed in this paper, is significantly cheaper than other similar systems, could contribute to its wider application, not only in classical distribution networks, but also in those with distributed generation (DG). Namely, in active distribution grid new

problems occur; power flows are more complicated, electricity can be produced at one voltage level and used at another one, energy balance could be difficult to achieve for some operational regimes and under extreme weather conditions, etc. In such circumstances, overloads of power transformers can occur even more often than in classical, passive distribution network. Hence, the need of improved monitoring and control of power transformers' top oil temperature becomes obvious. Proposed device and system therefore could contribute to the integration of DG in distribution network operation.

POWER TRANSFORMERS THERMAL MODELING

Heating of OIPTs is already quite investigated topic, [3]. Determination of HS temperature rise has been defined by several, now improved, international standards, [4], [5]. According to them, several assumptions and simplifications should be made by HS temperature determination: oil temperature rises linearly, from bottom towards top, winding's temperature rises linearly upwards the conductor, parallel with oil temperature and with constant difference between those two temperatures. This temperature difference is denoted with *gr* (gradient). The temperature of HS is higher than the temperature of windings' top. Consequently, the difference between top-oil temperature and HS temperature are greater than gradient. Therefore, at this point, temperature gradient has to be multiplied with HS factor, *H*. Its value, for different kinds of OIPTs, varies in the range between 1.0 and 1.27, [3], depending on OIPT's rated power, construction and shortcut impedance. However, factor *H* can be determined the most accurately through experiments, by measuring temperatures of each particular OIPT. For the most usual OIPT, with shortcut impedance of 5 % to 8 %, typical value of *H* is 1.1.

Taking into account the fact that the time constant of distributive OIPTs' windings has realtively small value (5 to 10 minutes), its influence to HS temperature is minor, even by great loads with short duration. The shortest overload, considered in tables comprised by related standards, lasts 30 minutes. Hence, windings' time constant can be disregarded, at all. In steady state, HS temperature of OIPTs with ON (oil natural) cooling type (typical for OIPTs used by distribution utilities), can be calculated according to:

$$\theta_h = \theta_a + \Delta\theta_{or} \cdot \left[\frac{1+R\cdot K^2}{1+R}\right]^x + H\cdot gr\cdot K^y \ , \qquad (2)$$

where: θ_h – HS temperature, θ_a – ambience temperature, $\Delta\theta_{or}$ – top-oil temperature rise, $R = p_{Cun} / p_{Fe}$ – the rate between variant and permanent rated power losses in OIPT, K – loading factor, x – oil exponent, y – windings' exponent. Using coefficient x, non-linearity of heat conductance between oil and ambience is taken into account. Coefficient y corrects non-linearity of heat conductance between windings and oil.

Applied thermal models

Thermal model applied for developed device for OIPT's thermal image recording, proposed in this paper, are shown in Fig. 1. It is used for HS temperature calculations, according to [4], valid at the time of development work, but it could be easily adapted to [5]. The temperature of OIPT's HS is determined based on measurings of oil temperature (θ_{oil}) and effective values of current in all three phases, L1, L2 and L3. Loading factor of OIPT is determined according to:

$$K = \frac{I_{\max}}{I_N} = \frac{\max(I_{L1}, I_{L2}, I_{L3})}{I_N} \ . \qquad (3)$$

where: I_N – rated current of power transformer.
This way, the value of θ_h will be slightly higher than in the case if in (2) the rate with average value of current was taken into account. However, the approach using (3) is more realistic and obtains higher OIPT's protection reliability, by thermal image device use.

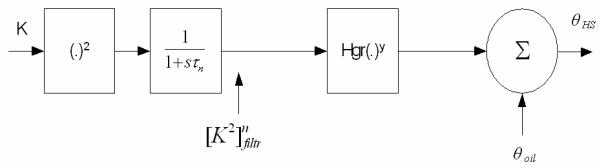

Figure 1. Thermal model applied for hot spot (HS) temperature determination

According to this thermal model, HS temperature of OIPT is determined from:

$$\theta_h(t) = \theta_{oil}(t) + H\cdot gr\cdot\left(\left[K^2\right]^n_{filtr}\right)^y \ . \qquad (4)$$

Thermal model presented in Fig. 2 has been used to determine available time (t_{av}), necessary for OIPT to reach the critical temperature, with assumption that K and θ_a remain unchanged during that period.

