IMPROVED HYDROGENERATOR ROTOR THERMAL SUPERVISION

PS 2: Developments in condition monitoring, diagnosis, prognosis to improve reliability and extend operational life of conventional plant, including data handling and digital modelling

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The ongoing energy transition to cleaner energy involves three main changes: using less energy (energy savings on the demand side), making energy production more efficient, and using renewable and low-carbon sources instead of fossil fuels. However, relying more on intermittent renewable energy sources means we need to balance them with conventional sources for a stable electricity supply. Hydrogenerators can provide this stability, but also flexibility, by quickly increasing power when needed. They are designed for a daily average number of start-stop cycles equal to twice per day. On the other hand, they will face new challenges, as they were not designed for frequent and large load changes, which will put additional stress to the hydrogenerator parts.

The continuous, safe, and reliable operation of the hydrogenator is determined by the boundaries of the capability curve (active-reactive power PQ diagram) provided by the generator manufacturer. Most of the limitations given in the PQ diagram are isotherms indicating permitted temperatures of certain generator parts. In the inductive region, the predominant limitation is on the rotor current. If we wish to use the hydrogenerator as a flexible power source and maximize its available capacities, it is crucial to know the rotor temperature. Unfortunately, temperature sensors are not typically installed on the rotor due to its rotation and various associated issues, such as problems with the proper installation of temperature sensors because of large centrifugal forces and strong electromagnetic fields that affect them, issues with the power supply of the measuring system, and difficulties with data transmission from transmitters mounted on the rotating rotor.

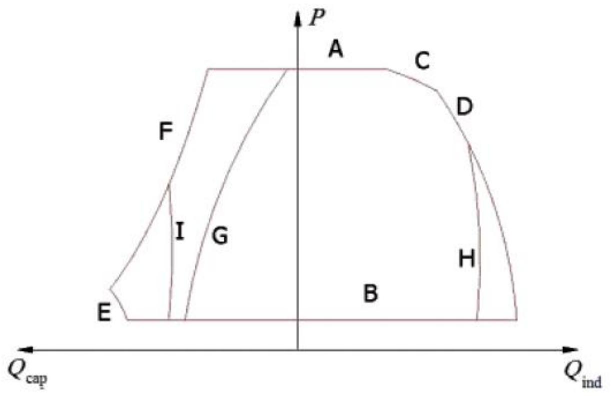
To ensure the safe operation of the hydrogenator, the field (rotor) winding temperature should be monitored. The field winding temperature can be determined either indirectly or by direct measurements. The indirect method is widely used and is based on measurements of the field winding resistance, as specified in relevant standards. It is relatively easy to apply, but the following should be kept in mind: it requires precise measurements of the rotor voltage and current, which can be challenging, and provides only information about the average field winding temperature. On the other hand, the direct method requires installation of temperature sensors on rotor parts and provides information about the local temperature of rotor part on which the sensor is mounted. The accuracy of the measurement is highly dependent on the way the temperature sensor is mounted and its position. Specifically, the sensor should be mounted in such a way that it is completely isolated from the cooling medium and at the same time has good thermal contact with the part of the generator which temperature is being measured.

This paper presents a comparison of two independent systems for hydrogenerator rotor thermal supervision, along with their respective advantages and disadvantages. The results of measuring the rotor temperature (both indirect and direct) during the heat run test of a hydrogenator at the hydro power

plant "Pirot" are also given. Models for comparing the two field winding temperature measuring systems are presented with the aim of enhancing the reliability of hydrogenerator rotor thermal supervision. These models can be used for hydrogenerator asset management, planning of near-term and long-term outage activities, improved rotor thermal supervision, and more.

1. INTRODUCTION

The field winding temperature of the synchronous generator represents one of the operating limitations indicated in the PQ diagram of the generator. For that reason, knowing its most accurate value is of extreme importance for safe and reliable operation of generator [1], [2]. The typical PQ diagram of the hydrogenerator (together with turbine and step-up transformer) with all limitations is shown in the Figure 1.



