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EXPERIMENTAL INVESTIGATION OVER IN SITE OPERATIONAL CHARACTERISTICS OF A HYDRO GENERATOR

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Any electrical machine, new or refurbished, must be subjected to tests to verify the compliance with technical requirements imposed by standards and, eventually, to determine some experimental data needed for the machine operation. This paper presents in site experimental determination of the operation electrical parameters of the hydro generators that equip a hydropower plant: the active power of the generator, the voltage and stator current, the characteristics and parameters of the system during no load operation and under load operation, and the generators efficiency curves. The results are presented for two of the generators analyzed, one of 26.8 MW and the other of 42.5 MW, at part load operation regimes.

Keywords: experimental investigation, hydro generator, no load operation, under load operation.

1. Introduction

Worldwide, the trend to use renewable sources of energy is observed in order to reduce environment impact. Therefore, major refurbishment activities take place in existing power generation plants, especially in hydropower plants, as hydropower represents the largest renewable source of energy in the world, with about 20% of the electricity production.

Refurbishment or commissioning of hydro units comprise on site efficiency measurement to control the performances claimed by the manufacturer, for the entire operation domain. A major objective of these measurements is to obtain the electrical performances of the machine, so the electrical generator is subjected to tests according to standard procedures [1-3]. The interest of specialists during the last years in generators operation is proved by the large number of papers that treat this topic [4-6].

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The present paper presents the electrical characteristics determination of two synchronous generators, G1 and G2, having the apparent power of 26.8 MW and 42.5 MW, a rated power factor of 0.85 and the rotational speed of 428 rot/min and 300 rot/min. They equip a hydropower plant that will start a refurbishment process. The aim of the analysis is to establish the actual state of the two electrical machines at part load operation regimes.

2. Theoretical Aspects

The operation of synchronous generators is described by the following characteristics: open circuit characteristic, short-circuit characteristic, "V" characteristics, external and control characteristics. In this paper the open circuit characteristic, the "V" characteristic and the efficiency characteristics are determined by in site measurements and discussed.

A. Open circuit Characteristic

The open circuit characteristic represents the relation $U_0=f(I_{ex})$ *for* n = ct. (f = ct.) *and* I = 0 A, where U_0 is the generator voltage during no load operation [4, 5].

As the electric current is zero during no load operation (I=0), the generator voltage will be equal to the internal generated voltage U_e, induced by the excitation flux Φ_p determined by the rotor winding current I_{ex}.

In the phase diagram, the internal generated voltage lies behind the excitation flux, therefore behind the excitation current with $\pi/2$ (Fig. 1).

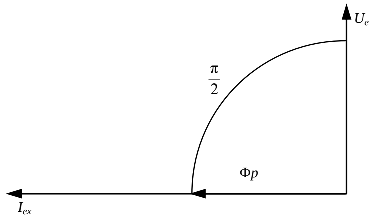


Fig. 1. Phasor diagram of the synchronous generator no load operation regime

B. "V" Characteristic

The synchronous generator "V" characteristics can be obtained when the generator is operated at a constant active power output and the excitation current is variable. In Fig. 2 are presented the theoretical characteristics I=f(I_{ex}) for different power outputs, P [4, 5].

The dashed line that connects the "V" curves peaks separates, from the reactive load point of view, the inductive generator operation domain from the capacitive generator operation domain (inductive receiver). The dashed curve from the capacitive operation domain indicates the limitation for decreasing the excitation, for different constant power outputs P = ct, in order to mantain a synchronous operation. The ”V” curves are obtained for different power output values.

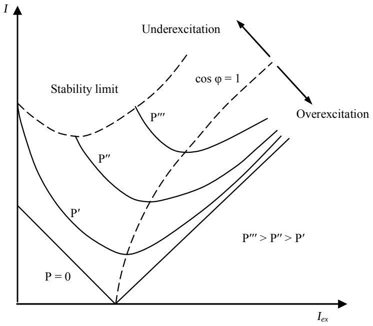


Fig. 2. "V" curves of a synchronous machine for different P = ct.

