

APPLICATION OF IR THERMOGRAPHY TO MEASUREMENTS ON SYNCHRONOUS HYDRO-GENERATOR IN ROTATION

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Abstract

Synchronous generator is the most common generator type used in power systems. Modern control and diagnostic systems require information of the excitation winding temperature. This winding is located on the rotor and therefore conventional temperature measurement requires slip-rings or wireless data transfer. IR thermography can be used to obtain average temperature of the surface of excitation winding while rotating and 3D FEM models can give temperature distribution. Laboratory model included synchronous hydro-generator (400 kW), IR thermometer and Bluetooth[®] wireless temperature acquisition system with temperature sensors placed on rotor. Two measurement systems were compared and experimental results are presented.

1. Nomenclature

T_p	-	Absolute temperature of salient pole surface
T_{ip}	-	Absolute temperature of interpolar surface
T_d	-	Absolute temperature measured by IR thermometer
ε_p	-	Emissivity of salient pole surface
ε_{ip}	-	Emissivity of interpolar surface
ε_d	-	Emissivity set on IR thermometer
I_p	-	Irradiance of salient pole surface
I_{ip}	-	Irradiance of interpolar surface
I_d	-	Irradiance read by IR thermometer sensor
S	-	IR target spot size diameter
S_p, S_{ip}	-	Salient pole surface and interpolar surface on annulus defined by radius $R-S/2$ and $R+S/2$ (Fig. 7)
o	-	Ratio of S_p and S_{ip}
D	-	Distance between IR thermometer and object
R	-	Radius of IR thermometer position

2. Introduction

Synchronous generators have an operational limit caused by excitation winding overheating. All operational limits can be seen in the PQ (active-reactive power) diagram shown in Fig. 1. Synchronous generator manufacturers usually define static PQ diagrams by static limits and a static operational area. The manufacturers guarantee safe and permanent operation without failure in the static operational area defined by the static limits. The operational area of a PQ diagram has a certain amount of built-in redundancy. On the other hand, if a machine starts from a cold state, it can operate under an overload during a short period of time until, for example, it reaches its operational temperature. Thus an excitation winding can be overloaded until it reaches its nominal temperature. In that case, a synchronous generator can operate outside of the operational area defined by the static PQ diagram ([7], [9]).

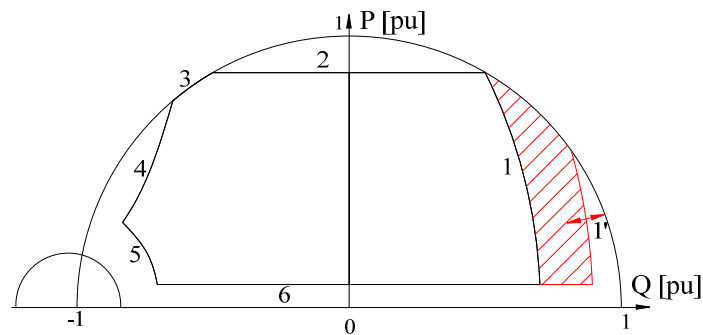


Fig. 1. PQ diagram

Of course, a synchronous generator cannot be overloaded at will, but with respect to temperature, stability etc. It means that short-time overload limits change in time. They are called dynamic limits and a PQ diagram with dynamic limits is called a dynamic PQ diagram. In order to determine the dynamic limit caused by the heating of an excitation winding in a certain moment, it is necessary to have reliable information on the winding temperature (i.e. maximum temperature of copper and insulation of the excitation winding).

Modern diagnostic systems for synchronous generators include advanced temperature monitoring, both on stator (armature winding) and rotor (excitation winding). Also, both active electromagnetic and constructive parts are monitored. Type of conductor isolation is divided in classes (A to F), and for every class, maximum allowed temperature is given.

An IR thermometer can be used to measure average surface temperature. Key value is the temperature on isolation-conductor contact, because heat is generated in conductors due to the Joule's losses. 3D finite element model would give temperature distribution on rotor if geometry, materials, and total heat power is known ([3], [4], [5], [6], [7], [8]).