A – maximum generator power,
B – minimum generator power,
C – heating of stator winding,
D – heating of rotor winding,
E – minimum excitation,
F – practical limit of static stability,
G – heating of stator end region,
H – maximum voltage of generator armature,
I – minimum voltage of generator armature

Figure 1. Limits of a PQ diagram of the hydro unit (turbine, generator and step-up transformer)

Even though the thermal stress is one of the most important causes of rotor winding failure, most often rotor is not equipped with temperature sensors. The field winding temperature of synchronous generator can be determined indirectly or measured directly. Indirect method or U-I method implies determination of the field winding temperature through the known change in the field winding resistance. This method is a part of relevant standards and technical practice and therefore is widely used. On the other hand, direct method requires the installation of temperature sensors on parts of the field winding of the hydrogenerator. The direct method is significantly less used because it is associated with numerous problems: the power supply of the measuring system, the choice of position and method of sensor placement, the wireless transmission of measured data from rotating rotor to steady acquisition system, etc [3]. Therefore, both methods have their advantages and disadvantages, and the main difference is that the direct method provides information about the local temperature of a specific rotor part, which is related to the average field winding temperature, which can be determined by the indirect method, through a corresponding linear relationship.
The architecture of the electric power system in the world is changing, with the tendency of increasing participation in the production of renewable energy sources [4]. The consequences of the ongoing energy transition are changes in the way conventional generating units work, and this certainly includes hydrogenerators. Namely, they face new operating modes characterized by an increased number of start-stop cycles, rapid and frequent load changes, etc. These modes of operation lead to increased thermomechanical stress on parts of the hydrogenerator, especially the rotor [5]. In such conditions, knowing the accurate field winding temperature of the hydrogenerator becomes very important from the aspect of knowing the dynamic rotor thermal capacity, thermal monitoring, planning maintenance and estimating the remaining life.

2. METHODS FOR HYDROGENERATOR ROTOR WINDING TEMPERATURE DETERMINATION

Hydrogenerator field winding temperature can be directly measured by placing temperature sensors on parts of the field winding or indirectly estimated based on the known change in field winding resistance (compared to the reference value). Indirect method is relatively easy to apply but it only provides information on the average field winding temperature which can be significantly smaller than the hotspot temperature. The direct method is still expensive, requires installation of additional temperature sensors on rotating rotor and wireless transmission of information about the measured temperatures to an external steady acquisition system. Both methods have their advantages and disadvantages, and the choice of which one to use depends on many factors and the purpose for which the measured field winding temperature is used.

2.1 Indirect method for field winding temperature determination

The indirect method is based on knowing the change in field winding resistance of the hydrogenerator in relation to the reference "cold" state. Since the field winding temperature depends on the field winding resistance, the field winding temperature is determined based on precise field winding voltage and current measurements. The main challenges encountered with this method are:

- The field winding, unlike resistance temperature detectors, is not a temperature-calibrated resistor and is not designed for temperature measurement. Additionaly, the rotor current is not constant and is rich in harmonics.
- Field current is most often available for measurement and measured quite precisely, except for brushless excitation systems. Opposite to the field current, the field voltage is most often measured at the DC side of the excitation system and it is necessary to take into account the voltage drops on the connections from the excitation system to the field winding and on the brushes themselves. This introduces a measurement error that increases as the generator load moves away from the rated operating point. Consequently, an error occurs in the estimation of the field winding temperature.

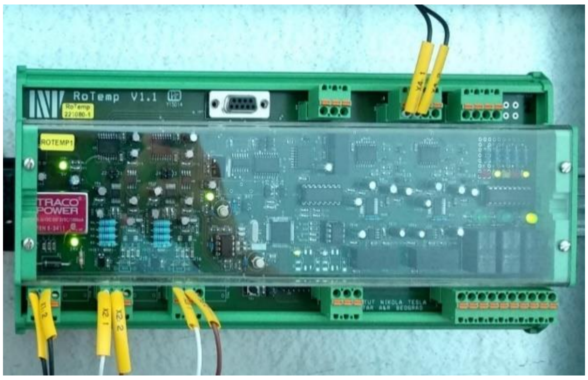
Based on the measured values of field winding voltage and current, and knowing the reference value of the field winding resistance R_{f0} at the reference temperature ϑ_{f0} , the field winding temperature ϑ_f can be calculated using following formula:

$$\vartheta_f = \frac{R_f}{R_{f0}}(\vartheta_{f0} + k) - k \tag{1}$$

where R_f represents the measured field winding ohmic resistance and k coefficient of the material from which the rotor winding is made.

Using the indirect method it is possible to determine only the average field winding temperature of the hydrogenerator, which represents the global thermal image of the entire field winding. It is not possible to determine local temperature values or hotspot temperature which must not be exceeded.

The hydropower plant “Pirot” is equipped with a device for indirect field winding temperature measurement. The operation of the device is based on the precise measurement of the field winding voltage and current, which are achieved using a precise measuring transducers. The Figure 2 shows the device for indirect field winding temperature measurement of the hydrogenator together with the measuring transducers installed within the excitation system at hydropower plant “Pirot”.



