Research Article

The Temperature Measurement in a Three-Phase Power Transformer under Different Conditions

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Abstract

Infrared thermography is a powerful non-contact method with the ability to fast inspection of abnormal situations in many electrical systems and equipments. With the aim of a high resolution thermal camera a laboratory power transformer was checked under different scenarios. These scenarios include thermal measurements for 58%, 87% and 116% of rated load conditions, problems in primary or secondary phases and an asymmetric charge. The thermographic system illustrate fast and reliable the changes in the windings of the power transformer.

Keywords: Thermography; Power transformer; temperature measurement.

1. Introduction

Power transformers is one of the most important and expensive elements in power generation and transmission systems. Considering the importance of the power transformers in the electric system their correct functioning or maintenance is vital to system operation. Commonly reasons for failure include external factors such as lightning strikes, short circuits, system overload, and internal factors such as insulation deterioration, winding failure, and overheating. For these reasons fault diagnosis power transformers is necessary. Even though a number of industrial methods exist (Visual Inspection, Insulation Resistance Test, Transformer Turns Ratio Test, Dissolved Gas Analysis, Magnetic Balance Test, Tan Delta Test, Transformer Oil Break Down Test, thermography) both for on-line and off-line monitoring of transformers, most of them are costly and complex [1-3].

Infrared thermography is a non-destructive and visualizing technique which commonly used in preventive maintenance for the advantage of carrying out rapid, precise, and broad area inspections. They can identify heat patterns or temperature changes in materials and structures. With thermography technique, defective parts can be identified through simple observation without disrupting the transformer's operation. According to Mady and Attia [4] the primary reasons for transformer overheating includes excessive transformer loading, excess current in the neutral of the transformer, high harmonic content in the power supply and continued overvoltage for a long period of time. The major goal of this work is to study the thermal behavior of a transformer under different operations conditions. All the measurements realized at the Kavala Institute of Technology in the electrical machine laboratory [5-6].

2. Background of infrared thermography physics

The principle of infrared thermography is based on the fact that any object that has a temperature above absolute zero (-273.15 °C) radiates energy at a wavelength corresponding to its surface temperature. In physics, a blackbody is defined as an object which absorbs all radiation that falls on it at any wavelength. Infrared thermography is the science of transforming infrared measurements to construct a radiometric image. In physics, a blackbody is defined as an object which absorbs all incident radiations it receives whatever the wavelength and re-emits all these absorbed radiations.

Electromagnetic radiation emitted from a blackbody (Wb) can be calculated using Planck’s law, as in Equation (1), where c is the speed of light, h is the Planck’s constant, k is Boltzmann’s constant, T is absolute temperature of the blackbody in Kelvin and λ is wavelength.

\[ W_b = \frac{2\pihc^3}{\lambda^5} \left( e^{\frac{hc}{\lambda kT}} - 1 \right) \cdot 10^{-6} \text{[watt / m}^2 \text{\mu m]} \]  

By integrating Planck’s formula from \( \lambda = 0 \) to \( \lambda = \infty \) it allows calculating the total amount of radiation (Wb) emitted by the blackbody at a certain temperature T (in every direction and over all wavelength)
\[ W_b = \sigma \cdot T^4 \]  

(2)

which states that the total emissive power of a blackbody is proportional to the fourth power of its absolute temperature while \( \sigma \) is the Stefan-Boltzmann constant, equals to \( 5.6704 \times 10^{-8} \) \( \text{W/m}^2\text{K}^4 \).

A more general case is of a non-blackbody emitters for which the emissivity is constant regardless wavelength are called grey bodies. In this case the total amount of radiation emitted by the grey body characterized by its emissivity, \( \varepsilon \) and can be calculated using the Stefan-Boltzmann law:

\[ E = \varepsilon \cdot \sigma \cdot T^4 \]  

(3)

where \( E \) is the electromagnetic radiation (\( \text{W/m}^2 \)), \( \varepsilon \) is the object surface emissivity after transmissivity (\( t \)) and reflectivity (\( \rho \)) are taken into account [7-9].

\[ \varepsilon = 1 - (t \rho) \]  

(4)

3. Case study

The Jenoptik VarioCAM® 7800 thermographic system was used for the purposes of this work. It is a high-resolution, portable, digital color infrared and visual camera with a noncooled Focal Plane Array microbolometer which is used as an infrared radiation sensor. The thermographic system during the measurement has a standard 30mm lens with minimum focus 0.3m IFOV 0.8 mrad and FOV (30×23)° and communicates with the PC via FireWire (IEEE 1394) and is nearly steady after this time. For 58% of rated load the temperature increases slowly during the first 90 minutes and is nearly steady after this time. For 58% load for two hours. Figure 2 illustrates the relevant results. It is clear from the measurements that for 58% load the temperature increases slowly during the first 90 minutes and is nearly steady after this time. For 58% of rated load