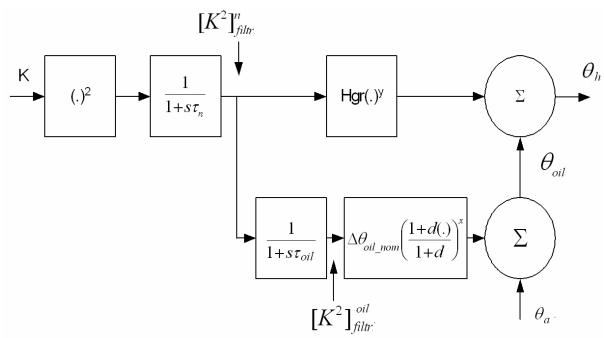

Figure 2. Thermal model for determination of heating time of power transformer

Data about time avaliable for reaching OIPT's critical temperature could be useful for those employees in distribution utilities which are in charge for distribution system management, i.e. networks operation and re-configuration. Necessary conditions are: to obtain these data availability (data delivery in due time) and technical ability for remote control of equipment in SS.
Estimated value of θ_h is used also to determine relative reduction of OIPT's lifetime. Relative velocity of lifetime reduction (*V*) is given with *Montsinger's relation*:

$$V = 2^{\frac{\theta_h + \theta_{h\_nom}}{6}} , \qquad (5)$$

where θ_{h_nom} is HS temperature by nominal load and nominal ambience temperature, θ_{a_nom}. Relative lifetime reduction of OIPT, between moments t_1 and t_2 is given by:

$$L = \int_{t_1}^{t_2} V \cdot dt \ . \qquad (6)$$

PRACTICAL REALIZATION OF DEVICE

Hardware of device for OIPT's thermal image

The structure of realized device for OIPT's thermal image recording can be comprehended from simplified block-scheme, presented in Fig. 3.

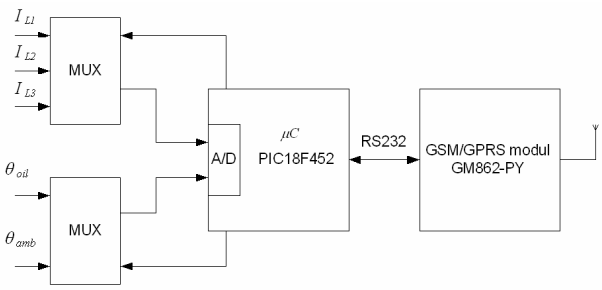

Fig. 3. Block-scheme of device for OIPT's thermal image

As it is possible to see from Fig. 3, the operation of the device is based on the micro-controller (µC) PIC18F452 and GSM/GPRS module GM862-PY. Operation of the device is managed by µC. Each 15 seconds currents in all three phases are measured, as well as ambience temperature and OIPT's oil temperature. Based on these measured data and according to previously elaborated thermal model, HS temperature was determined. It was compared then with pre-defined (by software) critical temperatures and consequent, alternative, decisions were made: forced cooling of OIPT or its switch-off. Measured values of currents in phases, temperatures of ambience and oil can be seen on 7-segmented LED display of the device. Also, µC contains additional informations about OIPT's condition (load, temperatures, relative ageing, set-up parameters for particular OIPT, etc). GSM/GPRS module occasionally (e.g. each 120 seconds), sends the demand to µC for information about OIPT's condition state. After receiving this information, GSM/GPRS module sends it to particular control point.
For oil and ambience temperature measuring platinum resistive sensors Pt 100 were used. Standard metereing clasp were applied, supplied with constant voltage. Together with 10-bits A/D converter it allows measuring of temperature with error less than ± 1 %.
Measuring of OIPT's load by phases is realized via built-in current transformers, which secondary circuits were closed with reference resistances. Voltages on them are corresponent with measured currents in phases, respectively. Before A/D conversion these voltages were rectified and filterred by low-passing filter (RC particle), in order to obtain DC voltages, proportional to average values of currents in phases. In the case of slightly distorted currents, these voltages would be quite satisfactory proportional to effective values of load currents. According to performed estimation and experimental check done, relative error by effective currents mesuring were less than ± 3 %. The other measuring and technical characteristics of the device for thermal image are:

- data input of OIPT's parameters via device's tastature,
- supply with network's voltage 220 V±15 %, 50 Hz,
- operational temperature range from 0 ºC to 50 ºC,
- device dimensions: 230 x 160 x 210 mm,
- device weight: 2 kg.

Software of device for OIPT's thermal image

If µC is the basic hardware element of the device for OIPT's thermal image recording, then its software is the key factor of its successful realization and operation. In the model proposed here, the role of software is multiple and significant. The software integrates operation of device's different elements: µC, multiplexer, A/D converter, GSM/CPRS module, tastature, display. Software allows measuring of all necessary physical magnitudes in their ranges, with demanded resolution and accuracy. The software obtains appropriate input and replacement of necessary OIPT's parameters. Measuring results data handling and calculation, according to chosen and elaborated thermal model, are also the result of the software implementation, as well as their visual representation on device's display, and data transmission via GPRS network.
Beside the software development for device for OIPT's thermal image recording, appropriate server's applications are realized too, in order to acquisite and present measuring results.

