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Thermographic monitoring of the power transformers

Abstract

Results of thermographic monitoring of exemplary power transformers are presented in the paper. Series of thermograms were taken. The areas on the transformer surfaces were analysed for higher temperature in aspects of: the electrical insulation condition of the transformer, the area on the surface, the season of the measurement. The thermograms indicated inefficient cooling for the transformers with deteriorated electrical insulation, especially during the summer season.

Keywords: Transformer, thermography, diagnostics, monitoring, cooling.

1. Introduction

Thermography is very sensitive, efficient and widely applied diagnostic technique [1], [2], [3], [4] which can be used for detection of overheating as well as for precise temperature measurements (under stated conditions). The emittance, the reflected temperature and the transmittance values must be analysed to calculate the temperature [1], [5]. The electrical equipment (motors, generators, transformers) as well as the elements of distribution system (clamps, connections, lines) are frequently diagnosed for the surface temperature [2], [5], [6]. The presence of a “hot spot” on the surface or some element overheating might be evidence of an improper machinery condition, or bad work parameters.

Power transformers are important elements in the distribution system. For this reason, their operating parameters are constantly monitored, in particular current, voltage, the core temperature of the transformer, winding temperature, oil temperature (the liquid is both an electrical insulator and a coolant) [2], [6], [7], [8]. The composition of the gases dissolved in the transformer oil is also monitored, and can be indicative of the machinery overheating [9]. However, the method itself is quite expensive.

Thermography is treated as an advanced diagnostic method for the transformer temperature monitoring [1], [2], [7]. Overheating of surface power transformers might occur due to energy losses or operational conditions which could be treated as faults [1], [10]. An untypical transformer surface overheating or an untypical temperature distribution on the surface might be evidence of the progressive deterioration of the machinery elements (core, winding, connections and clamps) and/or the deterioration of the electrical isolation (paper, oil) [10]. Also, it can be evidence of the improper work conditions (power system conditions that influence the transformer work parameters, improper ambient conditions etc.) [1], [10].

The transformer construction, its condition, or even quality of the electrical energy all have influence on the transformer work and the energy dissipation. Typical power transformer losses can be divided into two main components: no-load losses and load losses. So called “no-load losses” are composed of: hysteresis losses (responsible for more than a half of total no-load losses from 50% to 80%), and eddy current losses thus generating heat (20% to 50 % of total no-load losses). Load losses are composed of: a) Ohmic heat loss (“copper loss”, occurs in transformer windings and is caused by the resistance of the conductor), b) conductor eddy current losses (in the windings), c) auxiliary losses that are caused by using energy to run cooling fans or pumps which help to cool larger transformers. Extra losses due to harmonics and unbalance (voltages or currents) should be also taken into account [1], [10]. The mechanisms and effects of power losses and heat generation for different transformer construction can be found in the literature of the subject [11], [12].

The damage that occurs in the power transformers results from: partial discharges, complete discharges, overheating, damage done to the tap switch, oil contaminants (such as sulphur and fine particles). Electrical insulation materials inside the transformer are: paper, epoxy resin and oil. The electrical insulation condition deteriorates during operation. Paper is quickly degraded. Temperature and humidity exert the most negative influence on the paper insulation. Cellulose fibers are broken down. The degradation of the insulation causes damage to the transformer windings and can lead to short circuits and breakdowns [7].

Constant monitoring of power transformers involves: the temperature measurement of the core, the winding temperature and the oil temperature, measurement of oil humidity, analysis of gasses dissolved in the oil (for example: hydrogen, acetylene, other explosive gases, carbon dioxide, carbon monoxide). The scope of analysis and the frequency of the recording during operation may vary (depending on the device). The oil in the transformer is refilled and can be cleaned (by vacuum treatment) during service inspections. It allows for a removal of most of the water and the dissolved gases from the oil. This action indirectly improves the paper insulation (dehumidification of the paper insulation occurs by removing the water from the transformer oil) [7], [8]. As mentioned above, in addition to water, the second factor causing rapid and irreparable damage to the transformer electrical insulation is the increase in operating temperature [8]. The increase in temperature causes a decrease in the resonance peak in windings of different designs. It means that the overheating of metals but also of insulating oils can affect the condition of the electrical machinery (machinery condition and parameters of transformed energy) [13].

The analysis and experiments on temperature distribution inside the transformers core and the winding, as well as the cooling oil flow confirms that: the coolest should be lowest part of the transformer surface and the hottest should be the upper/ top part of the transformer surface [14]. The surface temperature increase is almost linear. A typical temperature distribution for the oil cooled power transformer was compared to international standards and the computer system (supporting the monitoring and the maintenance of the electrical power machinery). The thermal transformer model was also implemented in accordance with international standards. From the surface temperature the hottest point temperature inside the transformer (in the core or winding) can be predicted, using numerical methods. [8],[14], [15].