3. Idea

Temperature measurements on excitation winding of the generator are problematic for several reasons. Wired transfer of measured signals is not possible due to the rotation and U-I (voltage-current) method requires calculation and is therefore inadequate for "on-line" information and sometimes not applicable. In case of wireless transfer of signals from rotor to outside system, adequate mechanical fixation of probes must be assured and acquisition system must be placed on rotor. An IR thermometer can be used to determine average temperature of excitation winding front surface with certain facts and phenomena taken into account. The IR thermometer used for the measurement (Fig. 2) is an industrial sensor with a thermopile detector. The specifications are listed in Table 1.

Table 1. Technical Specifications of IR thermometer

Temperature range	-18 to 500 °C
Optical resolution (90 %), D/S	15:1
Spectral response	8 to 14 μm
Accuracy	$\pm 1\%$ of reading or ± 1.4 °C, whichever is greater
Repeatability	$\pm 0.5\%$ of reading or ± 0.7 °C, whichever is greater
Detector	Micro machined thermopile
Response time (95 %)	165 ms
Temperature resolution	0.1 K



Fig. 2. IR thermometer

4. IR Measurement in rotation

Several facts have to be considered when measuring the surface temperature of an excitation winding in rotation (Fig. 3). Due to the high emissivity of the observed surfaces, low ambient temperature and clear atmosphere, the reflected radiation and atmospheric absorption are neglected in order to simplify the mathematical model of a thermometer ([1], [2]). Further analysis is carried out with the assumption that the IR thermometer is pointed perpendicularly on the surface of a pole (parallel to the machine's axis).

The observer (IR thermometer) distinguishes two different surfaces in terms of infrared radiation: an excitation winding placed on a salient pole and an interpolar surface (Fig. 4). The space between the salient poles can include mechanical elements for the fixation of the salient poles and winding or it is practically hollow and the device "sees" the generator housing plate on the other side (Fig. 4, Fig. 6). Due to the rotation, the IR thermometer absorbs thermal radiation from the excitation winding on the salient pole and from the interpolar space as well (Fig. 3, Fig. 4).

The temperature measured by the IR thermometer depends on rotation speed and response time of a thermopile detector because temperature and emissivity of an excitation winding surface and interpolar surface are not equal in general. If detector response time is rather fast with respect to rotation speed, the thermopile detector can distinguish irradiation from the pole and interpolar space and one can see a change in the output temperature. On the contrary, if the detector is slow with respect to rotational speed, it reads the average irradiance of a rotor. The observed generator has the nominal speed of 1000 rpm (50 Hz, 6 poles). One pair of the pole and interpolar space takes 10 ms to pass in front of the thermometer, and during the response time of 155 ms the rotor makes 2.5 turns. The detector is slow with respect to rotational speed and the following equation can be set for a simplified model of the infrared thermometer:

$$I_d = \frac{I_p \cdot S_p + I_{ip} \cdot S_{ip}}{S_p + S_{ip}} = \frac{I_p \cdot o + I_{ip}}{o + 1} \quad (1)$$

Ratio o can be determined from the geometry of the rotor by a known distance D and radius R . It is different for every machine and a position of the IR thermometer. Applying Stefan-Boltzmann's law on Eq. (1) gives:

$$\varepsilon_d \sigma T_d^4 = \frac{\varepsilon_p \sigma T_p^4 \cdot o + \varepsilon_{ip} \sigma T_{ip}^4}{o + 1} \quad (2)$$

