MATHEMATICAL MODEL AND SOFTWARE FOR THE SIMULATION OF THE BEHAVIOR OF HYDRO GENERATOR AND AUTOMATIC VOLTAGE REGULATOR AT THE THROWING RATED LOAD

ZLATANOVICI D. *, IONESCU F.**, HERISANU A.***, CICIRONE C.*
*ICEMENERG Bucharest,
** Polytechnic University of Bucharest,
*** HIDROELECTRICA Branch Curtea de Argeş
danz@icemenerg.ro

Abstract - The paper presents a mathematical model and a computer program for determining the override parameters of the hydro generator and automatic voltage regulator (AVR) at the throwing rated load: terminal voltage override of the generator, override time of 1,1U_{gn}, total response time or transient duration. Essentially the method consists of simulating the application of a negative step type perturbation at the AVR input stage, equivalent to a throw rated load and determine the override parameters. Further the paper presents an experimental test on the hydro generator from HPP Light Tape Lereşti – Arges, provoking a live load rated throwing and determination of the same parameters. Finally, compare the experimental results and required values by international standards.

Keywords: Automatic voltage regulators, calculation software, throw load simulation, override parameters

1. INTRODUCTION

Interaction between a hydro-electric generator and electrical power grid (EPG) occurs essentially by the action of two automatic voltage and speed regulators. Automatic voltage regulator (AVR) provides electrical interaction (voltage, current, reactive power, power factor) and automatic speed regulator (rpm) (ASR) provides electromechanical interaction (frequency, active power).

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.

If it occurs a throwing rated load, AVR will act in different manner, it will quickly reduce the generator terminal voltage and it will maintain it at rated value.

The throwing rated load is an action that an electric generator coupled to a power grid is suddenly disconnected from it and the power output is reduced instantaneous to zero. The throwing rated load can be caused by the action of the generator external protection (power grid protections, high voltage bar protections, transformer protections) or by a deliberate action.

During the high voltage switch block trigger, the generator will remain in the first 0.2-0.3 s with a corresponding excitation for it's load, what will cause a rapid increase of the generator terminal voltage (the generator will operate without load, on the idle running curve). AVR role is to reduce the voltage value to it's rated load. AVR's reaction rate is conditioned by the time constants and by the gain of the transfer function.

Due to the moving mass inertia, the hydro generator rotative speed will remain for 0.2-0.5 s at baseline (rated rotative speed) and then starts to increase after 2-3 s and reaches a maximum value. The ASR role is to stop increasing speed and bring it back to the rated rotative speed. It should be noted that practically the rotative speed increasing has no effect on the generator terminal voltage during throwing rated load.

In conclusion, the two regulators will maintain the generator in excited idle running mode in order to be restarted after the fault that caused the throwing rated voltage (Electrical Power Grid code requirement).

The main parameters that characterize the AVR behavior in throwing rated load (override parameters) are:

- Generator terminal voltage override (SR) represents the increase from rated value of the terminal voltage after throwing rated load;
- 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 throwing rated load;
- Total response time or transient duration (Δt_{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 throwing rated load.

2. MATHEMATICAL MODEL

The developed mathematical model aims the simulation of a hydro generator throwing rated load mode.

The chosen model for studying the interaction between the hydro generator and the electrical power grid (EPG) is a simple scheme in which the generator is connected via a transformer (transformer block) and a line with known parameters to an infinite power bar (fig. 1).

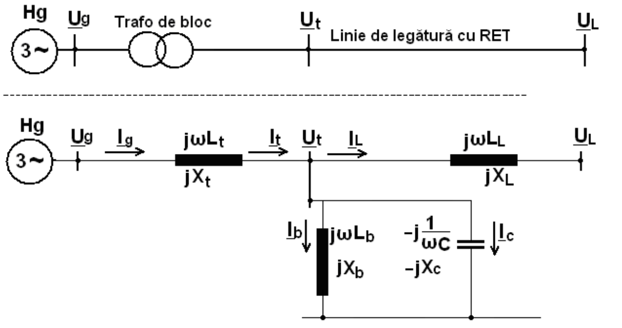

Fig. 1. The employment of hydrogenerator in electrical power grid

In fig. 1. sizes with index „g" refers to the generator, the index „t" to the transformer, the index L – to the infinite power line and index b and c to inductive and capacitive consumers conected to the tension line.

