THE INFLUENCE OF DIRECT INSOLATION ON OUTDOOR POWER TRANSFORMERS LOADABILITY

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ABSTRACT

This paper presents an evaluation manner of the influence of direct insolation on outdoor power transformers' loadability reduction. Described methodology has been based on experimental results. Namely, to enlighten this topic, during two sunny days in the summer of 2009 the "temperature rise test" was conducted over two power transformers' units, by their local producer. Both units were for 10/0.4 kV voltages, of 400 kVA rated power, placed outdoor, at the same environmental temperature, but one in the shadow, and another exposed to direct sun radiation. The paper presents results of this examination, as well as data about insolation intensity, according to relevant metheorological measurements. Based on data about insolation intensity and the difference of temperature increases for power transformer exposed to sun and another one in the shadow, transformer's coefficient of solar radiation absorption has been calculated. Based on this result and using superposition method, it is possible to calculate additional heating of loaded power transformer, for any date during year. To perform such thermic calculations, neccesary data are those about insolation, environmental temperature, wind, electrical load chart, etc. Methodology of these calculations has been elaborated in the paper, describing the test example mentioned above. The paper emphasizes the result, achieved in test example by using realistic load profile: Maximum of measured difference between top oil temperatures in power transformers exposed to and hidden from sun was 10.2 K, reducing the first transformer's loadability for even 17%.

INTRODUCTION

During summer season, many power transformers are exposed to intensive, direct insolation. On the other hand, in recent years, the use of increasing number of air-conditioning systems during summer, caused growing trend of electrical load. As the consequence, black-outs of power transformers occurred during summer, unprecedented in previous years in Electricity Distribution Company in Serbian capital, Belgrade. Such supply interruptions have been recorded by power transformers 10/0.4 kV of rated power 250 and 400 kVA (installed on poles of overhead networks), as well as by 35/10 kV transformers, of rated power 8 and 12.5 MVA, positioned on the ground.

Power transformers 10/0.4 kV are usually protected from overload by contact thermometer, adjusted to enable transformer's disconnection if its top oil temperature reaches 80 ^{o}C (or 95 ^{o}C, in some cases). Power transformers 35/10 kV of rated power 8 and 12.5 MVA are protected by contact thermometers, overload protection relays, and – additionally, in some cases – by so-called "thermal picture". In IEC recommendations, [1], factors of influence on power transformers' loading calculations are: load intensity, daily load chart (profile) and environment temperature. Intensity of direct solar radiation has not been mentioned at all.

All previous facts led to consideration about necessity for estimation of direct solar radiation influence on power transformers' loadability reduction. That estimation could be done by adequate calculations or experimentally. Therefore, in attempt to enlighten this topic, an experiment of power transformers "heating" by sunlight had been performed.

THE EXPERIMENT DESCRIPTION

Power transformers' temperature rise tests were done during July 23rd and 24th, 2009, in their producer's factory in Mladenovac, small town near the city of Belgrade.

Two electrically unloaded power transformers 10/0.4 kV, each of rated power 400 kVA, have been subjected to this experiment. The environment temperature was the same, both days were cloudless, transformers positioned outdoor, on the ground, but one in the shadow and another exposed directly to sunlight. Both transformers were coloured by grey-blue, oil-based tincture. Their heating was monitored with 23 temperature probes, placed at each transformer according to Figure 1.

Probes 1-20 were installed at ten places in upper and ten places in lower parts of cooling radiators, two probes at upper cover plate and one (No. 21) in the pocket for contact thermometer. Environmental temperature was measured with three additional thermal probes. Measuring results have been shown in Table 1. The marks in it are:

θ_{ru} – average temperature value of upper part of cooling radiator, θ_{rl} – average temperature value of lower part of cooling radiator, θ_p – the temperature in the pocket for contact thermometer. Top oil temperatures, for transformers exposed to and hidden from sunlight are shown in Figure 2. Figure 3 shows their differences: dots present measured-based values, and dashed line – fitted curve.

