# METHOD FOR DETERMINING PARAMETERS OF THE HIDROGENERATORS VOLTAGE REGULATORS

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**Abstract - The paper presents an original method in live determination of the main parameters of the automatic voltage regulator of hydro generators. The proposed method can be used for any kind of AVR and excitation system. The proposed method consists in simulating voltage variations on the reaction channel of AVR and recording its response in its size while the generator is still connected to the grid. The technique of measuring is based on using virtual instrumentation. The sampling rate for recording quantities is 0.2 ms. In the end it is presented an exemplification of measurement result to a 5.75 MW hydro generator with DC excitation generator and a 19.51 MW hydro generator with rotating diodes excitation and digital AVR.**

**Keywords:** voltage regulator, excitation, parameters, virtual instrumentation.

## 1. INTRODUCTION

Excitation system and automatic voltage control is made up of adjustable high D.C. power source and control circuits, protection, supervision and control (known as Automatic Voltage Regulator - AVR). This system ensures the rotor current (excitation current) suppling and adjustement of an operating generator and the prefixed value maintaining of the terminal voltage. AVR is an automatic adjustement system with negative feedback from the generator terminal voltage and with variable tension setting to external command.

In case of a sudden reduction/drop of the generator terminal voltage, AVR will occur by the rapid growth of the excitation voltage, action called excitation forcing for returning to initial value.

AVR's main parameters which ensure interaction between generator and grid that is connected are: AVR's statism ($S_{SU}$), excitation forcing threshold ($K_f$), excitation system nominal response of the excitation voltage ($t_{RUex}$), excitation system nominal response ($R_n$), AVR's accuracy (□), AVR's behavior in automatic operate of a reserve electricity power on AVR's suppling voltage and override tension values at full load throw (override, override time and the total response time).

## 2. METHOD FOR DETERMINING THE AVR PARAMETERS

The AVR manufacturers determine these parameters by software simulation of AVR's setting voltage perturbations and recording their effects. But the software of the AVR is not available for exploitation. In these circumstances it has been developed a method to determine these parameters [1,2] and an appropriate measurement system based on hard simulation of disturbances on the voltage response and recording their effects.

For some of the parameters it is used the simulation method of perturbation on the AVR input response voltage. The disturbances are made with 3-phase assembly having equal resistance shunting contactor, serially connected on the three wires that bring response voltage to AVR input from measurement transformers (voltage reducer) from the generator terminals . (Fig. 1). The initial state contactor is closed. By opening the contactor, the resistance are placed in circuit and voltage drop occurs on the AVR input. Therefore, AVR will command increasing excitation voltage to bring the voltage initial value to the AVR input, the action having the effect of increasing the terminal voltage about perturbation value.

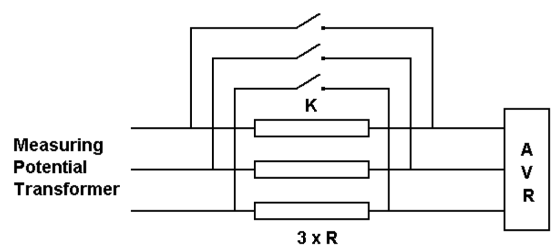


**Fig.1. Scheme of montage for disturbance simulation**

The value of the disturbance created depends on the resistance R and on the AVR current drawn. For digital AVR the drawn current by AVR is of the order 0.02 ÷ 0.05 A, so that creating 10 ÷ 30% disturbances, the resistance should be in the 1000 ÷ 6000 Ω and 0,5 ÷ 2 W For analog AVR the drawn current is of the order 1.5 to 2 A, so that creating 10 ÷ 30% disturbances resistors of 2-50 Ω and 20 to 40 W are necessary. The simulation of the disturbances is made with the generator connected to the grid, operating at rated load.

Figure 2 shows the scheme of measurement used to determine the above parameters, placed in the wiring diagram for HG excitation system with rotating diode excitation (a) and DC generator (b).