For this scheme were writing Park Blondel transient electric generator equations. After successive processing and customization for case study –throwing rated voltage-resulting equations were[1]:

Mechanical equations:

$$\frac{d\delta_g}{dt} = \omega\, s \tag{1}$$

$$\frac{ds}{dt} = -\frac{D}{T}s + \frac{1}{T}\frac{C_{mec.0}}{C_{mec.n}} - \frac{1}{T P_n}\left[\frac{1}{X''_q} e''_d U_L \cos\delta_g + \frac{1}{X''_d} e''_q U_L \sin\delta_g + \left(\frac{1}{X''_q} - \frac{1}{X''_d}\right) U_L^2 \sin 2\delta_g\right] \tag{2}$$

where:

T – mechanical timp constant

$D = \frac{\Delta C_{mec}}{C_{mec.n}}$ - turbine auto-regulation constant

$C_{mec.0}$ - synchronous mode turbine mechanical torque

δ - hydro generator internal angle

s – hydro generator slip

U_L –line voltage

Electrical equations:

$$\frac{de'_q}{dt} = \frac{1}{T'_{d0}}\frac{\overline{X}''_d - \overline{X}_\sigma}{\overline{X}'_d - \overline{X}_\sigma} e_f - \frac{1}{T'_{d0}}\frac{\overline{X}_d - \overline{X}_\sigma}{\overline{X}'_d - \overline{X}_\sigma} e'_q + \frac{1}{T'_{d0}}\frac{\overline{X}_\sigma}{\overline{X}''_d}\frac{\left(\overline{X}_d - \overline{X}'_d\right)\left(\overline{X}''_d - \overline{X}_\sigma\right)}{\left(\overline{X}'_d - \overline{X}_\sigma\right)^2} e''_q + \frac{1}{T'_{d0}}\frac{\left(\overline{X}_d - \overline{X}''_d\right)\left(\overline{X}''_d - \overline{X}_\sigma\right)}{\overline{X}''_d\left(\overline{X}'_d - \overline{X}_\sigma\right)^2} U_L \cos\delta_g \tag{3}$$

$$\frac{de'_q}{dt} = \frac{1}{T'_{d0}} e_f - \frac{1}{T'_{d0}}\frac{X_d - X''_d}{X'_d - X''_d} e'_q + \frac{1}{T'_{d0}}\frac{X_d - X'_d}{X'_d - X''_d} e''_q \tag{4}$$

$$\frac{de''_q}{dt} = \frac{1}{T''_{d0}}\left(e'_q - e''_q\right) \tag{5}$$

where:

X_d, X_d', X_d'', X_q, X_σ generator's reactances

T'_{do}, T''_{do} generator's time constants

e_q, e'_q, e''_q, electromotive force

e_f rotor electromotive force (rotor related excitation voltage).

For the complex system automatic voltage regulator + exciter (digital type) it has been used a developed structure with one additional signal at the AVR input (after hydrogenerator slip / rpm) and the transfer function from the main AVR's line has 2 poles and one zero[7,10] (fig. 2.)

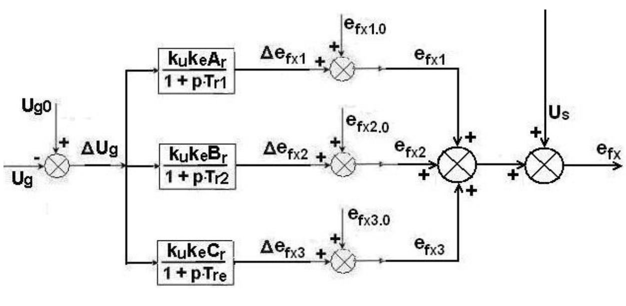

Fig. 2. RAT general block diagram with transfer functions [7]