(a)

(b)

Figure 2. (a) Device for indirect field winding temperature measurement, (b) Field current and voltage measuring transducers

2.2 Direct method for field winding temperature measurement

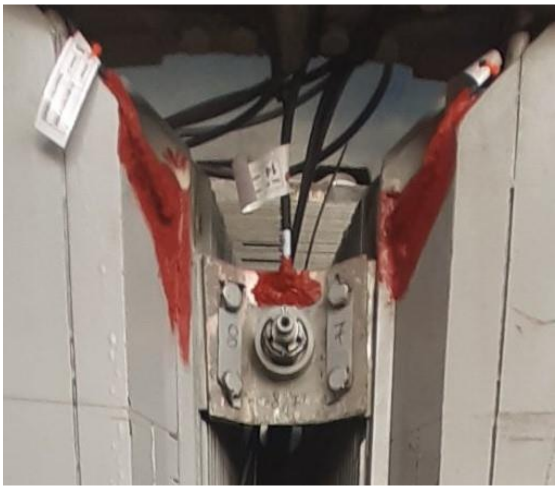
The direct method for field winding temperature measurement is based on temperature sensor measurements which are installed on parts of the field winding of the hydrogenerator. Unlike stator, hydrogenator rotor is not usually equipped with temperature detectors [6]. This method enables to measure local temperatures at the positions where the temperature sensors are installed. In this way, it is possible to monitor the temperature of a certain part of the rotor, to detect malfunction of the cooling system and possible overheating during exploitation of the hydrogenerator. However, special attention should be paid to the way of installation and the selection of the sensor location since they are of utmost importance for the measurement accuracy and usability. Also, another problem is the harsh environment (large centrifugal force, rotating shaft etc.) in which this system must work reliably.

A wireless on-line monitoring system has been installed in the hydropower plant “Pirot” in order to monitor the temperature of all twelve pole-to-pole connections as well as the temperature of the iron poles in the vicinity of the pole-to-pole connections. The system consists of the following elements: rotor processing unit (slave), stator processing unit (master), 48 high-precision digital temperature sensors DS18S20 and other auxiliary elements (junction boxes, connections, power supply, etc.). All measured temperatures enter the rotor processing unit from where are wirelessly transmitted to the stator processing unit located outside the generator pit. The system starts automatically when the hydro unit is started, i.e. immediately after the excitation is switched on, because the entire system is powered from the connections from the excitation system to the rotor winding. The main parameters of the hydrogenator at hydropower plant “Pirot” are shown in Table 1. Figure 3 shows a detail of the installed temperature sensors.

Table 1. Main parameters of the hydrogenerator at HPP “Pirot”

Item	Value
Rated power (MVA)	44,5
Frequency (Hz)	50
Rated line-to-line voltage (V)	10500
Rated current (A)	2447
Rated power factor	0,9
Rated field voltage (V)	223
Rated field current (A)	604
Rated speed (min^{-1})	500
Stator insulation class	F
Rotor insulation class	F

Figure 3. A detail of installed temperature sensors



3. HEAT RUN TEST OF HYDROGENERATOR

The heat run test or temperature rise test is one of the hydrogenerator type tests. During the test the hydrogenerator is connected to the grid and operates at desired active and reactive power that makes generator parts heating. The test is maintained until thermal steady state is reached [7]. The heat run test of hydrogenator at HPP "Pirot" was performed with aim to determine the temperature rise of the hydrogenerator active parts and to check the possible overheating. During the test, the hydrogenerator worked in 6 different operating regimes until the thermal steady state was established and all relevant electrical quantities and hydrogenerator part temperatures were measured simultaneously. Some measured electrical quantities and hydrogenator part temperatures of interest are summarized in the Table 2. Hydrogenerator is equipped with a closed air-cooling system with 6 air coolers distributed symmetrically around the periphery of the stator frame. The cooling air circulation is provided by two axial fans mounted on the bottom and upper side of the rotor. Generated heat from the stator winding and core, and field winding is removed by cooling air and then transferred to the cooling water in the air-to-water heat exchangers.

Table 2. Measured hydrogenerator rotor part temperatures and electrical quantities during the heat run test

Regime no.	ϑ_1 [°C] min/max	ϑ_2 [°C] min/max	ϑ_3 [°C] min/max	ϑ_4 [°C] min/max	ϑ_f [°C]	I_f [A]	ϑ_{ca} [°C]	*P* [MW]	*Q* [MVAr]
1.	43/44	46/48	38/40	42/44	78	384.4	23.00	30	0
2.	48/49	52/54	42/44	47/50	90	450.8	24.50	40	0
3.	52/54	58/60	45/48	52/57	113	604.2	25.30	40	19.4
4.	47/48	51/54	41/44	47/50	97	534.8	23.70	30	14.5
5.	42/44	46/48	38/39	41/44	76	333.2	23.10	30	-5.5
6.	47/49	51/53	42/43	46/49	86	412.2	24.50	40	-4.5