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The measurement system was developed based on using virtual instrumentation. System includes transducers, the system of creating step disturbance, data acquisition system and dedicated software package. The system allows simultaneous recording of generator parameters, with a sampling rate of 0.2 ms.

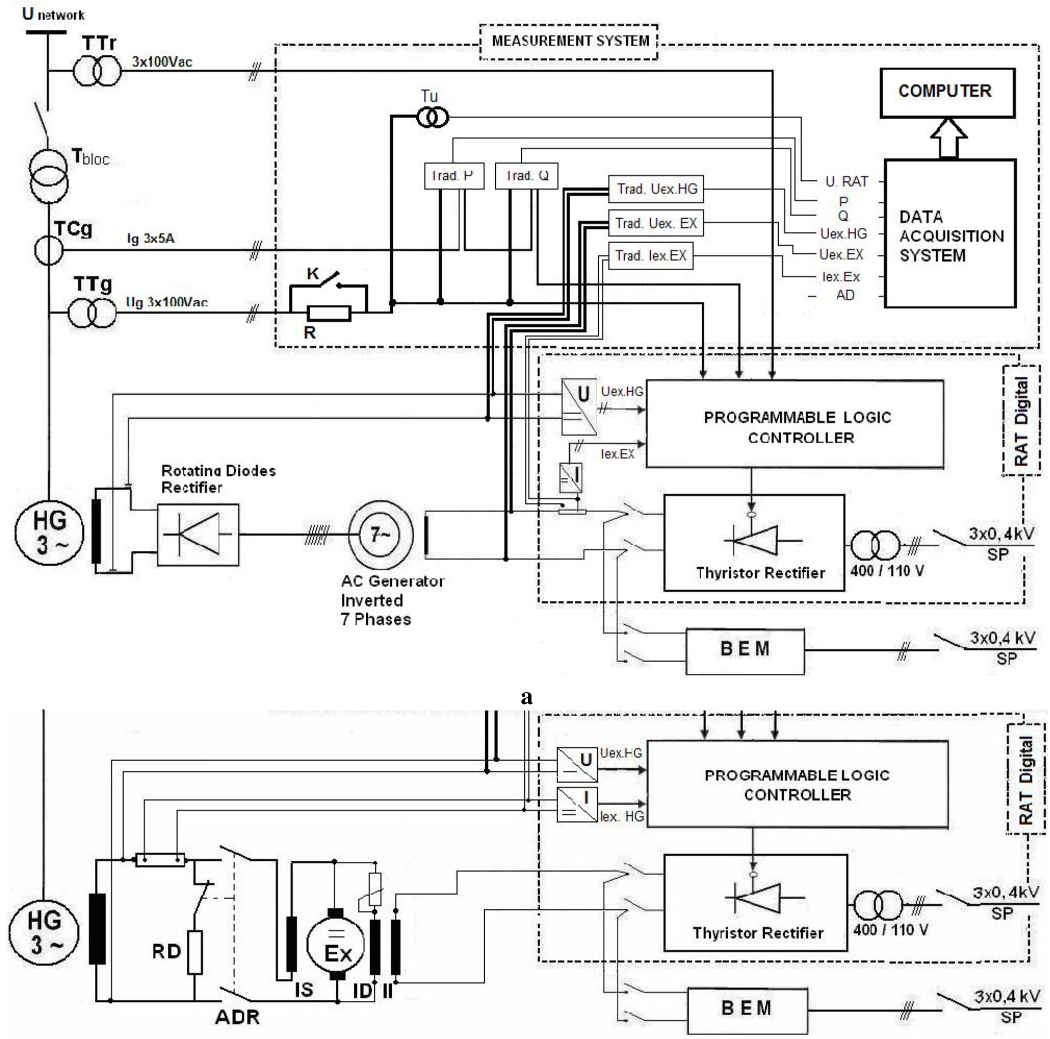


**Fig.2. Measurement scheme for excitation with rotating diodes (a) and DC rotating machine (b)**

The measurement system was developed based on using virtual instrumentation. System includes transducers, the system of creating step disturbance, data acquisition system and dedicated software package. The system allows simultaneous recording of generator parameters, with a sampling rate of 0.2 ms.