| Parameter                      | Value                          |
|-------------------------------|--------------------------------|
| Spectral range                | 7.5 – 14 \( \mu \)m            |
| Resolution                    | 640 \times 480 pixels (resolution enhancement onto 1280 \times 960 pixels) |
| Temperature measuring range   | -40 – 1200 °C                  |
| Temperature resolution at 30°C| Better than 0.08 K             |
| Measurement accuracy           | \pm 1.5 K (0 – 100 °C), ± 2% (< 0 and >100 °C) |
| Emissivity                    | Adjustable from 0.1 to 1, in increments of 0.01 |
| Spatial resolution/IFOV       | 0.8 mrad                       |
| Field of view/FOV             | 30° (H) \times 23° (V)         |

In this article a 3-phase, 2 kVA transformer (Terco MV 1972) with E-type core was used (Figure 1). Table-2 provides the specifications of the transformer. The necessary load was supplied by the Terco MV 1100 load resistor which contains three ganged resistors with continuous spindle regulation. The current in the resistor is limited by tubular wire fuses in each phase. Last but not least the Terco MV 1300 power pack, which is suitable for laboratory experiments, was used as power supply unit. All outputs are fused by MCB’s and have load switches. The Power Pack has also Earth Leagues Circuit Breaker (ELCB). The technical specifications both for load and power supply unit era also presented in Table 2 while the Figure 1 is a picture of the experimental test bed [12].

### Table 2. Specifications of the used electrical equipment

| MV 1100 Load Resistor | MV 1972 Transformer 3-phase |
|-----------------------|-----------------------------|
| **Type**               | **Type**                    |
| 3-phase 3.3 kW,       | MV 1300-405 Supply voltage |
| continuously adjustable| 380-400 / 220-230 V 50 / 60 Hz 3-ph. |
| Star connection       | DC fixed 220 V 3.5 A        |
| 400/230 V 0.8 - 5 A   | DC variable 0-220V 16A     |
| Star connection       | AC fixed 230/133V 10A 3-ph |
| 230/133 V 0.5-5 A     | AC variable 3 x 0-230V, 10A 3-ph |
| Delta connection      |                             |
| 400/230 V 2.4-8.7 A   |                             |
| Delta connection      |                             |
| 230/133 V 1.03 - 8.07 A|                             |
| DC parallel connection|                             |
| 220 V 2.3 \( \varepsilon \sigma \delta \) 15 A |                             |
| Overload capacity, brief duration | approx. 20%. |
| Dimensions            |                             |
| 630 x 250 x 890 mm    |                             |
| Weight                |                             |
| 46 kg                 |                             |

### Terco MV 1300 power supply unit

| Type               | Value                          |
|--------------------|--------------------------------|
| Type               | MV 1300-405 Supply voltage 380-400 / 220-230 V 50 / 60 Hz 3-ph. |
| Primary voltage    | DC fixed 220 V 3.5 A          |
| Secondary voltage  | DC variable 0-220V 16A       |
| Efficiency         | AC fixed 230/133V 10A 3-ph |
| Dimensions         | AC fixed 230V 10A            |
| Weight             | 660x435x790 mm                |
|                    | 103 Kg                        |

### 4 Results and discussion

In order to study the thermal behavior of transformer the Terco MV 1972 was tested under different operations conditions. In the first scenario the transformer was operated at 58% load for two hours. Figure 2 illustrates the relevant results. It is clear from the measurements that for 58% load the temperature increases slowly during the first 90 minutes and is nearly steady after this time. For 58% of rated load
conditions the maximum temperature in the transformer remained in low levels reaching up to approximately 43°C. Figure 3 illustrates the real thermal images for 58% load after 30, 60, 90 and 120 minutes of continues operation.

In the second scenario the rated transformer load was 87% and the relative results are shown in Figure 4. As expected the temperature rise faster and after 2 hours is above than 60°C. In this case the temperature rises rapidly in the first 40 minutes, with slower speed for the next 60 minutes and is almost fixed after 100 minutes continuous operation. The relatively thermographs after 30, 60, 90 and 120 minutes and are given in Figure 5. The third scenario includes the case in which the transformer operates in overload conditions (116% of rated load). As a sequel to this event there is a steep increment in temperature during the first 60 minutes, with lower rates for the next 35 minutes and almost stops to increase after 95 minutes of continuous operations. The maximum temperature is nearly 89.5°C (see Figure 6). Figure 7 provides the thermal images with steps every 30 minutes for total 2 hours operation.
In the last experiment the transformer supplied with unbalanced load in every phase. L1 has 116\% of rated load, L2 has 87\% of rated load and L3 has 58\% of rated load. The real thermal images after 0, 30, 60, 90 and 120 minutes of operation are shown in Figure 10 while the Figure 11 illustrates the results. The difference in temperature between the phases is noticeable instantly. After 1 hour operation L1, L2, and L3 have temperature approximately equal to 70, 53 and 41°C correspondingly while after 2 hours the relevant values are 83, 64, and 51°C. Common deduction in all cases is the ability of the thermal camera to detect very fast the changes on the operation conditions.