The common problems with the power transformers that have been working in Polish distribution system since the 1970s` and 1980s`, under voltage 220 and 400 kV are: overheating and breakdown. Both problems cause degradation in the insulators and the metal elements of the construction (nearest the voltage gap) [16]. As components deteriorate, their resistance increases, causing a local increase in heat. Thermography can detect thermal anomalies of the equipment, caused by many factors [18]. Measurements are usually performed at least every 6 - 12 months [5], [7].

2. Methods

Diagnosed objects

Several transformers have been evaluated at selected high voltage stations. Comparison was made between the arrangements of two transformers constructed by the same manufacturer but different in design. The parameters of the transformers were as shown in Table 1. The transformers vary in production year, degree of exploitation, construction. The power load of the transformer is about 40-50% of the nominal power. This is a typical power load for regular work of the power transformers in the distribution system. The diagnostic instructions and standards also recommend minimum 40% of the nominal power as well as the power level during thermal tests of electrical equipment [1], [6].

Tab. 1. The characteristics of the transformers analysed in the experiment

	Transformer 1.	Transformer 2.	Transformer 3.
winding voltage	220/110 kV	220/110 kV	400/110 kV
winding power	160/160 MVA	160/160 MVA	250/250 MVA
cooling	ONAN/ ONAF	ONAF	ONAN/ ONAF
Time of exploitation	~ 50 years	~ 10 years	~ 40 years

The transformer surface emissivity was tested. Elements analyzed in the experiment are covered with paint. One of the transformers was painted with white matte paint, the others with gray matte paint. The emissivity of the surface covered with white or gray paint was the same as the surface of the known emissivity (black tape). The coefficient ε = 0.96 was used for the thermographic analysis of transformer surfaces. Metal surfaces (for example galvanized surfaces of radiators) were not analyzed for temperature distribution (their emissivity was significantly lower).

Diagnostic procedure

During the investigation the temperature distribution on the surface of a single device was examined. In the course of investigation more than 300 thermograms were made in January 2010, July 2012, August 2016, September 2016 and January 2017. FLIR thermal imaging cameras were used to assess the condition of the devices. Measurements were made with several cameras and their specifications were shown in Table 2. The measurements were taken from different sides of every transformer in order to cover most of the surface and to compare different areas. The distance between the camera and the analysed object varied from 2 to 4 meters.

Tab. 2. The characteristics of the IR cameras used in the experiment

	FLIR InfraCAM SD	FLIR P640	FLIR E50
Spectral range	7.5 - 13 μm	7.5 - 13 μm	7.5 - 13 μm
Detector Type - focal plane array, uncooled microbolometer	120 × 120 pixels	640 × 480 pixels	240 × 180 pixels
Image refresh rate	9 Hz	30 Hz	60 Hz
Thermal sensitivity (N.E.T.D.)	0.12°C, at + 25°C	0.03°C, at + 30°C	0.05°C, at + 30°C
Precision	±2°C	±2°C	±2°C
Temperature range	−10°C to 350°C	−40°C to 500°C	−20°C to 650°C
Operating temperature range (environmental specification)	−15°C to +50°C	−15°C to +50°C	−15°C to +50°C
Time when the equipment was used in the experiment	2010, 2012, 2016, 2017	2016, 2017	2017

In the course of measurements additional information was collected: air temperature, relative humidity (measured with mercury thermometer and hygrometer or "Kestrel" meter). The main meteorological information was as follows: on 06-01-2010 the temperature was 4°C, RH 30%; on 17-07-2012 the temperature was 20°C, RH 90%; on 12-08-2016 the temperature was 15°C, RH 30%; on 27-09-2016 the temperature was 14.5°C, RH 30%; on 19-12-2016 the temperature was 4°C, RH 90%; on 03-01-2017 the temperature was –2°C, RH 30%. During the measurements the sky was overcast, the wind speed being less than 1 m/s (the heat surface loss by the convection was minimal). Also, some other data were collected such as the date and place of measurement, the type of object (device), type of material from which the surface of the object is made, approximate distance between the camera and the object. Additional comments were recorded along with the thermogram data which would affect the subsequent interpretation of the thermograms. Along with the thermograms, photographs of the objects under examination were taken with a digital camera. Records were made as to which photo taken with a digital camera refers to which thermogram number. In order to avoid reflections (or direct sunlight that could disturb thermographic analysis), the summer measurements and the autumn measurements were made at night. The winter measurements were made during a very cloudy day (the winter measurements were not possible at night, because the expected −15°C ambient temperature could be a factor that interfered with the measurement result).