C. *Efficiency Characteristic*

The generator efficiency, η_G, is given by

$$\eta_G = \frac{P_G}{P_m} = \frac{P_m - p_{tot}}{P_m} = 1 - \frac{p_{tot}}{P_m}, \tag{1}$$

where P_m is the mechanical consumed power, P_G – the produced power and p_{tot} - the total losses inside the generator.

The total losses are determined as

$$p_{tot} = p_{mec} + p_{Fe} + p_{Cust} + p_{ex}, \tag{2}$$

where p_{mec} are the total mechanical losses inside the generator, p_{Fe} are the losses inside the stator iron, $p_{Cu\ st}$ are the losses in the stator copper winding and p_{ex} are the excitation losses.

The generator efficiency characteristic can be obtain using different standard procedures [3]. In the present work, the reporting method is used, as a tolerated method. It consists in evaluation of the generator losses based on the rated losses of the machine known from technical specification book.

The total mechanical losses p_{mec} consist of: losses due to air friction with the rotor, ventilation losses, losses due to the brushes friction, losses in generator bearings and sealings. The mechanical losses are considered constant and independent of the load. Their value is determined according to generator technical specifications.

The losses inside the stator iron p_{Fe} are given by the magnetic induction values. They are considered proportional to the induction in the air gap square, so with the stator voltage square. For an operating point, they can be obtained using

$$p_{Fe} = p_{Fen}\left(\frac{U}{U_n}\right)^2 . \tag{3}$$

The losses inside the stator copper windings $p_{Cu\ st}$ are given by the Joule effect losses and additional losses. They varies with the stator current square. The total losses in the stator copper windings can be computed using

$$p_{Cu\,st} = p_{Cu\,st\ n}\left(\frac{I}{I_n}\right)^2 . \tag{4}$$

The excitation losses p_{ex} represent the sum between the electrical losses due to the contact with brushes and the losses inside the rotor copper. According to (5) they are proportional to the excitation current square.

$$p_{ex} = p_{ex,n}\left(\frac{I_{ex}}{I_{ex,n}}\right)^2 . \tag{5}$$

3. In Site Measurements

The generators electric parameters were measured using a specialised electric parameters monitoring system, that measures independently the output and excitation parameters of electric generators (Fig. 3).
The system has an accuracy of ± 0,1%.

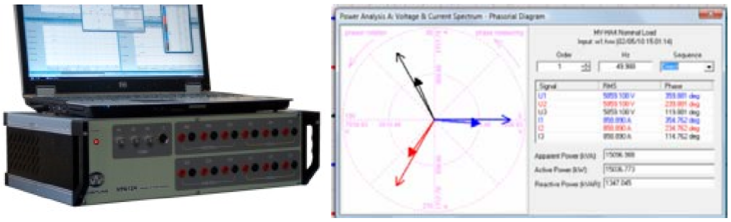


Fig. 3. Electric parameters monitoring system

4. Test Procedures

A. Open circuit Characteristic

The open circuit characteristic is obtained by decreasing the excitation current and the generator voltage. According to the standard procedure [3] aproximative 12 measuring points are required. The excitation current variation is made uniform, without any return. After establishing the correct values, the measuring is made simultaneously for all the parameters. The measuring scheme for this test is presented in Fig. 4.

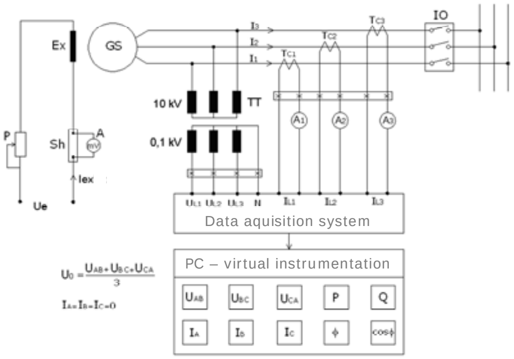


Fig. 4. Measuring scheme for open circuit regime

B. ”V” Characteristic

The ”V” characteristics, $I = I$ (Iex), for constant values of voltage, U, frequency, f, and a power output, P, were obtained with the generator connected to the grid. The reactive power was varied for a constant power output [3]. The test followed the steps:

- first was set a constant value for the power output;
- then, the generator was subjected to excitation up to the allowed maximum inductive reactive power;
- the excitation was gradually reduced, mantaining the power output at a constant value, and for each excitation current value the following quantities were acquired: power output P, reactive power Q, stator current I, stator voltage U, excitation current I_{ex}, excitation voltage U_{ex} and power factor, cosφ;
- for each value of the power output, 6 or7 values for the excitation current were set;
- the procedure was repeted for another power output value.

The measuring scheme for this test is presented in Fig. 5.

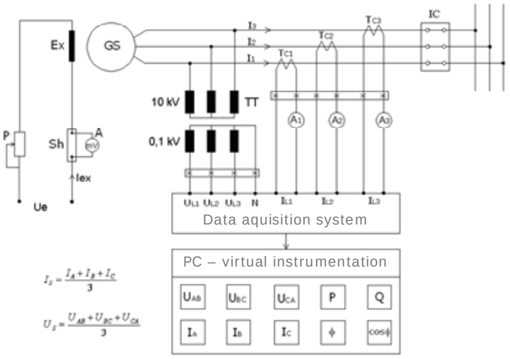


Fig. 5. Measuring scheme for load operation regime

C. *Efficiency Characteristic*

The efficiency measurements were made with the generator connected to the grid. Several operating regimes were set (different power output values P), and the power factor was mantained at the rated value.

For each analysed regime the following quantities were measured: power output P, stator voltage U, stator current I and excitation current I_{ex}.

The losses were determined using the rated losses values from the generator technical specifications.

The generator efficiency was computed with (1) and the real efficiency curve was obtained for the rated power factor.

5. Experimental Results And Performances Analyze

D. *Open circuit Characteristic*

The open circuit characteristics, $U = f\ (I_{ex})$, for rated rotational speed, obtained for the two analyzed generators are presented in Fig. 6 and Fig. 7.

Using these characteristics, the following quantities were determined: $\Delta I_{ex,0} = 42$ A for generator G_1 and ΔI_{ex},0 = 43.6 A for generator G_2, representing the excitation current value used to horizontally shift the curves to the axis origin.

After shifting, the excitation current value corresponding to no load operation, at the rated voltage, was obtained. The values corresponding to the analysed generators were: $I_{ex,0} = 233.3$ A for G_1 and $I_{ex,0} = 339.7$ A for G_2.

These values were used further in ”V” characteristics determination.

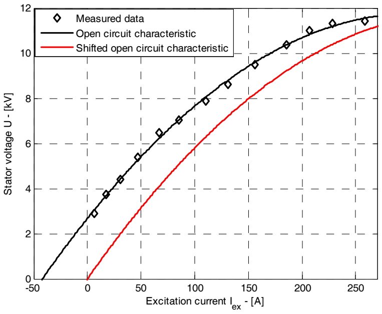


Fig. 6. Open circuit characteristic for G1

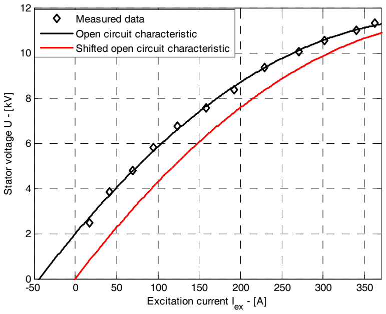


Fig. 7. Open circuit characteristic for G2

B. *”V” Characteristic*

The ”V” characteristics were obtained for the analysed generator considering different values for power output at part load operation. For the first generator (G1), the following power output values were considered: $P = 8$ MW, 10 MW, 14 MW, 17 MW, 19 MW, 21 MW and for the other (G2): $P = 15$ MW, 28 MW, 23 MW, 28 MW, 35 MW, 38 MW. The results are presented in Fig. 8

and Fig. 9 having the stator current reported to the rated stator current and the excitation current reported to the rated value.