The resulting differential equations are:

$$\frac{de_{fx1}}{dt} = \left[e_{fx1.0} - e_{fx1} + k_u k_e A_r\left(U_{g0} - (1-dU)U_g\right)\right]\frac{1}{T_{r1}} \tag{6}$$

$$\frac{de_{fx2}}{dt} = \left[e_{fx2.0} - e_{fx2} + k_u k_e B_r\left(U_{g0} - (1-dU)U_g\right)\right]\frac{1}{T_{r2}} \tag{7}$$

---

[1] The mathematical model and computer program presented in this article has entirely original character. Equations and models used were selected from bibliography, have been converted, processed and custom parameters to determine parameters of the interaction between hydro generator and electrical power grid.

$$\frac{de_{fx3}}{dt} = \left[e_{fx3.0} - e_{fx3} + k_u k_e Cr\left(U_{g0} - (1-dU)U_g\right)\right]\frac{1}{T_{r3}} \quad (8)$$

where:

$$A_r = \frac{T_{r1}\left(T_{r1} - T_{ru}\right)}{\left(T_{r2} - T_{r1}\right)\left(T_{re} - T_{r1}\right)}$$

$$B_r = \frac{T_{r2}\left(T_{r2} - T_{ru}\right)}{\left(T_{r1} - T_{r2}\right)\left(T_{re} - T_{r2}\right)}$$

$$C_r = \frac{T_{re}\left(T_{re} - T_{ru}\right)}{\left(T_{r1} - T_{re}\right)\left(T_{r2} - T_{re}\right)}$$

$T_{r1}, T_{r2}, T_{ru}, T_{re}$ - time constants
k_u, k_e – gain constants
e_{fx1}, e_{fx2}, e_{fx3} - e_f electromotive force e_f components
$e_{fx.0}$, $e_{fx2.0}$, $e_{fx3.0}$ – e_f initial components

For automatic speed regulator (ASR - digital type) of hydro turbine it has used a simplified structure (fig. 2.) of transfer function whose parameters were chosen from the thecnical literature because it hasn't an essential role in the events that cause forcing excitation.

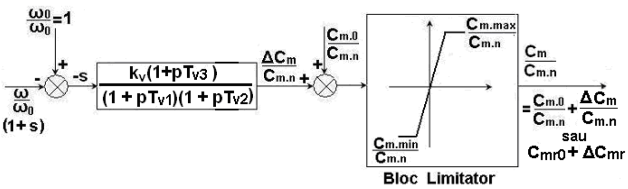

Fig. 3. ASR general block diagram with transfer functions (index "m" => mechanical)

The resulting differential equations are:

$$\frac{dC_{mr1}}{dt} = \frac{1}{T_{v1}}\left[C_{mr1.0} - C_{mr1} - k_v A_{v1} s\right] \quad (9)$$

$$\frac{dC_{mr2}}{dt} = \frac{1}{T_{v2}}\left[C_{mr2.0} - C_{mr2} - k_v A_{v2} s\right] \quad (10)$$

where:

$$A_{v1} = \frac{T_{v1} - T_{v3}}{T_{v1} - T_{v2}}, \quad A_{v2} = -\frac{T_{v2} - T_{v3}}{T_{v1} - T_{v2}}$$

k_v, T_{v1}, T_{v2}, T_{v3} - AVR transfer function constants
$C_{m.r}$ - relative mechanical torque related to the rated mechanical torque ($C_{mec.n}$)

For the perturbed mode of throwing rated load, it is considered that rotative speed remains constant during the period after triggering ($\delta = 0$, $e_d'' = 0$). That for we will consider only generator electric equations (3) and (4) and AVR's equations (5), (6) and (7).

3. PROGRAMME AND RESULTS

The differential equations system were solved by finite difference method, Runge Kutta [6]. The program was written in C++. The program was called PRO-DINA-ArSa.