The transformer surface was divided into 3 main segments: "upper part" (4/5 of height), "middle part" (1/2 of height), "lower part" (1/5 of height). For every thermogram the temperature of the visible surface was analysed, and only the maximum temperature was indicated for the distinguished elliptical area (the hot spot of the transformer surface, in three segments: "upper", "middle", "lower part"). The flat areas of the surface were taken under consideration, because the temperature of the pipes or the screws was generally higher than the temperature of the other visible elements.

Each thermogram then underwent processing and was subjected to analysis with the software provided by the camera manufacturer, "FLIR Tools professional". The information entered in the programme, relating to each thermogram, was as follows: air temperature, relative humidity in %, emissivity (ε), distance of the camera from the object. The thermograms analyzed the temperature distribution and it`s maximal value for a given area. In the thermographic analysis, focus was primarily laid upon analysis of hot spots in particular areas. Thermograms were analyzed for updated and outdated transformers with deteriorated insulation. Two transformers were constructed by the same manufacturer but different in design were chosen for statistical comparison analysis. The first transformer was in good condition (about 10 years of operation, some monitoring data did not indicate faults at its work), the other transformer was in a worse condition (about 50 years of operation, some monitoring data indicated errors in operation). For each segment of the transformer surface visible on the thermograms, the maximum temperature (hot spot on the transformer surface) is indicated. The thermograms are divided into 3 groups in order to determine the influence of the season on the temperature: summer, autumn, winter.

The results of the measurements (temperature) were analyzed by means of three-way variance analysis (ANOVA) for the following factors: the seasons ("summer", "autumn", "winter"), the transformer condition ("good" or "deteriorated" electrical insulation) and the transformer's surface segment ("upper", "middle", "lower part") while the changes between the groups were tested "post hoc" by Tukey's test. All statistics were conducted with the use of SigmaStat 3.5 programme (Systat Software Inc. 2006) tools. The results are presented as: the mean ± the standard deviation (*SD*) and the significance level (*P*) considered as "significant" at $P \leq 0.05$, "highly significant" at $P \leq 0.01$. and "very highly significant" at $P \leq 0.001$.

3. Results

The temperature distribution on the transformer tank was analyzed. In all devices under analysis, regardless of the season, the hottest areas were recorded on the upper surfaces of the transformers. Higher temperatures were detected for the transformers working under higher voltage 400/110 kV as compared to the transformers working under 220/110 kV voltage. For two transformers working in parallel under voltage 220/110 kV it was found (Table 3) that the state of the transformer (the condition of the electrical insulation) had a significant influence on the temperature of its surface ($P \le 0.01$). Also, the season had a significant impact on the surface temperature of the transformer ($P \le 0.01$), regardless of its type (condition). The coolest areas (but also with respect to hot spots) were recorded on the lower part of the tank.

Tab. 3. Transformer surface temperature distribution (surface maximum temperature) with reference to: condition, season and the part of the transformer tank

		Summer			Autumn			Winter		
	Part of the trafo tank	mean	*SD*		mean	*SD*		mean	*SD*	
Transformer with deteriorated electrical insulation	upper	51.6	7.65	i,j	62.8	5.20	j,k	46.1	14.27	i
	middle	44.4	0.83	i	50.4	2.14	i	30.9	15.74	f
	lower	46.2	0.06	i	48.1	2.21	i	26.1	17.12	c,d, f
Transformer with good electrical insulation	upper	31.9	1.41	f	33.5	0.98	g	20.3	1.22	h
	middle	23.9	0.50	c	27.2	1.30	d	13.8	3.38	e
	lower	21.2	0.13	b	23.6	1.66	c	6.3	0.99	a

a b c d e f g h i j k - values marked with various letter differ significantly ($P < 0.05$).

For a well- insulated transformer, the lower areas on the surface of the device were cooler. In Table 3 three groups are indicated with different letters ("transformer with good electrical insulation" – "upper", "middle" "lower" part of the tank surface). The coolest areas (also regarding the hot spots) were recorded on the bottom of the tank. In the case of a transformer with good insulation, the biggest differences in temperature were recorded between the upper and lower tank areas (regarding hot spots), which was not affected by season of year and which renders the cooling very efficient.

During the summer, intensive sunshine during the day and a high air humidity both exert a negative impact on the cooling of the transformers. The hot oil floating in the tank of the transformer mostly concentrates at the top of the device [8], [15], where the hottest spots (the temperature maximum) were detected.