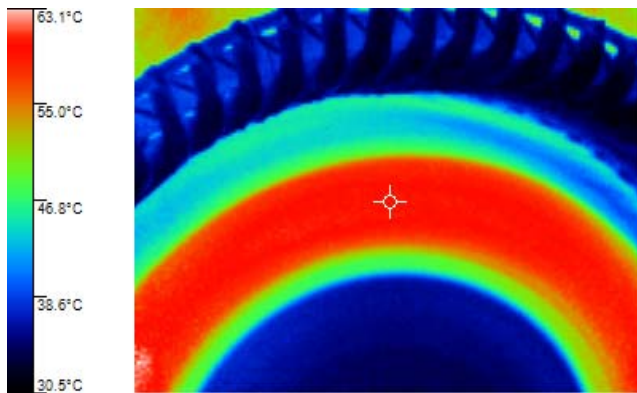


Fig. 3. Thermal image of excitation winding in rotation

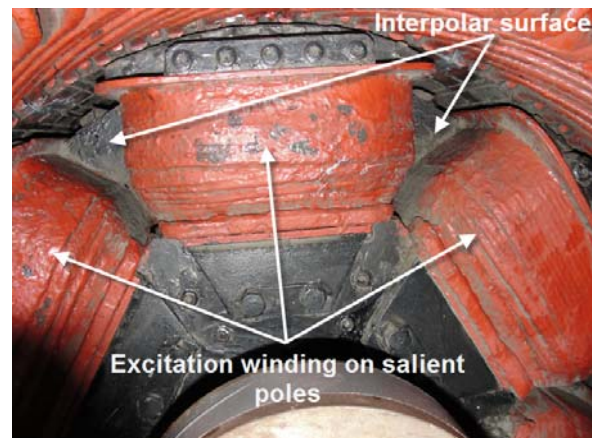


Fig. 4. View on the rotor of the observed generator

The temperature measured by the infrared thermometer is given by Eq. (3).

$$T_d = \sqrt[4]{\frac{\varepsilon_p T_p^4 \cdot o + \varepsilon_{ip} T_{ip}^4}{\varepsilon_d (o + 1)}} \quad (3)$$

It is a function of the emissivity and temperature of the pole surface and interpolar surface and ratio o . Particular attention has to be paid for setting the device emissivity. For a given generator (known o) it is relatively easy to determine the emissivity for the pole surface and interpolar surface when the rotor is in a standstill with the use of the conventional temperature measurement. As the excitation winding heats, its temperature in general differs from the temperature of the interpolar space. The IR thermometer will measure temperature according to Eq. (3), but the aim is to measure the pole temperature correctly ($T_d = T_p$).

For a certain range of pole and interpolar space temperatures, the device emissivity can be set to minimize the difference between the pole temperature and the temperature measured by the IR thermometer. In any case, for ensuring the correct pole temperature measurement by the IR thermometer, the effect of term $\epsilon_{ip}T_{ip}^4$ in Eq. (4) must be somehow cancelled or substantially reduced.

Equation (3) can be rewritten as:

$$T_d = \sqrt[4]{\frac{\epsilon_p T_p^4 + \frac{\epsilon_{ip} T_{ip}^4}{o}}{\epsilon_d (1 + \frac{1}{o})}} \tag{4}$$

Some terms in Eq. (4) can be neglected for large ratio o . In that case, by setting device emissivity equal as pole emissivity we get:

$$T_d = \sqrt[4]{\frac{\epsilon_p T_p^4 + \frac{\epsilon_{ip} T_{ip}^4}{o}}{\epsilon_d (1 + \frac{1}{o})}} = \sqrt[4]{\frac{\epsilon_p T_p^4 + \frac{\epsilon_{ip} T_{ip}^4}{o}}{\epsilon_p (1 + \frac{1}{o})}} = T_p \tag{5}$$

By introducing difference between pole surface temperature and temperature space ΔT_p , measurement error ΔT can be expressed as:

$$\Delta T = T_p - T_d = T_p - \sqrt[4]{\frac{\epsilon_p T_p^4 \cdot o + \epsilon_{ip} (T_p + \Delta T_p)^4}{\epsilon_d (o + 1)}} \tag{6}$$

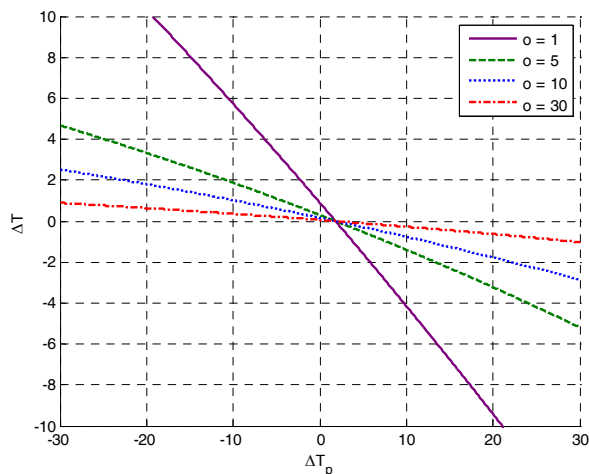


Fig. 5. Measurement error for various o and ΔT_p ($\epsilon_{ip} = 0.9$, $\epsilon_p = \epsilon_d = 0.93$, $T_d = 333$ K (60 °C))