Measurement scheme is the same whatever the type of excitation is: AC reversed rotary machine and rotating diodes or DC machine, excepting the purchase of the generator excitation current. For excitation with rotating diodes and AC reversed rotary machine there is no acces to the generator excitation current and therefore are acquired the excitation current and voltage of the exciter.

Apart from trying to simulate the operation perturbation at nominal load, the following tests are made: idle running, automatic operate of a reserve electricity power on the AVR suppling bar and rated load throw [3,4,5].

The statism is determined by applying a step disturbance of approximately -5% in AVR input response voltage, generator operating with rated load (for example Fig.3). From records the values are determinated before and after a disturbance (stabilized values) for the terminal voltage and reactive power. AVR statism value is calculated with:

$$S_{SU} = 100 \frac{\Delta U_g}{U_{gn}} \frac{Q_{gn}}{\Delta Q_g} \quad (\%) \qquad (1)$$

$$\Delta U_g = U_{gf} - U_{g\,i}$$
$$\Delta Q_g = Q_{gf} - Q_{g\,i}$$

where:

$\Delta U_g$ - terminal voltage variation due to disturbance;
$\Delta Q_g$ - reactive power variation due to disturbance;
$U_{gi}$, $Q_{gi}$ - baseline terminal voltage and reactive power;

$U_{gf}$, $Q_{gf}$ - final values of terminal voltage and reactive power;



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$U_{gn}$,$Q_{gn}$ - nominal values of terminal voltage and reactive power;

Threshold forcing excitation, the response time of the excitation voltage and excitation system nominal response is determined by applying a step disturbance of -20 ÷ - 30% to AVR voltage response and registration generator excitation voltage and terminal voltage (for example Fig.4)

Threshold voltage forcing excitation $U_{exp}$ is the maximum value of the generator excitation voltage, at forcing, after a disturbance.

The response time in excitation voltage $t_{R\ Uex}$ is the time elapsed since disturbance application moment, read on AVR curve $U_{g\ RAT} = f\ (t)$, and the moment on $U_{ex} = f(t)$ when the generator excitation voltage reaches:

$$U_{R\ ex} = U_{exn} + 0{,}95\ (U_{ex.p} - U_{ex.n}) \qquad (2)$$

where:
$U_{ex.p}$ - threshold voltage of excitation forcing,
$U_{ex.n}$ - excitation rated voltage.

If is impossible to reach the rated voltage excitation, the calculation takes into account the initial value of excitation voltage.

To determine the excitation system rated response on the same diagram it is delimited the range from 0.5 s when the excitation voltage begins to rise as a result of the step disturbance. It is determined by graphical integration the surface AMNPA between the portion of the curve $U_{ex}$ bounded by the interval 0.5 s and horizontal interval corresponding to the rated voltage excitation $U_{exn}$. Triangle APQ is constructed so that its surface is equal to the area AMNPA. QP segment is determined by the relationship:

$$QP = \frac{2\ S_{AMNPA}\ (V\ s)}{AP\ (s)}\quad (V) \qquad (3)$$

The response of the excitation system nominal response is calculated with:

$$R_n = \frac{QP\ (V)}{U_{ex\ n}\ (V)}\ \frac{1}{0{,}5\ (s)} \qquad (4)$$

Determination of the AVR accuracy is made with generator in the no load excited regime at rated voltage (for example Fig.6). There are recorded every 5 seconds 181 RMS values of terminal voltage for 15 minutes (starting at t = 0). Recording values of voltage across the generator, calculate the average value $U_{g\ med}$ of the 181 values recorded:

$$U_{g\ av} = \frac{\sum U_{g\ i}}{N}\quad (V) \qquad (5)$$

Absolute error from the mean values:

$$\Delta U_{gi} = \left| 100 \frac{U_{gi} - U_{g\ av}}{U_{g\ av}} \right| \quad (\%) \qquad (6)$$

where:
$U_{g\ i}$ - voltage effective value between phases measured during moment ‘i’;
$U_{g\ av}$ - average value of all the 181 measured values;
N - number of measured values of voltage