The input vales of the program PRO-DINA-ArSa were read of 4 data files:

1. File „AVR Value - ArSa" which read:
   - Tr1, Tr2, Tru, Ku - time constants and the gain factor of the AVR's transfer function;
   - Te, Ke - time constant and transfer coefficient for Exciter;
   - dU - applied disturbance value;
   - JP1 number of steps for integrating differential equations in the initial steady state (0.2 s);
   - JP2 - total number of steps for the entire period (steady state and perturbed regime);
   - H - integration step (typically 0.001 s).
2. File „ASR-PSS-ArSa characteristics":
   - time constants and coefficients of ASR's transfer function gain;
3. File „Date HG-Trafo-LEA Regim-ArSa":
   - time constants of the hydro generator, transformer, high-voltage line, infinite power bar;
   - initial data for stationary operation mode before applying dU disturbance.
4. File „Reactance HG-Trafo-LEA-ArSa":
   - reactances of the hydro generator, transformer, high-voltage line, infinite power bar;

Further the calculations and export the results:

- Calculation of HG+Transformer+line parameter;
- Calculation of stationary regime initial values: the hydrogenerator and transformer terminal voltage and other variables of the mathematical model;
- Calculation of differential equations coefficients for stationary mode;
- Application Runge Kutta numerical integration algorithm for a short period of stationary mode. This yields constant and equal values to the calculated values for the stationary mode;
- After each integration step numerical values resulting from integration: T U_{ex}, U_g, E_f, $U_{g.RAT}$, δ, P_g, Q_g. Results are written to the excel file Results-ArSa.xsl;
- The system initializes disturbance regime: $U_{g.RAT} = U_{g.0}$, $\delta=0$, $e_d''=0$;
- Calculation of differential equations coefficients for throwing rated load mode;
- Application Runge Kutta numerical integration algorithm for disturbance mode between 6 s;
- At the end of each integration step is calculated hydrogenerator excitation voltages and the other operating parameters of schema elements, and resets $U_{g.RAT} = Ug.0$;
- After each integration step numerical values resulting from integration: T U_{ex}, U_g, E_f, $U_{g.RAT}$, δ, P_g, Qg. – Results are written in excel file results –Results-ArSa.xsl;
- At the end of the disturbance mode is calculated the AVR's performance achieved by throwing rated voltage SR, t_{SR}, Δt_{as}.

Performance values are written to the Performances-ArSa.dat file.

Calculation results are obtained in two Excel files:

1. The file Results-ArSa.xls comprising a table with variables' values at each integration step results calculated in program in u.r. reported at their rated values;
2. The file „Performances-ArSa.dat" including AVR's performances achieved and the main input values used by the program to verify the accuracy of reading their entry into the program.