Fig. 6. View on the rotor of the generator in Hydro Power Plant HE "Vinodol" ($o = 40$)

Measurement error depends on emissivity values, parameter o , pole temperature and temperature difference between pole and interpolar space. Figure 5 shows measurement error in dependence on temperature difference ΔT_p , for different ratio o .

For most hydro-generators (slower than 500 rpm), parameter o is significant (30 or higher), therefore the effect of irradiation radiated from the interpolar space can be neglected as shown on Fig. 5. Excitation winding of such generator is shown on Fig. 6.

The o parameter can be artificially increased even for generators with substantially low o because IR thermometer can be positioned in the way that it "sees" only pole surface but never the interpolar surface. Lambert's law states that irradiance of a flat surface is same in all directions. The effect of irradiation radiated from the interpolar space can be disregarded if the IR thermometer is pointed to the excitation winding by a certain angle with respect to the excitation winding

surface normal. In that case the IR thermometer reads only the irradiance of the excitation winding pole surface because due to geometry and rotation, the interpolar surface cannot radiate towards the thermometer.

The temperature of the excitation winding surface on the salient pole sides differs from the temperature on the frontal surface because of the different ventilation conditions, but the difference is negligible, especially in case of forced air cooling. The emissivity of the surface varies according to the angle of observation, but does not change significantly for the angles between 0° and 45° . Emissivity for a certain angle of view can be determined when a rotor is in a standstill.

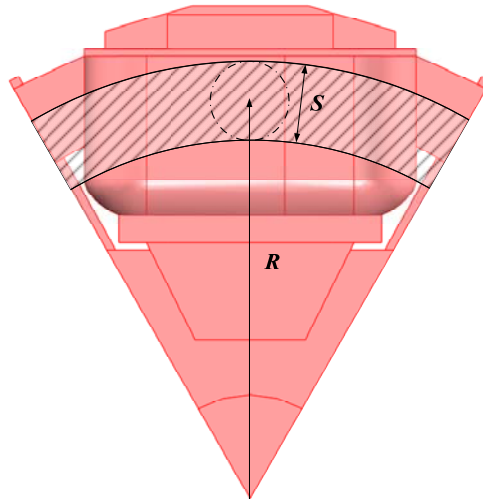


Fig. 7. Definition of radius R and spot size S . Hatched area is observed by IR thermometer in rotation

5. Alternative (referent) system

The wireless acquisition system was developed at our Department and it can be used for achieving “on-line” data of the excitation winding surface temperature even during rotation. It uses modified, high precision digital temperature probes DS18S20, connected by the 1-Wire[®] interface to the Bluetooth[®] module. 26 probes were mounted on the excitation winding surface with special thermal conductive epoxy metal glue which assures accuracy, mechanical fixation and a small time constant of the probes themselves. The system was thoroughly tested and the methodology for preparation, wiring and mounting of DS probes has been determined. The obtained results were compared to the readings from class A Pt1000 probes (generally used in electrical machinery design). Excellent matching was determined, both in a steady-state and dynamics. This wireless system was used to verify the IR temperature measurements. The accuracy of the digital probes is $\pm 0.5^\circ\text{C}$ ([8]).