AVR accuracy is the maximum deviation $\Delta U_{g\ i}$

$$\varepsilon = MAX\ (\Delta U_{g\ i}) \qquad (7)$$

Determination of the override parameters are made in rated load throw test, which corresponds to the application of a disturbance with an amplitude of about (+) 18 ÷ (+) 25%. The test is done by opening the switch on from the high voltage transformer block, as an unexpected event, caused by a grid protection. When disconnecting the load, the generator remains in idle mode and at the first moments (at least 1-2 times) the excitation current has the generator rated value (much more than the idle runnig excitation current). Therefore, the terminal voltage (and hence voltage seen by AVR) is a step leap which can reach a value of about 1.18 to 1.25 of $U_{gn}$ (maximum value is a function of reactances and time constants of the generator). AVR intervention occurs and how quickly it occurs to restore the terminal voltage to a steady value should be admissible for this band around the nominal value (± 5% of $U_{gn}$). Terminal voltage and generator excitation voltage are recorded (for example Fig.7).

Terminal voltage override (SR) is the increasing of the terminal voltage value from rated value, after the rated load throw and it is determined by the relationship:

$$SR = \frac{U_{g\max} - U_{gn}}{U_{gn}}\ (\%) \qquad (8)$$

where:
$U_{g\ max}$ - the maximum terminal voltage after rated load throw ;
$U_{g\ n}$ - terminal rated voltage;

Override time of $1{,}1U_{gn}$ ($t_{SR}$) is the length of time that the terminal voltage has a value greater than 1,1 $U_{gn}$, after rated load throw and it is read from the chart curve $U_g = f\ (t)$

Total response time or duration transient ($\Delta t_{as}$) is the interval between the start of the terminal voltage increase and when it finally comes back in a band of ± 5% as a result of AVR action, after rated load and it is read from $U_g = f\ (t)$.

The determination of AoR behavior in automatic operate of a reserve electricity power on the 0.4 kV bar is made by disconnecting the main power switch of the AVR an of the exciter excitation transformer. After the automatic operate of a reserve electricity power break the switch of suplemental reserve is automatically closed. During automatic operate of a reserve electricity power break generator operating without excitation. After the appearance of AOR supply voltage and excitement exciter, he restored the excitation parameters, the



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terminal voltage and reactive power, practically to the same values as those from the beginning. The test is made during the generator is operating at minimum technical power. Terminal voltage, generator excitation voltage, exciter voltage excitation from manual disconnection time to return to the original parameters (for example Fig.10) are registred. Initial parameters and ending parameters are compared after the break. The test is considered to be successful if the generator remains stable, without oscillations and if the excitation parameters, the terminal voltage and reactive power get back to the same values as those from the beginning.

Acceptance criteria of AVR parameters [6,7,8] are presented in Table 2.

## 3. TWO HYDROGENERATORS WITH DIGITAL AVR APPLICATION

Tests were conducted at two hydro generators from two different plants: HG1 of 5.75 MW with DC excitation generator and HG2 of 19.5 MW with reversed AC generator and rotating diodes excitation (Table 1). Both have digital AVR with indirect regulation.

**Table 1. Tested generators parameters**

| Parameters | Simbol | UM | HG 1 | HG 2 |
|---|---|---|---|---|
| Generator rating | $P_{gn}$ | MW | 5,75 | 19,5 |
| Rated reactive power | $Q_{gn}$ | MVAr | 2.78 | 9.8 |
| Rated power factor | cos $\varphi_n$ | | 0,9 | 0,9 |
| Rated terminal voltage | $U_{gn}$ | kV | 6,3 | 10,5 |
| Rated stator current | $I_{gn}$ | kA | 587 | 1250 |
| Excitation type | | | DC generator | Rotating diods |
| Rated load field voltage | $U_{ex.n}$ | $V_{cc}$ | 150 | 104 |
| Rated field current | $I_{ex.n}$ | $A_{cc}$ | 387 | 710 |
| AC exciter voltage | $U_{ex.Ex.n}$ | $V_{ca}$ | | 36,5 |
| DC exciter voltage | $U_{ex.Ex.n}$ | $V_{cc}$ | 390 | 42 |
| Exciter field current | $I_{ex.Ex.\ n}$ | $A_{cc}$ | 230 | 29,4 |