Figure 4 shows the Organizational chart of the PRO-DINA-ArSa software

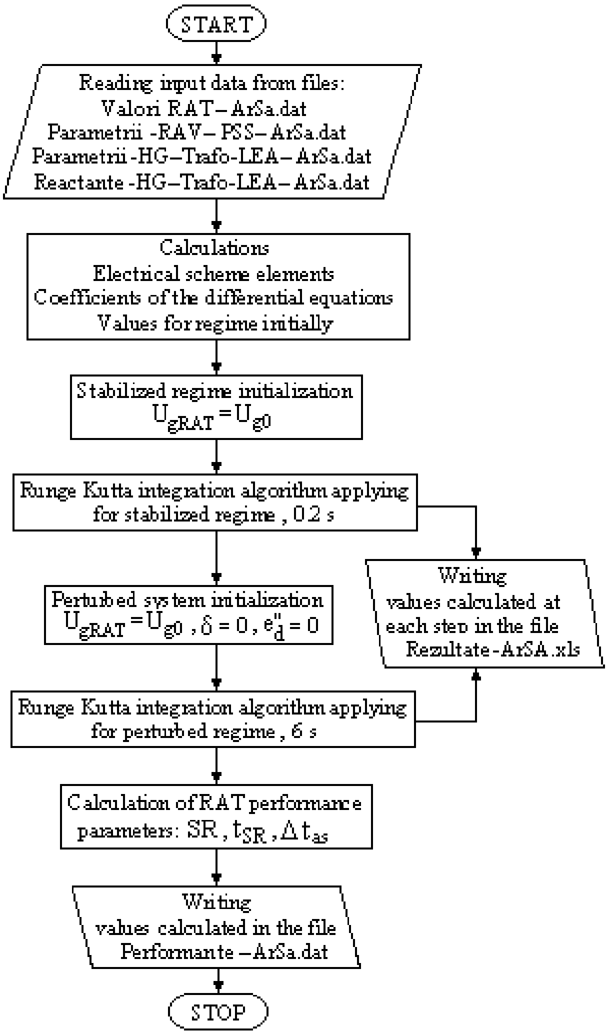

Fig. 4. Organizational chart of the PRO-DINA-ArSa software

The program was run for the HPP Lereşti with P_n = 19.5 MW and U_n = 10.5 kV for throwing rated load in the following versions (Table 1):

- Four different values for the time constant T_{rl} = 0.04s, 0.15s, 0.20 and 0.40 and the other constants remain the same;
- Three different values for the time constant T_{ru} = 0.30s, 0.18 and 0.08s, the other constants remain the same to a disturbance $dU_{g.RAT}$ = -20%;
- Three different values for the constant gain K_u = 30, 20, 10, the other constants remain the same; Constants T_{r2} = 0.07s, T_e = 0.25s, K_e = 0.5 u.r / u.r remained unchanged.

RAT parameters resulting from throwing rated load, shown in Table 1:

- generator terminal voltage override (SR);
- override time of 1,1U_{gn} (t_{SR});
- total response time or transient duration (Δt_{as}).

Table 1. The results obtained with the program PRO-DINA-ArSa for HG Lereşti

Variable parameter	Fig./ Curve	Initial inputs			Resultes		
		T_{rl}	T_{ru}	K_u	SR	t_{SR}	Δt_{as}
		s	s	u.r.	%	s	s
T_{rl}	5/1	0.04	0.30	20	0.051	0.587	2.25
	5/2	0.15	0.30	20	0.060	0.753	2.65
	5/3	0.20	0.30	20	0.063	0.825	2.95
	5/4	0.40	0.30	20	0.072	1.088	4.55
T_{ru}	6/1	0.04	0.30	20	0.051	0.587	2.25
	6/2	0.04	0.18	20	0.057	0.756	2.72
	6/3	0.04	0.06	20	0.066	1.053	2.9
K_u	7/1	0.04	0.30	30	0.046	0.397	2.05
	7/2	0.04	0.30	20	0.051	0.587	2.25
	7/3	0.04	0.30	10	0.065	>7.66	3.91

Figures 5, 6 and 7 presents examples of variation of response curves for throwing rated load for 4 values of the AVR time constant of the Tr1 respectively for 3 values of the gain coefficient