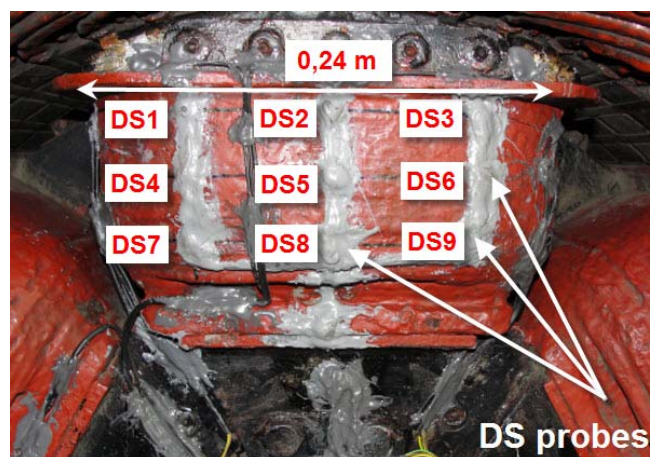


Fig. 8. DS probes mounted on excitation winding

6. Experiment

The experimental model included a synchronous hydro-generator (400 kVA, 400 V, 1000 rpm) with 25 DS probes mounted on one salient pole and 1 DS probe mounted on the adjacent control pole. Power generating unit of respectable power like this one, not commonly seen in electric machinery laboratories, can be found in small hydro power plants.

The experiments included heating and cooling of the excitation winding in a standstill and in rotation with various positions and a setup of the IR thermometer (angle, distance and emissivity). The emissivity for a certain angle has been determined when the rotor was in a standstill. Readings from the IR thermometer have been compared to the average readings of 6 DS probes mounted on the frontal surface of the excitation winding. The following experiments have been conducted (the parameters in Table 2) and the results are presented (Fig. 9 to Fig. 13):

1. Heating of the excitation winding with a constant current (40 A), first in a standstill, afterwards in rotation, which was followed by cooling in rotation.
2. Heating of the excitation winding with a constant current (45 A) during rotation.
3. Heating of the excitation winding with a constant current (40 A), first in a standstill, afterwards in rotation.

Table 2. Parameters of experiments

Experiment Number	1	2	3
Distance (D), cm	37	60	92
Spot size (S), cm	2.5	4	6
Angle, °	45	45	0
Emissivity	0.94	0.93	0.94

The results of the experiments which involved measurement in a standstill and in rotation are shown in the two figures. In the first figure, the infrared thermometer reading is compared with the reading of the DS5 probe (the central probe, nearest to the thermometer spot position). In the second figure, the infrared thermometer reading is compared with the average reading of the 6 frontal probes (DS4 to DS9) placed on the spot trace. The temperature difference at the start of rotation must not be considered due to the time constant of the DS probes. Namely, the surface temperature of the excitation winding decreases immediately with the start of rotation because of increased convective heat transfer. The temperature of the sensor in the DS probes lags a certain amount of time due to the nature and encapsulation of the sensor.