At HG1 trials were conducted in two stages. Results from the first stage showed that a number of parameters: voltage threshold of forcing, response time, rated response and override value are not within the acceptance criteria laid down in standards. Accordingly AVR supplier was requested to modify gain coefficients and time constants transfer function of the AVR for improvement of these performances. After completing the settings, it was performed a new round of tests. Table 2 presents results of the two stages of testing.

Fig. 3 shows the registration test to determine statism. Test results for the two stages are similar and therefore this parameter is presented only in stage II test results. The generator operated in charge at $P_g$ = 5 MW and 0.73 MVAr constant. It was performed by simulation, a step disturbance on the AVR entry of -5.3%. There were recorded the generator terminal voltage $U_g$, the AVR input voltage, $U_{RAT}$ and reactive power $Q_g$. From the records it was extracted initial and final values of voltage and reactive power: $U_{gi}$ = 0.977 u.r., $U_{gf}$ = 1.001 u.r., $Q_{gi}$ =0.73 MVAr., $Q_{gf}$ =2.41 MVAr, which by using relation 1 is determined the statism $S_u$ = 4.0 %. The value corespond to the requirements acceptance criteria.

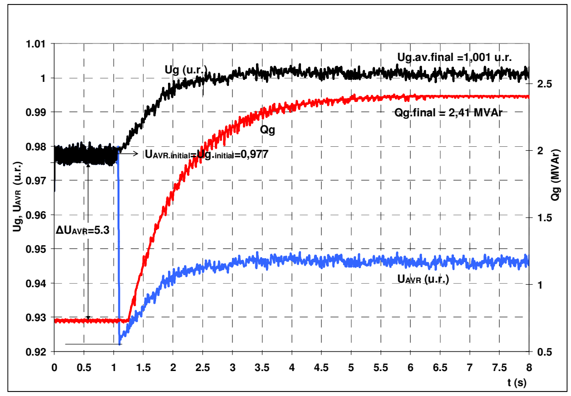


**Fig. 3. Registration test to determine statism, HG1**

Fig. 4 presents the test recording for determining the forcing threshold, response time and rated response at the test stage I. The generator operated with the following parameters: $P_g$ = 5.5MW, $Q_g$ = 1.8 MVAr, $U_{g.i}$ = 5985 kV (0.95 u.r) and $U_{ex.i}$ = 130 $V_{DC}$ (very close to the rated regime of HG). It was applied a step perturbation $\Delta U_{AVR}$ = - 23 %. Threshold value obtained was $U_{exp}$ = 272 V respectively 1,34 u.r. and exciter excitation voltage was $U_{ex.Ex.}$ = 138 $V_{cc}$. The procedure described in paragraph 2 and the relations 2, 3 and 4 were determined successively: $U_{Rex}$= 1.32 u.r. resulting response time $t_{RUex}$ = 0.48 s, $S_{AMNPA}$ = 0.09 u.r/s, QP = 0.36 u.r. and rated response u.r. $R_n$ =0.72 u.r./s. The conclusion was that the AVR does not realize criteria for acceptance threshold voltage of forcing (minimum 1.8), for response time (max. 0.4 s) and nominal response (minimum of 1.5 u.r. / s).