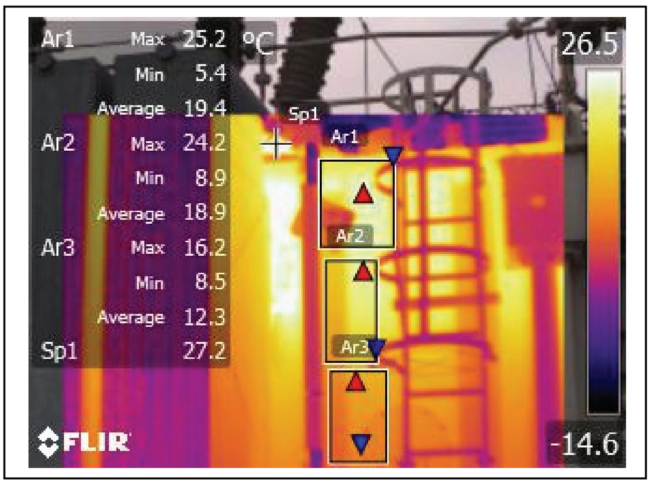

Fig. 1. Thermogram of a power transformer with good electrical insulation (about 10 years of exploitation). The lower parts are usually cooler than the upper parts of the machinery

In the case of a transformer with deteriorated insulation, other tendencies were detected. Hot spots of the upper part of the tank as well as the hot spots of the middle part of the tank sometimes appeared within a similar temperature range to that of the lower part of the tank. The analysis (Table 3.) shows that for the summer measurements there are no differences between the lower, middle and upper parts of the transformer tank. For the autumn and winter measurements there are no differences between the middle and the lower parts of the transformer tank.

In many thermograms, hot spots of higher temperatures were detected in the lower tank areas rather than in the middle parts. These cases pertained to the thermograms made on summer evenings, which could be due to the fact that for many hours during the day the air temperature and humidity were high, which made it much more difficult to cool down. The cooling efficiency of the device was therefore far from satisfactory.

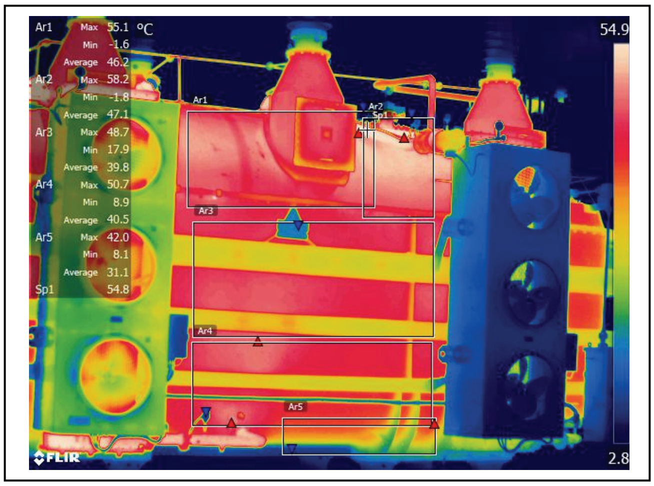

Fig. 2. Thermogram of the power transformer with deteriorated electrical insulation (about 50 years of exploitation). High temperature areas can be seen in the upper, middle and lower parts of the machinery surface

Cooling with the use of a forced oil circuit in combination with a forced air circulation system, with high air temperatures (heatwaves) and high humidity may prove ineffective and cause overheating of a transformer. As a consequence, the insulation conditions deteriorate even further (oil and paper aging occurs) [10], [16]. Also, in the course of analysis of the thermograms for the poorly insulated transformers, the biggest differences were detected between the hot spots at the middle surface and at the bottom of the enclosure during the summer. Depending on external conditions, the transformer surface was subjected to cooling, with cooler parts of the oil flowing down to the bottom of the device. In the case of bad weather conditions (high temperatures during the day, intensive sunshine on the surface, high humidity, no wind), the oil, despite the forced circuit and airflow to the tank, would almost completely not cool down, and, as a result, overheated areas were detected both in the upper, middle and lower parts of the tank.

4. Conclusions

The hottest areas were recorded on the upper surfaces of the transformer tanks.

For a transformer of good condition of electrical insulation, the lower areas on the surface of the device were cooler, but for a transformer with deteriorated electrical insulation the maximum temperatures areas (hot-spots) on any surface could be observed (especially in summer measurements).