The next testing setups comprise theoretical problems in the primary or secondary windings. Specifically for 87\% of rated load conditions after 30 minutes normal operation we cutoff the transformer in L1 phase of the primary windings. Immediately the temperature in the other two phases (L2 and L3) drops down while the temperature in the L1 increases normally. Figure 8 shows the related results. In the next step after again 30 minutes normal operation we cutoff the L3 in the secondary winding. The results were plotted in the Figure 9 and are obvious that the "problem" transpires very quickly.

Fig. 6 The measured temperatures in the 3 phases for 116\% of rated load conditions.

Fig. 7 Thermographs of the transformer after a. 30 minutes, b. 60 minutes, c. 90 minutes and d. 120 minutes for overload (116\%) conditions.

Fig. 8 The measured temperatures with break circuit in the L1 phase on the primary.

Fig. 9 The measured temperatures with break circuit in the L3 phase on the primary.

Fig. 10 The real thermographs in the 3 phases for asymmetric load a. at the begin of the experiment and after b. 30 minutes, c. 60 minutes, d. 90 minutes and e. 120 minutes after continues operation.
5. Conclusions

Power transformers play a vital role in every electric system. Owing to this fact a numerous diagnosis methods have been developed. Infrared thermography is a helpful non-destructive method for the conditioned monitoring and diagnosis of transformers. In this work a small power transformer tested under different scenarios with the aid of a portable and high-resolution infrared thermographic system. In any case the system is suitable to detect rapidly the problems on the transformer operation.

Fig. 11 The measured temperatures in the 3 phases for asymmetric charge (L1 116%, L2 87%, L3 58%).

References

1. Ladani Dhaval H., Sandeep A. Mehta, Pallav Gandhi, “Predictive maintenance and modeling of Transformer”, International Journal of Engineering Trends and Technology (IJETT) 4 (4), (2013), 1186-1189
2. Kudelčík, Jozef, Miroslav Gutten, and Martin Brandt. “Development of electrical breakdown in transformer oil”, Advances in Electrical and Electronic Engineering 5, 1-2 (2011), 277-280.
3. Cabanas M. F., Pedrayes González F., Melero M. G., Rojas García C. H., Oraeco G. A., Cano Rodriguez J. M., & Norniella J. G., “Insulation fault diagnosis in high voltage power transformers by means of leakage flux analysis”, Progress In Electromagnetics Research, 114, (2011), 211-234.
4. Mady Ibrahim, Attia Aman, “Infrared Thermography and Distribution System Maintenance in Alexandria Electricity Distribution Company”, 21st International Conference on Electricity Distribution, Frankfurt, 6-9 June 2011.
5. Bagavathiappan S., Lahiri B. B., Saravanan T., Philip J., & Jayakumar T. “Infrared thermography for condition monitoring— a review”, Infrared Physics & Technology, 60 (2013) 35-55.
6. Chou Ying-Chieh, Yao Leehter. “Automatic diagnostic system of electrical equipment using infrared thermography”. In: Soft Computing and Pattern Recognition, 2009. SOCPAR’09. International Conference of: IEEE, 2009, p. 155-160.
7. Bortoni E. C., Siniscalchi R. T., Jardini J. A., “Hydro generator efficiency assessment using infrared thermal imaging techniques”, In: Power and Energy Society General Meeting, 2010 IEEE, IEEE, 2010, p. 1-6.
8. Barreira E., de Freitas V.P., Delgado J.M.P.Q. and Ramos N.M.M., “Thermography Applications in the Study of Buildings Hygrothermal Behaviour, Infrared Thermography”, Dr. Raghu V Prakash (Ed.), ISBN: 978-953-1-0242-7 (2012).
9. Stipetic S., Kovacic M., Hanic Z., Vrazic M., “Measurement of Excitation Winding Temperature on Synchronous Generator in Rotation Using Infrared Thermography”, IEEE Transactions on Industrial Electronics, 59 (5): 2288-2298 (2012).
10. Fantidis J. G., Karakoulidis K., Lazidis G., Potolias C., Bandekas D. V., “The study of the thermal profile of a three-phase motor under different conditions”, ARPN Journal of Engineering and Applied Sciences, 8 (11): 892 – 899 (2013).
11. Fantidis J. G., Bandekas D. V., Karakoulidis K., Lazidis G., Potolias C., “The temperature measurement of the windings in a three-phase electrical motor under different conditions”, Gazi University Journal of Science Part A: Engineering and Innovation, (2015), 3.2: 39-44.
12. http://www.tercosweden.com (Transmission Line, Transformer & Protection Laboratory)