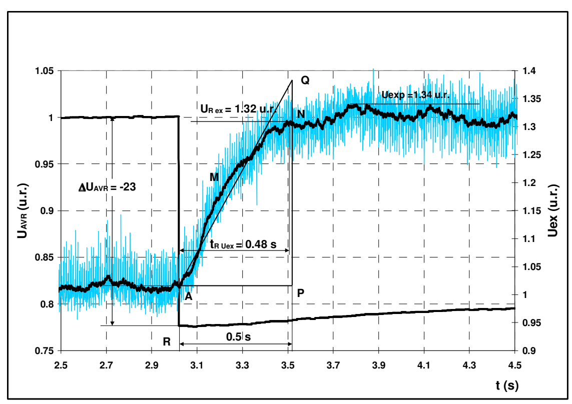


**Fig.4. The test for determining the forcing threshold, response time and rated response, stage I, HG1**

After changing the AVR's settings it was performed phase II trials and the following values were obtained: $K_f$ =1,95 $U_{R\ ex}$= 1.9 u.r., $t_{RUex}$ = 0.325 s, $S_{AMNPA}$ = 0.345 u.r. s , QP = 1.38 u.r. şi $R_n$ =2.76 u.r./s, (Fig.5) which correspond to the acceptance criteria.



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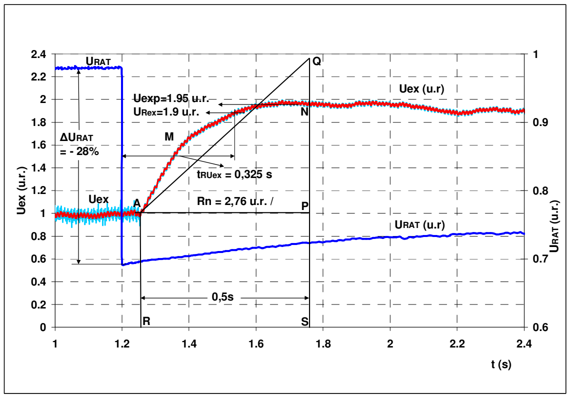


**Fig.5. The test for determining the forcing threshold, response time and rated response, stage II, HG1**

Figure 6 presents the test recording to determine the accuracy. Test results for the two stages are similar and therefore this parameter is presented only in stage II test results .The generator operated in the no load exited regime at rated voltage 6.3 kV. Was recorded voltage at the generator terminals $U_g$ for 15 min = 900 s, with a cadence of a 5 point and obtaining 181 values. With relations 5,6,7 calculate $U_{g\ average}$ =6.0 kV and ε = 0,39 %

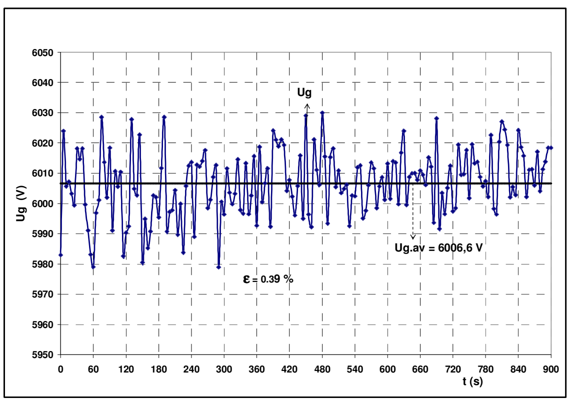


**Fig.6. Registration test to determine accuracy , HG1**

Figure 7 presents the rated load throw test to determine the override values. This was tested by disconnecting the line switch on the 20 kV in secondary transformer block.

Initial load values were $P_g$ = 5.55 MW and $Q_g$ = 1.2 MVAr and at stage II $P_g$ = 5.77 MW, $Q_g$ = 1.00 MVAr. In the first phase there were obtained nonconforming/inconsistent values with the requirements: SR = 0.125 u.r., override time of 1.1 $U_{gn}$, $t_{SR}$ = 1.2 s and total response time $\Delta t_{as}$ = 3 s. After changing the settings there were obtained SR=0.101 u.r., $t_{SR}$ = 0, $\Delta t_{as}$ = 1.36 s, and values were consistent/ conforming with the acceptance criteria (Tab.2)

Fig. 8 shows the registration test to determine statism at the HG 2. The generator operated in charge at $P_g$ = 15 MW and 0.21 MVAr constant. It was performed by simulation, a step disturbance on the AVR entry of - 5.45 %. From the records it was extracted initial and final values of voltage and reactive power: $U_{gi}$ = 0.9832 u.r., $U_{gf}$ = 1.0025 u.r., $Q_{gi}$ =0.21 MVAr., $Q_{gf}$ =4.21 MVAr, which by using relation 1 is determined the statism $S_u$ = 4.73 %.