- *ϑ_1-ϑ_4 temperatures obtained from wireless on-line temperature monitoring system, ϑ_f indirectly measured field winding temperature, ϑ_{ca} cold air temperature, I_f field current, P and Q active and reactive power of hydrogenerator, respectively.*

4. COMPARISON OF MEASURED FIELD WINDING TEMPERATURES OBTAINED FROM ON-LINE MONITORING SYSTEM AND FROM DEVICE FOR INDIRECT FIELD WINDING TEMPERATURE MEASUREMENT

By statistical analysis of the measured field winding temperatures, large deviations of the temperatures obtained from wireless on-line temperature monitoring system in relation to the indirectly measured field winding temperature were observed (Table 2). The reason for the large deviation in the measured field winding temperatures between these two independent methods lies in the fact that the temperature sensors are installed in the flow of the cold cooling air and that local cooling is present. Consequently, it was necessary to correct the direct temperature measurements according to the more reliable indirect U-I method.

Analysis of the measured field winding temperatures showed the dependence of the measured temperatures on the square of the rotor current and the cold air temperature. These are quantities that are precisely measured in the power plant anyway. In this way, the problem with inaccurate field voltage measurement was overcome.

The dependence of the measured temperature of temperature sensor within the on-line monitoring system (ϑ_i) as a function of the square of the field current I_f, the cold air temperature ϑ_{ca} and the indirectly measured temperature using U-I method ϑ_f can be expressed as follows:

$$\vartheta_i = \vartheta_f - aI_f^2 - b\vartheta_{ca} \tag{2}$$

where *a* and *b* represent constant coefficients. For each individual group of temperature sensors within the on-line monitoring system (ϑ_1-ϑ_4), the values of the coefficients *a* and *b* were determined using the least squares method [8]:

$$\vartheta_1 = \vartheta_f - 1{,}024 \times 10^{-4} I_f^2 - 0{,}837\vartheta_{ca} \quad (3)$$
$$\vartheta_2 = \vartheta_f - 9{,}337 \times 10^{-5} I_f^2 - 0{,}716\vartheta_{ca} \quad (4)$$
$$\vartheta_3 = \vartheta_f - 1{,}028 \times 10^{-4} I_f^2 - 1{,}042\vartheta_{ca} \quad (5)$$
$$\vartheta_4 = \vartheta_f - 8{,}879 \times 10^{-5} I_f^2 - 0{,}916\vartheta_{ca} \quad (6)$$

Obtained errors are within 1,5°C which is a quite satisfactory value.
In addition to this model, another model was developed that links the measured field winding temperatures obtained from these two independent systems only using the cold air temperature:

$$\vartheta_i = c\vartheta_f + d\vartheta_{ca} \quad (7)$$

where c and d represent constant coefficients. For each individual group of temperature sensors within the on-line monitoring system (ϑ_1-ϑ_4), the values of the coefficients c and d were determined using the least squares method:

$$\vartheta_1 = 0{,}173\vartheta_f + 1{,}349\vartheta_{ca} \quad (8)$$
$$\vartheta_2 = 0{,}245\vartheta_f + 1{,}282\vartheta_{ca} \quad (9)$$
$$\vartheta_3 = 0{,}165\vartheta_f + 1{,}172\vartheta_{ca} \quad (10)$$
$$\vartheta_4 = 0{,}284\vartheta_f + 0{,}978\vartheta_{ca} \quad (11)$$

Obtained errors are less than 1,0°C. This model can be particularly important for generators with brushless exciters where field current measurement is not available.
Developed models can be used for monitoring of direct temperature measurements of installed sensors within the rotor on-line monitoring system and the occurrence of possible increased heating. In this way, the reliability of measurements as well as the rotor thermal supervision of the hydrogenerator is enhanced.

5. CONCLUSION

Direct field winding temperature measurements provide information about the local temperature of the rotor parts where the temperature sensors are mounted. One should be very careful when interpreting them, because the accuracy and reliability of the measurements depend a lot on the sensor position and the way the sensor is mounted. On the other hand, the indirect method which is more reliable and widespread, provides information only about the average field winding temperature. Although it is quite easy to apply, it also has certain drawbacks: dependence on precise measurement of field current and voltage, primarily field voltage. Developed models can be used to calibrate the measured temperatures obtained from the on-line monitoring system based on the average field winding temperature and standard measurements of electrical quantities and temperatures that are available in the power plant. These models can improve temperature monitoring of the hydrogenerator, can be used for predictive maintenance and ultimately increase the reliability of the hydrogenerator.

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