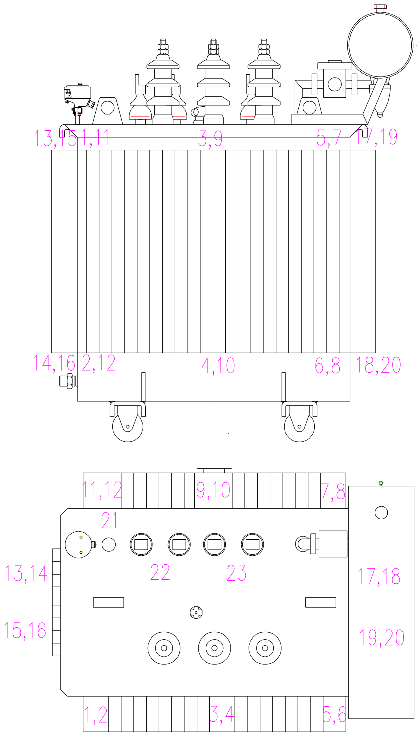


Figure 1 – Positions of 23 temperature measuring points

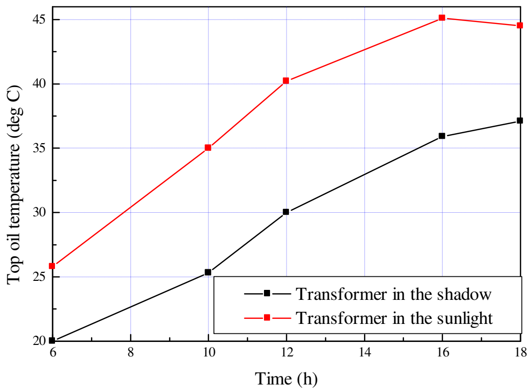
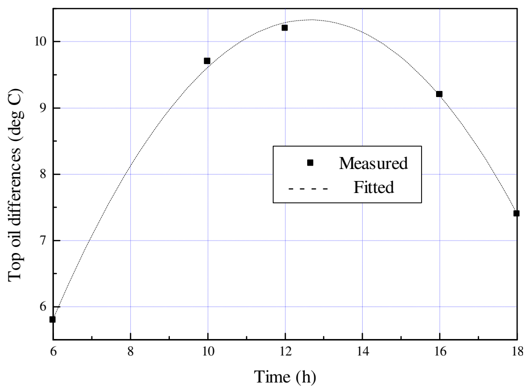


Figure 2 – Top oil leyers' temperatures, July 23rd, 2009



Slika 3 – Top oil temperatures differences, July 23rd, 2009

Table 1 – Transformers' temperature measuring results

	23.07.2009.					24.07.2009.		
°C / h	6	10	12	16	18	8	12	16
Power transformer in the shadow								
θ_{ru}	19.5	25.6	30.4	35.5	37.1	23.3	31.0	32.8
θ_{rl}	18.9	23.0	26.5	32.5	34.8	21.9	28.5	30.8
θ_p	20.0	25.3	30.0	35.9	37.1	22.9	31.5	33.8
Power transformer exposed to sunlight								
θ_{ru}	22.4	35.9	40.2	44.8	43.0	28.9	41.5	43.2
θ_{rl}	22.3	31.0	35.3	40.8	39.7	26.3	36.3	39.5
θ_p	25.8	35.0	40.2	45.1	44.5	28.5	41.2	44.2

Data about environmental temperature, wind velocity and solar radiation intensity, in five-minute resolution, have been obtained from Department for Metheorology of Power Industry od Serbia. They are presented in Fig. 4, 5 and 6. Figures 3 and 6, compared one with another, show that the maximum difference of top oil temperatures of power transformer exposed to and hidden from sunlight responses to the maximum of sun radiation (at 01:00 PM). Maximum of top oil temperature in power transformer in the shadow was reached at 06:00 PM (Fig. 2), after the maximum of environmental temperature, reached at 05:00 PM (Fig. 4). This effect was the consequence of thermal inertion of oil, related to the temperature of environment. Table 1 and Figure 4, compared, shows also that the top oil temperature in the transformer in the shadow was higher than the temperature of environment (measured by Department for Metheorology), in that period of day. This is the result of increased temperature of local environment, at lower level than measured, in metheorological station, and caused by heated ground (concrete surface), under the transformer.