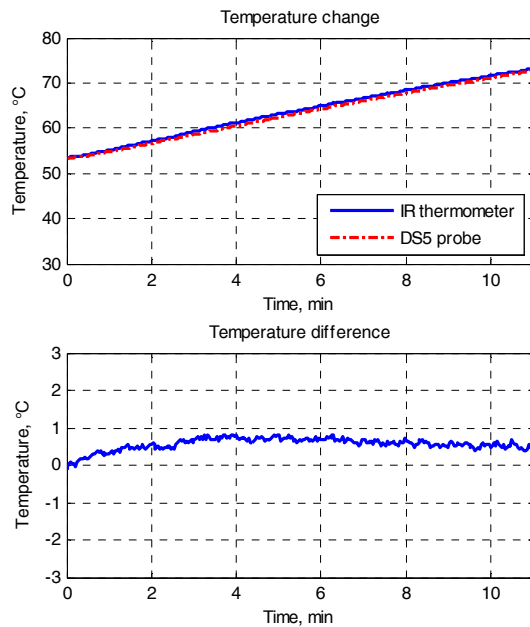


Fig. 9. Heating in a standstill, experiment 1

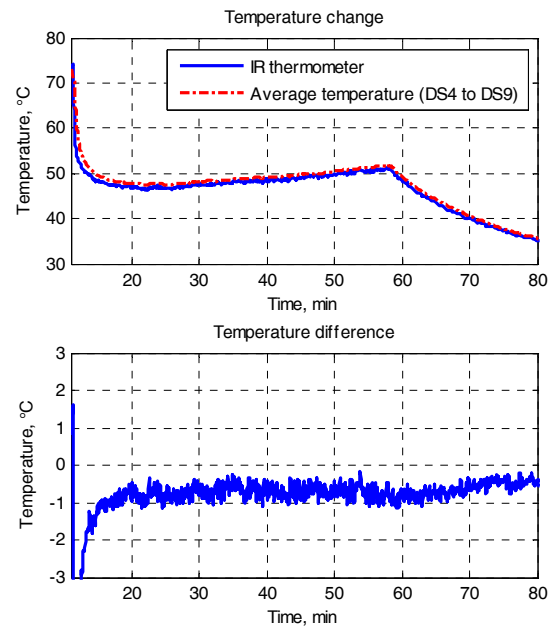


Fig. 10. Heating and cooling in rotation, experiment 1

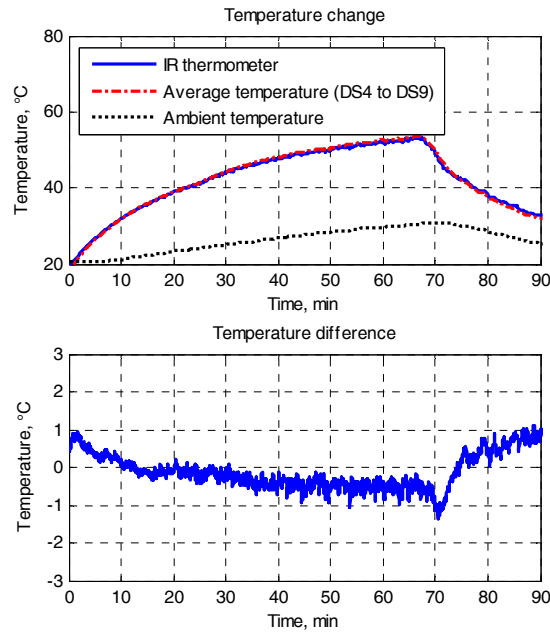


Fig. 11. Heating and cooling in rotation, experiment 2

The accuracy of the measurement system (IR thermometer + wireless data acquisition system with DS probes) can be roughly estimated to ± 2 °C.

The first experiment (Fig. 9, Fig. 10) shows a very good match in a standstill as well as in rotation with a temperature difference smaller than the accuracy of the IR thermometer and the measurement system itself. As it has been said previously, a major difference in temperature reading in rotation was caused by the different time constant between the thermopile device and the DS probe.