GPRS-based monitoring of measurement

Relized prototype of device for OIPT's thermal image recording were tested, in laboratory conditions at first.

Those examinations shown that wanted functionality of the device was achieved completely. Real, determined technical characteristics of the device were even better than demanded ones. However, it was necessary to provide prototype's testing under real conditions of its operation, i.e. in some particular SS. In order to achieve permanent, real-time monitoring of this device's operation, a system of remote control and data acquisition via GPRS were designed and realize, too.
For remote control and monitoring via GPRS, a CLIENT-SERVER configuration were used, shown in Fig. 4. Vague number od clients send data to the server, which receives, handles and stores them in appropriate data base. GSM/GPRS module has built-in TCP/IP stack, which allows the approach to Internet. That way, a remote server can be positioned anywhere in the world, where Internet connection is available. On the other hand, if a web-server with appropriate Internet presentation (i.e. web page) is installed on the server, the device's monitoring would be possible from any PC which has the approach to Internet.

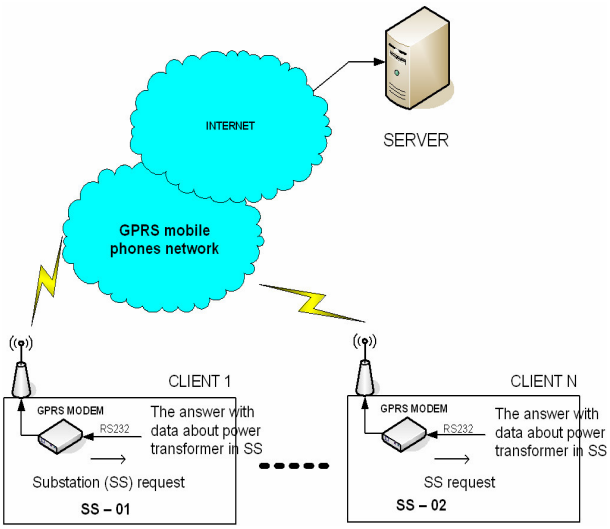

Figure 4. Measuring remote control and monitoring

APPLICATION OF DEVICE TS-02

The prototype of described device was designed and realized by experts of the Institute „Nikola Tesla" in Belgrade, and denoted as TS-02. It was installed in SS 10/0.4 kV/kV No. V-1157, the property of „Elektro-distribucija Beograd", the authorized electrical power distribution utility in serbian capital. This SS supplies one settlement, predominantly with multi-stored buildings. The prototype of described device operated there in real exploitation conditions, more than six months. During that period, the device had no failures nor malfunctions and shown no constructive deficiences. Data about measured values of currents and temperatures were delivered permanently (each two minutes) to the server installed in the Institute „Nikola Tesla", via GPRS. The results were available at Institute's official web site (*www.ieent.org*). As the illustration, one daily report, presenting measuring results, are shown here, in Fig. 5.

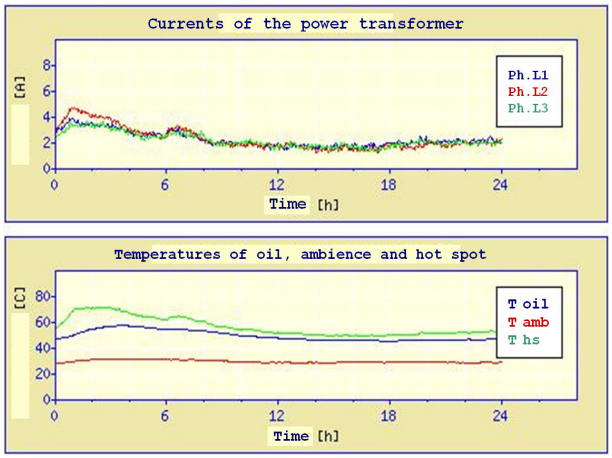

Figure 5. Review of daily measuring results

CONCLUSIONS

New concept of OIPT's overload protection, elaborated here, could be useful for improvement of distribution networks' security and reliability. Proposed, advanced metering infrastructure has been developed as significantly cheaper then other similar systems, and successfuly applied in real-time operation. These facts could contribute to its wider application, not only in classical distribution networks, but also in those with distributed generation (DG), supporting their more extent introduction.

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