It can be seen for G1 that most of the operation points are placed in the right side of the minimum value of the ”V” curves, which comes to the conclusion that this generator has a magnetic core saturation. Because of this, there is a pronounced increase in excitation current for the generator load operation. According to [7] the generator behaves as a capacity in relation to the grid.

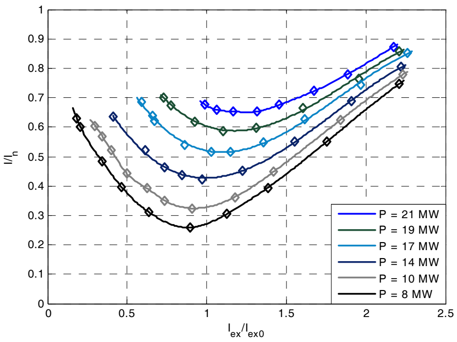


Fig. 8. "V" characteristic for G1

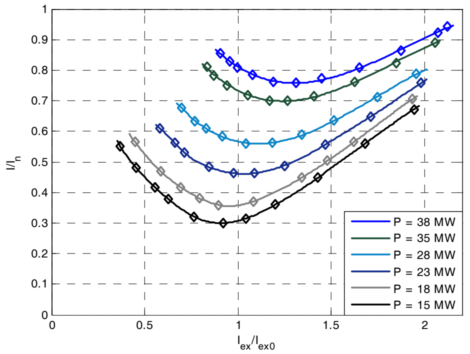
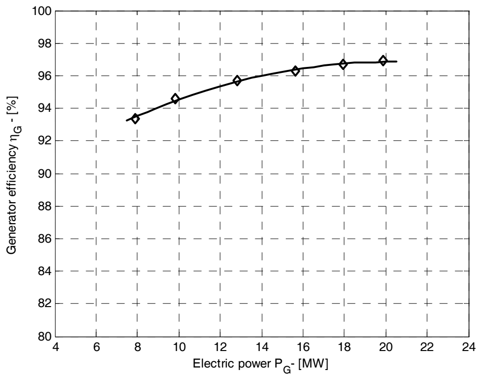


Fig. 9. "V" characteristic for G2

C. *Efficiency Characteristic*

Fig. 10 and Fig. 11 present the real efficiency characteristics obtained for the analysed generators.



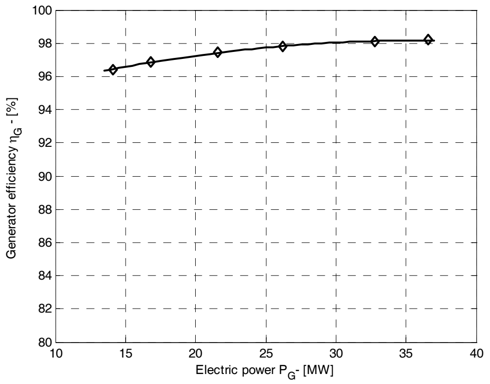


Fig. 10. Efficiency characteristic for G1 Fig. 11. Efficiency characteristic for G2

The experimental results were compared to data presented in literature [8]. It could be observed that generator G1 has lower values of efficiency than the theory, corresponding to a speed of 428 rot/min. For generator G2 the efficiency results were according to those presented in theory.

6. Conclusions

The electrical tests presented in this paper were conducted in order to determine the open circuit charactersitc, the "V" characteristic and the efficiency characteristic curve. The experimental tests were conducted for operation at part load.

Open circuit characteristics have a linear variation, which is according to the literature. These characteristics were used to determine the value for the excitation current in open circuit operation at nominal voltage.

The "V" characteristics showed the normal operation of the generators, the minimum value of the constant power output curves, $I/I_n = f\,(I_{ex} / I_{ex,0})$, slipping to the right direction while the power output increases, as presented in the standards.

The efficiency for generator G1 varies between 0.94 and 0.97 for 10 MW to 20 MW power output. The efficiency for generator G2 varies between 0.96 and 0.98 for the power output analized domain. A slight decrease of the efficiency was observed for G1 compared to the theoretical values for this kind of electircal machines.

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