SOLAR RADIATION INFLUENCE ANALYSIS

Maximum temperature increase in the pocket of transformer's contact thermometer

As it can be seen from Table 1 and Figures 2 and 3, maximum difference of oil temperatures in the pockets of transformers exposed to sunlight and in the shadow, was: $\Delta\theta_p$ =10.4 K, July 24th at 04:00 PM, and 10.2 K, July 23rd at noon. Maximum solar radiation intensity at July 24th was P_i = 832 W/m^2, and at July 23rd P_i = 860 W/m^2. As far as both transformers were exposed to the same temperature of environment and same wind velocity, the only cause of temperature increase of transformer exposed to sunlight was the impact of solar radiation. Based on data about temperature increase of transformers's upper cover plate, caused by insolation and its intensity, transformer's coefficient of solar radiation absorption can be calculated:

$$K_a = P_i / \Delta\theta_p \qquad (1)$$

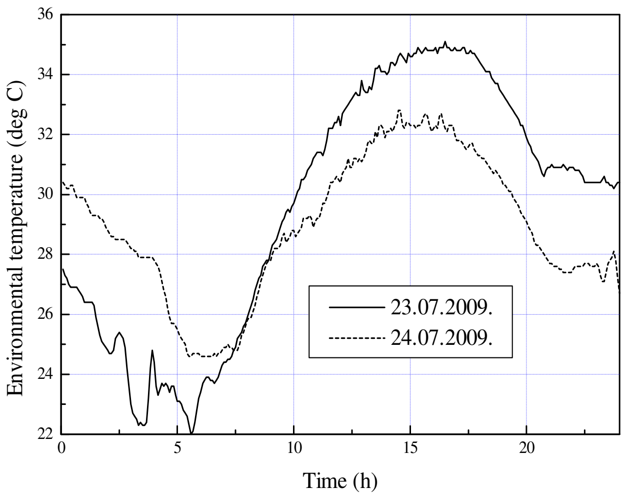


Figure 4 –Environment temperature data

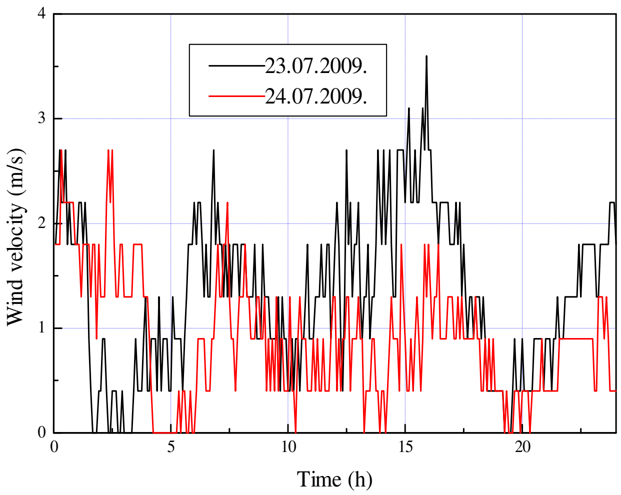


Figure 5 – Wind velocity data

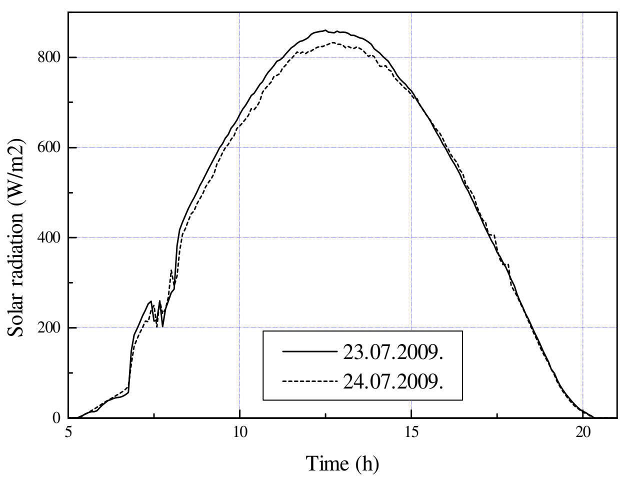


Figure 6 – Solar radiation intensity data

This coefficient's value during the experiment, under its conditions, was between 80.0 and 84.3 W/m^{2}K. Based on it and data about solar radiation intensity at particular day during year, it is possible to calculate additional temperature increase in transformer's pocket with contact thermometer, caused by direct insolation. For example, ten-years-long observation (1972-1981) of metheorological parameters during the peak loads of Electricity Distribution Company Belgrade's integral consumption area, shown that absolute maximum of solar radiation intensity (977 W/m^2) was recorded at June 25th, 1972, but average air temperature (22 ^{o}C) that day was much lower than usual one. Under such conditions, the increase of top oil temperature would be 11.6 – 12.2 K. These values would be much less critical than those calculated for conditions recorded at July 23th, 2009, when average daily air temperature was 29.6 ^{o}C. It is obvious that combined consideration of influences of both environmental temperature and solar radiation on power transformers' loadability, leads to following conclusion: There is a critical combination of these two variables, both values big enough to produce common influence which results in maximum increase of top oil temperature.