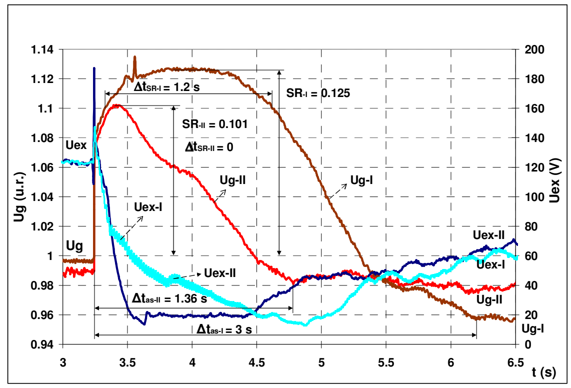


**Fig.7. Rated load throw test to determine override values, HG1**

At HG 2 all tests were performed to determine the AVR's parameters. All parameters were within the acceptance criteria requirements. In load throw with line disconnect switch, the automatic system disconnected the AVR and thus ordered the HG de-energize and could not determine the total response time, the generator didn't come back to its rated voltage. Measurement results are presented in Table 2.

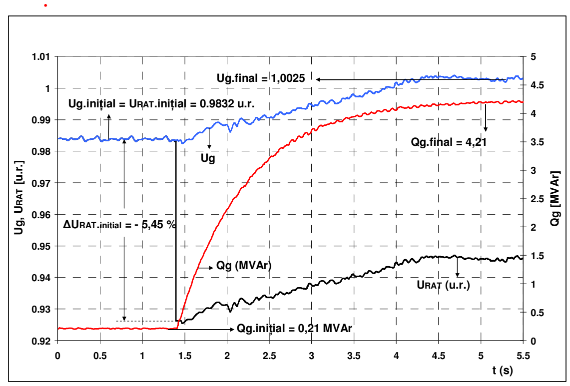


**Fig. 8. Registration test to determine statism, HG2**

Fig. 9 presents the test recording for determining the forcing threshold, response time and rated response at the HG 2. The generator operated with the following parameters: $P_g$ = 20 MW, $Q_g$ = 6.5 MVAr, $U_{g.i}$ = 10.49 kV (0.99 u.r) and $U_{ex.i}$ = 101 $V_{DC}$ (very close to the rated regime of HG). It was applied a step perturbation $\Delta U_{AVR}$ = - 32 %. Threshold value obtained was $U_{exp}$ = 175 V respectively 1,74 u.r. and exciter excitation voltage was $U_{ex.Ex.}$ = 138 $V_{cc}$ (respectively 3.3 $U_{ex.Exn}$ ). The procedure described in paragraph 2 and the relations 2, 3 and 4 determined successively: $U_{Rex}$= 0.772 u.r., $t_{RUex}$ = 0.24 s, $S_{AMNPA}$ = 0.265 u.r/s, QP = 1.06 u.r. and rated response u.r. $R_n$ =2.12 u.r./s.



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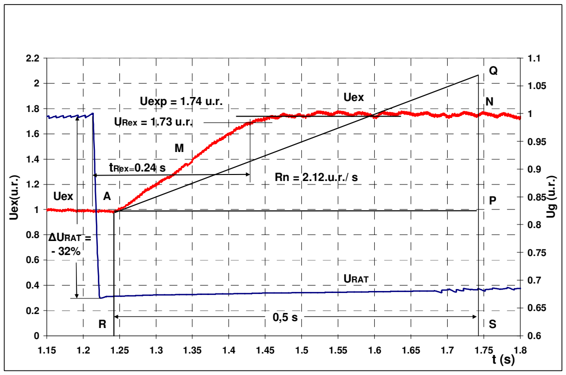


**Fig.9. The test for determining the forcing threshold, response time and rated response, HG2**

Figure 10 presents the test recording to verify the behavior on high voltage supply to the automatic operate of a reserve (AOR) electricity power for HG 2.