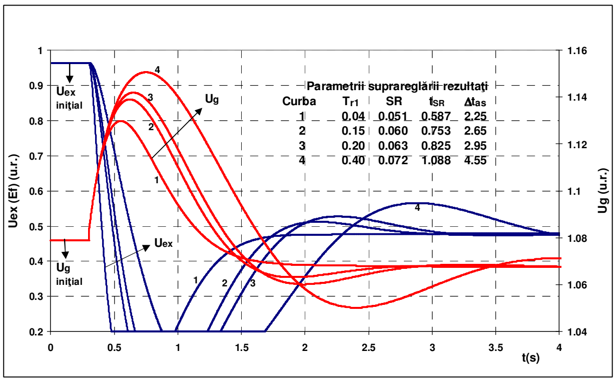

Fig. 5 Throwing rated load response curves for 4 values of AVR's T_{r1} constant

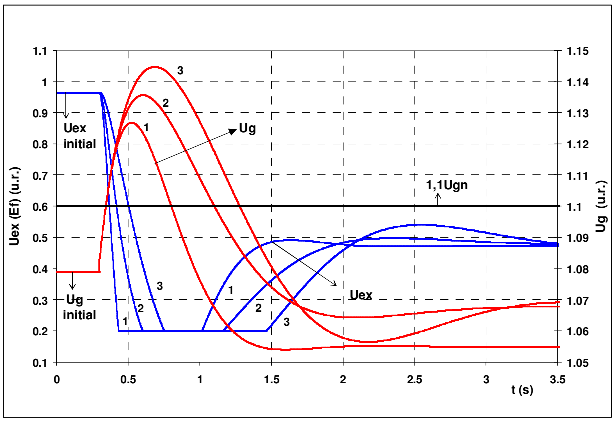

Fig. 6. Throwing rated load response curves for 3 values of AVR's T_{ru} constant

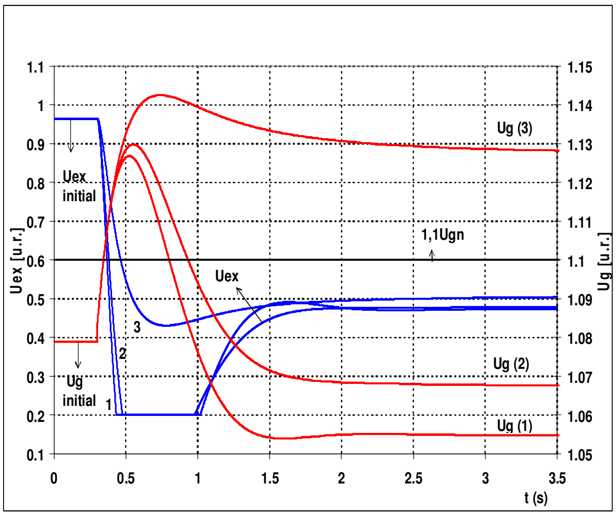

Fig. 7 Throwing rated load response curves for 3 values of AVR's K_u constant

In diagrams can follow the evolution of stationary mode, in perturbated mode for excitation voltage Uex and the generator terminals voltage Ug.

It is noted that throwing rated load occurred after 0.3 s of steady mode and excitation voltage at the generator terminals voltage begin to stabilize after 2 -3.5 s depending on the parameter that varies.

4. MESURMENT RESULTS

Tests were performed on hydro generator of 19.5 MW and 10.5 kV of HPP Lereşti, equipped with rotating exciter and a.c. reverse generator and RAT - powered digital indirectly.

The rated load throw test was performed by disconnecting block switch on the 110 kV in secondary traformer block of HPP Lereşti with generator operating at close to rated load. There were registred the generator terminal voltage and excitation voltage (Fig. 8)

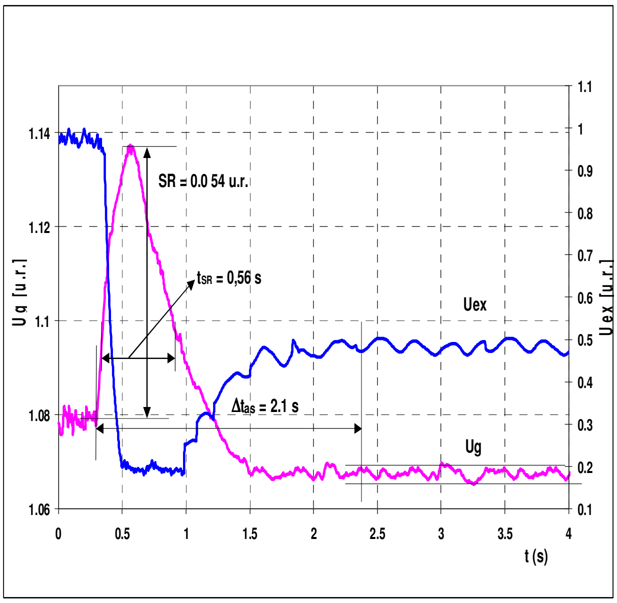

Fig.8. HG HPP Lereşti - throwing rated load test and graphic determining of the override (SR) quantities

Override sizes were determined graphically [12] by recording the terminal voltage:

- generator terminals voltage override, SR, was calculated using [12]:

$$SR = \frac{U_{g\,max} - U_{gn}}{U_{gn}} \qquad (7)$$

where:

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

U_{gn} - 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 as defined at the end of paragraph 1.