Loadability reduction

Assessment of loadability reduction of the transformer exposed to direct insolation, compared with another one in the shadow, was performed using superposition method. It was supposed that both power transformers would be loaded by the same load profile during such experiment. Another presumption was that top oil temperatures within them would be results of superposition of temperature increase, caused by load, on temperatures reached under influences of environmental temperature and solar radiation. Calculations of top oil temperature increase, caused by load, had been conducted according to the model proposed in [1]. By that model, if transformer load profile has been divided on the hourly basis, final top oil temperature increase in the hour *i*, for transformer with cooling type ONAN, would be:

$$\Delta\theta_{ito,i} = \Delta\theta_{iton}\left(\frac{1+RK_i^{\,2}}{1+R}\right)^{0,8} ; \quad i=1,...,24. \qquad (2)$$

Relation (2) shows that $\Delta\theta_{ito,i}$ depends on K_i – relative load of hour *i*, (if it lasts to the infinity), ratio *R* between rated losses in Cu and Fe, $R=P_{Cun}/P_{Fe}$, and $\Delta\theta_{iton}$ – rated top oil temperature increase, according to [1].
If the load during day varies, increase of top oil temperature ($\Delta\theta_{to,i}$) at the end of activity of relative load K_i, will be:

$$\Delta\theta_{to,i} = \Delta\theta_{to,i-1} + \left(\Delta\theta_{ito,i} - \Delta\theta_{to,i-1}\right)\cdot\left(1-e^{-\frac{t}{\tau_o}}\right); \qquad (3)$$

where: i = 1,...,24; $\Delta\theta_{to,i-1}$ – top oil temperature increase during previous hour, (i-1); τ_o – oil's thermal time constant.

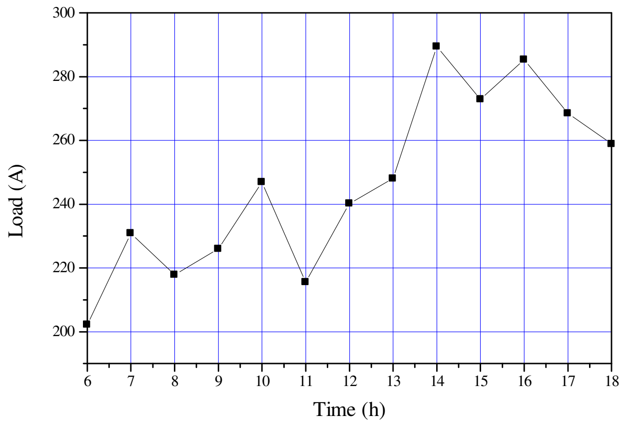


Figure 7 – Real load profile used for calculations

According to data obtained from power transformers' temperature rise test, [2], there are:
$\Delta\theta_{iton}$ = 45.5 K, τ_o = 1.5 h, R = 5.65. Maximum permitted value of $\Delta\theta_{iton}$, according to [3], is 60 K.
Absolute top oil temperature is obtained by summing of environmental temperature ($\theta_{a,i}$), in the hour i, and correspondent top oil temperature increase ($\Delta\theta_{to,i}$), related to $\theta_{a,i}$:

$$\theta_{to,i} = \theta_{a,i} + \Delta\theta_{to,i},\ i = 1,...,24\ . \qquad (4)$$