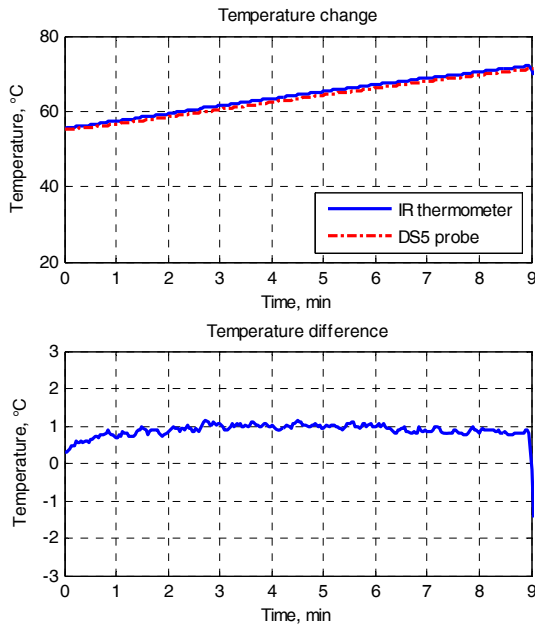


Fig. 12. Heating in a standstill, experiment 3

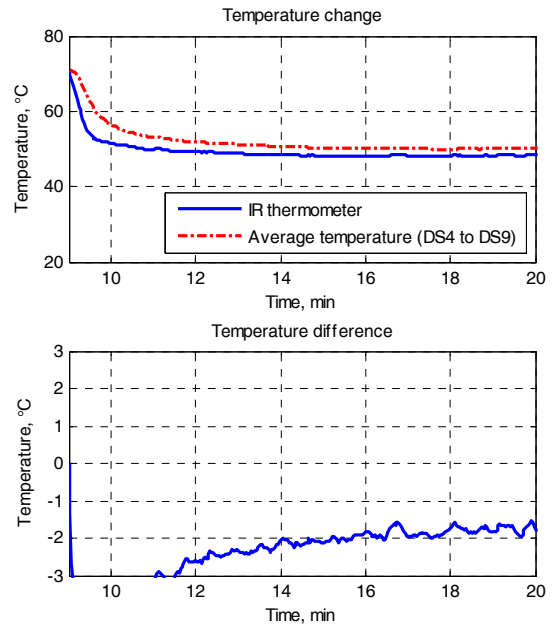


Fig. 13. Cooling in rotation, experiment 3

The second experiment (Fig. 11) shows an excellent match in rotation. The IR thermometer was placed on a larger distance than in the previous experiment, which leads to an increased spot size. Both the distance and spot size define an amount surface area viewed at a certain angle, so the calibration of emissivity for this experiment resulted in a slightly different emissivity factor, 0.93. Ambient temperature (reference temperature of the IR thermometer) is also shown on the graph. The temperature difference is again smaller than the accuracy of the IR thermometer.

The third experiment (Fig. 12, Fig. 13) shows how even frontal placement of the IR thermometer can result in satisfactory accuracy. The spot was larger, due to a larger distance, and the radius of the IR thermometer position was carefully chosen to minimize the interpolar effect. The temperature difference also tends to be smaller due to slow equalization of the pole and interpolar temperature.

7. Conclusion

This paper presents the analysis of the method of surface temperature measurement on an object in rotation (e.g. an excitation winding of a synchronous hydro-generator) with the use of the industrial IR thermometer. As the mathematical model shows, the correct temperature reading will be obtained if the effect of the interpolar space on irradiation can be neglected. This can be achieved by choosing a favorable point of view of the IR thermometer. The accuracy of such measurement system is satisfactory for its targeted application (determination of the dynamic limit in the P-Q diagram of a synchronous generator).

This methodology will be used on synchronous generators (31.5 MW) in hydro power plant HE "Vinodol" for measuring average heating of excitation winding. A hole in the generator housing plate has already been drilled for placement of IR thermometer. Measurements will be used as an input to complex data acquisition system for creating the actual P-Q diagram of a synchronous machine.

REFERENCES

- [1] W. Minkina, S. Dudzik, "Infrared Thermography: Errors and Uncertainties", New York: Wiley, 2009
- [2] X. Maldague, "Theory and practice of infrared technology for non-destructive testing", John Wiley and Sons Inc, New York, 2001.
- [3] Shanel, M.; Pickering, S.J.; Lampard, D.; "Conjugate heat transfer analysis of a salient pole rotor in an air cooled synchronous generator", Electric Machines and Drives Conference, 2003. IEMDC'03. IEEE, International, Volume: 2 1-4 June 2003, Page(s): 737- 741 vol. 2
- [4] Traxler-Samek, G.; Zickermann, R.; Schwery, A.; "Advanced Calculation of Temperature Rises in Large Air-Cooled Hydro-Generators", International Conference on Electrical Machines, ICEM, 6-9 Sept. 2008 Page(s): 1- 6
- [5] Aglén, O., Andersson, A.; "Thermal analysis of a high-speed generator", Conference Record of the IEEE Industry Applications Conference 2003, vol. 1, pages 547-554
- [6] M. Moria, L. Novaka and M. Sekavcnik, "Measurements on rotating blades using IR thermography", Experimental Thermal and Fluid Science Volume 32, Issue 2, November 2007, Pages 387-396
- [7] M. Vražić, I. Gašparac, M. Pavlica, "Some Problems of Synchronous Hydro-Generator Temperature Measurement"; A.P.D.E.E. 2008, Coimbra, Portugal, Page(s): 1-4, September 2008
- [8] M. Vražić, S. Stipetić, M. Kutija, "Methodology of verifying IR temperature measurement on synchronous generator in rotation", EDPE 2009, Dubrovnik, Croatia
- [9] I. Ilić, Z. Maljković, I. Gašparac, M. Pavlica, D. Ilić-Zubović, V. Jarić, A. Višković, R. Belobrajčić, "Methodology for Determining the Actual PQ Diagram of a Hydrogenerators" Journal of Energy, Vol.56 No.2 pp. 141 - 181, February 2007