5. References

[1] Šebŏk Milan, Gutten Miroslav, Kučera Matej: Diagnostics of electric equipment by means of thermovision. Przegląd Elektrotechniczny (Electrical Review), vol. 87 no. 10/2011 (331-317). http://red.pe.org.pl/articles/2011/10/68.pdf

[2] NETA MTS-2001 Maintenance Testing Specification for Electrical Power Distribution Equipment and Systems, International Electrical Testing Association. www.netaworld.org

[3] Lis Marcin, Augustyn Jacek, Lisowska-Lis Agnieszka, Niedziółka Jerzy. Application of thermography to monitoring of thermoregulation development of chick embryo (Gallus gallus). PAK 2011 no.10 (pp. 1150-1153).

[4] Łapiński Stanisław, Augustyn Jacek, Lis Marcin, Kanik Weronika, Niedbała Piotr, Lisowska-Lis Agnieszka: Changes in domestic rabbit (Oryctolagus cuniculus) thermographic image, depending on its age and physiological condition. PAK 2011 no. 10 (pp. 1154-1156).

[5] ISO 18434-1:2008. Condition monitoring and diagnostics of machines — Thermography .

[6] ASTM E1934-99a(2014), Standard Guide for Examining Electrical and Mechanical Equipment with Infrared Thermography, ASTM International, West Conshohocken, PA, 2014, www.astm.org.

[7] Szymański Z.: Ramowa instrukcja eksploatacji transformatorów. Wyd. Energopomiar-Elektryka. Gliwice 2012.

[8] PN-EN 60076-1:2011E Transformatory -Część 1: Wymagania ogólne, Część 2: Przyrosty temperatury dla transformatorów olejowych. Część 3: Poziomy izolacji, próby wytrzymałości elektrycznej i zewnętrzne odstępy izolacyjne w powietrzu. /Power transformers - Part 1: General; Part 2: Temperature rise for liquid-immersed transformers; Part 3: Insulation levels, dielectric tests and external clearances in air.

[9] C57.130-2015 - IEEE Guide for the Use of Dissolved Gas Analysis Applied to Factory Temperature Rise Tests for the Evaluation of Mineral Oil-Immersed Transformers and Reactors.

[10] Baggini Angelo: Power Transformers - Introduction to measurement of losses (INTAS project). Bergamo, 2016. http://www.intas-testing.eu/storage/app/media/INTAS_trasformers_descr.pdf

[11] Kasikowski Rafał, Gołaszewski Jerzy, Więcek Bogusław, Farrer Mike: Thermal Characterization of High-Frequency Flyback Power Transformer. Measurement Automation Monitoring, Jun. 2015, vol. 61, no. 06 (237-241) - yadda.icm.edu.pl

[12] Więcek Bogusław, De Mey Gilbert, Strąkowska Maria, Chatziathanasiou Vasilis, Gmyrek Zbigniew, Strzelecki Michał, Chatzipanagiotou Panagiotis: Various applications of complex thermal impedance for transient and AC heat transfer analysis. MAM 2015 no. 06 (210-214). http://www.pak.info.pl/index.php?menu=artykulSzczegol&idArtykul=4351

[13] Florkowski Marek, Florkowska Barbara, Furgał Jakub, Pająk Piotr: Influence of temperature on overvoltages in transformer windings. PAK 2013 no. 02(156-160).

[14] Gawliczek Przemysław, Przygrodzki Maksymilian: Practical aspects of selected UHV power transformers operation.www.energetyka.eu (377-382) 2016.

[15] Gościński Przemysław, Dombek Grzegorz, Nadolny Zbigniew, Bródka Bolesław: Obliczenia numeryczne rozkładu temperatury w transformatorze dystrybucyjnym. Przegląd Elektrotechniczny (Electrical Review), vol. 92 no. 10/2016 (46-49).

[16] Partyga Sławomir. Produkcja i eksploatacja transformatorów. Podstawowe maszyny i urządzenia stosowane w elektroenergetyce polskiej (doświadczenia produkcji, eksploatacji, diagnostyki), transformatory - historia, dzień dzisiejszy i przyszłość. www.elektroenergetyka.pl, no. 04/2001 (167- 170). http://elektroenergetyka.pl/upload/file/2001/4/transformatory.pdf

[17] Subocz Jan, Mrozik Andrzej. The use of thermovision measurements for diagnostics of HV transformer bushings PAK 2011 no. 05 (491-495). http://www.pak.info.pl/index.php?menu=artykulSzczegol&idArtykul=2760

[18] Suguna M. Mohamed Mansoor Roomi S., Sanofer I.: Fault localisation of electrical equipment using thermal imaging technique. 2016 International Conference on Emerging Technological Trends (ICETT). http://ieeexplore.ieee.org/document/7873778/

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