In (4), as the temperature of local environment, $\theta_{a,i}$, in the case of power transformer in the shadow, we accepted the top oil temperature, heated only by the environmental temperature. In the case of the transformer exposed to direct solar radiation, it would be reached by common influence of environmental temperature and direct insolation. Calculations were performed using realistic load chart, recorded at July 10th, 2007 and shown in Figure 7.
Calculations were done iteratively, by scaling the power transformer's load profile from Figure 7, until the top oil temperature within it, reached the value of 80 °C. The difference between values of relative loads of transformers in the shadow and that one exposed to sunlight, obtained in such manner, is the result of insolation influence, only. As the result of described iterative procedure, it has been obtain that the load limit of power transformer in the shadow is 102 % of its rated power, and for transformer exposed to sunlight – only 85 %. The conclusion was that loadability is reduced, by direct insolation influence, for even 17 %!
Figure 8 presents the charts of top oil temperatures of transformers loaded with load profile from Figure 7, one in the shadow and another exposed to sunlight. The lowest curve in Figure 8 presents top oil temperature increase caused by electrical load.

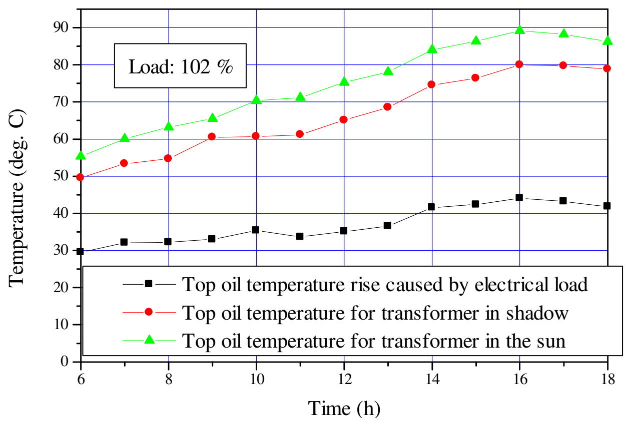


Figure 8 – Final results for top oil temperature

As it can be seen in Figure 8, especially for the transformer exposed to sunlight, greater part of total top oil temperature was caused by atmospheric influences, and lesser part by electrical load. Described calculations were performed also for the case of transformer produced with $\Delta\theta_{iton}$ maximum value, which is 60 K, according to [3]. In that case, maximum permitted relative load of such transformer in the shadow would be 83 %, and 68 % if it would be exposed to direct solar radiation. Therefore, its influence would reduced transformer's loadability for 15 %!

CONCLUSION

Direct solar radiation has great influence on transformer's loadability, especially during months in which it is the most intensive. Testing example, described in this paper, shown that loadability reduction was between 15 and 17 %. Concerning the fact that statistical maximum of solar radiation and statistical maximum of environmental temperature occur in different moments (in Belgrade's area around June 22nd and July 22nd, respectively), there is a critical moment for combined influence of both variables. It can be determined, based on statistics. Unfortunately, complete data set of solar radiation statistics in Belgrade area was unavailable at the time of this paper preparation. Therefore, this part of research remained uncompleted, and left for some other time and future paper.

REFERENCES

[1] *P-IEC 60354 ed2.0 Loading guide for oil-immersed transformers*, 1992, International Electrotechnical Commision.
[2] Z. Stanković, S. Radojević, D. Radić, 2008, *Merenje povišenja temperature distributivnog transformatora EDK 400-10, Technical Report,* Minel-Trafo ABS, Mladenovac, 3-4.
[3] *EN 60076-2 Power transformers, Part 2: Temperature rise*, 1997, CENELEC, 7.