The test was performed by disconnecting manually the main power switch of the exciter excitation transformer, which supply also the AVR causing the action of the automation AOR to thr bar on 0.4 kV. The generator was loaded at $P_{gi}$ =3.47 MW and $Q_{gi}$ = 4.05 MVAr. After disconnecting the primary power supply switch, the Automatic Transfer Switch connected up to approx. 9 seconds (pause AOR), during which HG worked without excitation and reactive power almost zero. After AVR's emergence power, it restored the excitation parameters, the terminal voltage and reactive power, practically the same values as those from the beginning: $P_{gf}$ = 3.48 MW, şi $Q_{gf}$ = 4.075 MVAr. The AVR behaved correctly on the automatic operate of a reserve electricity power break. (pause AOR)

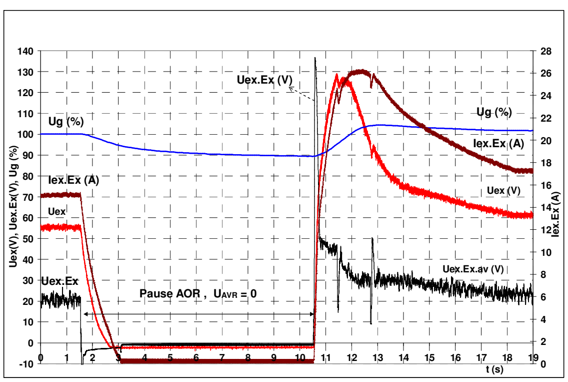


**Fig.10. AOR break behavior for HG 2**

Table 2 presents summary results of measurements at two hydro generators and acceptance criteria. For HG1 presents results from the two stages, before and after changing the AVR's settings

**Table 2. Test results**

| Parameter | UM | Demand* | HG1 st I | HG1 st II | HG 2 |
|---|---|---|---|---|---|
| AVR Statism | % | (1-12) | 4.56 | 4,00 | 4,73 |
| Voltage forcing threshold | u.r. | ≥1.6 (≤ 5 MW) ≥1.8 (≥ 5 MW) | 1.34 | 1.95 | 1.75 |
| Response time in excitation voltage | s | ≤ 0,4** | 0.48 | 0,325 | 0,24 |
| Excitation system rated response | u.r./s | ≥ 1,5 | 0.264 | 2,96 | 2,12 |
| AVR accuracy | % | ≤ 1 | 0.74 | 0,39 | 0.67 |
| AVR behavior to pause AOR | | | OK | OK | OK |
| Generator tension override | u.r. | ≤ 0,1 | 0.13 | 0,1 | 0,1 |
| Override time of $1{,}1U_{gn}$ | s | ≤1 | 1.2 | 0*** | 0*** |
| Total response time | s | ≤ 3 | 3 | 1,36 | - |

*According SR 9385-1:2008, cap. 6.4,
** For indirect regulation system,
*** The voltage didn't pass over $1{,}1U_{gn}$

## 4. CONCLUSIONS

Test methods, by live attempts with the generator connected to the grid and presented in this paper have revealed the real performance of the AVR and determine the classification or not to the acceptance criteria requirements. It has to be mainly mentioned the hard simulation method of disturbance on the input side of the AVR, which is an original method of the authors' work. The hardware and software equipment, also original, allowed detailed record of transitory events and a high degree of precision machining.

Applications presented have confirmed the efficiency of testing and allowed parameters were found not fit the requirements and acceptance criteria, and thus able to intervene and correct settings so that the performance can be improved. The improvement was confirmed by a new phase of testing. Currently AVR ensure correct interaction, free of any problem, between generator and grid.

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