Resulting values: SR = 0.054 u.r., t_{SR} =0.56 s şi Δt_{as} = 2.1 s

5. COMPARISON BETWEEN RESULTS

Table 2 shows, for comparison, results of the calculation, the results of measurements and requirements of international standards [8, 11] for the three parameters of voltage override.

Table 2. Comparative values, calculated and measured

Values types	Sets values	Imposed values			Result		
		T_{rl}	T_{ru}	K_u	SR	t_{SR}	Δt_{as}
		s	s	u.r.	u.r.	s	s
Demands	0	≤0.1	≤ 0.3	10-50	≤ 0,1	≤1	≤ 3
Calculated	1	0.04	0.30	20	0.051	0.587	2.25
	2	0.15	0.30	20	0.060	0.753	2.65
	3	0.20	0.30	20	0.063	0.825	2.95
	4	0.40	0.30	20	0.072	1.088	4.55
	5	0.04	0.18	20	0.057	0.756	2.72
	6	0.04	0.06	20	0.066	1.053	2.9
	7	0.04	0.30	30	0.046	0.397	2.051
	8	0.04	0.30	10	0.065	>7.66	3.91
Measured	9	0.04	0.30	15	0.054	0.56	2.10

From calculated values were chosen 8 sets of distinct calculated results, for comparison and selection.

The analysis of calculation results for HG HPP Lereşti compared to international standards criteria for performance parameters resulting 5 sets of values (1,2, 3, 5, 7) which fully satisfy these criteria (table 2). For these sets of parameters corresponding sets of values for the AVR transfer function constants.

Comparing the performance parameters calculated with measured performance parameters is observed that the set of values as 1 are very close to the set of existing HG constant and determined by measurements (4.5 % – 6.6 %). Calculation error is acceptable.

So the set of values for the AVR transfer function constants for the HG HPP Lereşti determined by calculation and verified by measurements and providing performance parameters as required international standards are: T_{rl} = 0.04s, T_{ru} = 0.30s, K_u = 20 u.r / u.r.

Other values constant does not change and has no effect on the performance parameters: T_{r2} = 0.07s, T_e = 0.25s, K_e = 0.5 u.r / u.r

6. CONCLUSION

Design software delivers accurate to about ± 7% measured values for override parameters. So it has sufficient precision to predetermined transfer function constants. After setting the transfer function constants it can be set measurements which will validate the constant set or will require other set constants or change only a constant.

Computer program developed can also be used to check a set of constants already set in case of misconduct in relation between hydro-electric generator and electrical power grid. It can run variants and choose another set of constants. After setting it will be do the measures to validate this new set of values.

ACKNOWLEDGMENT

The authors thank the staff of Electrical Machines ICEMENER, Curtea de Arges Hydropower Subsidiary - HPP Lereşti, Department of Measurement, Electrical Apparatus and Static Converters from University Politehnica of Bucharest, for their support in carrying out research work led to the development of theoretical and experimental methods determining performance parameters of the interaction between hydro generator and electrical power grid.

REFERENCES

[1] Olive, D.W. - New Techniques for the Calculation of Dynamic Stability, IEEE Transactions on Power Apparatus and Systems 08/1966

[2] Mello, F.P.de - Power System Dynamics-Overview" Symposium on Adequacy and Philosophy of Modelling: Dynamic System Performance 1970, Winter Power Meeting, IEEE Publication 75CH0790-4-PWR (1970).

[3] Crary, S.B. - Power System Stability. Tranzient Stability, PH John Wiley & Sons, New York 1965.

[4] Levi, E. - State-space d-q models of saturated salient pole synchronous machines, IEEE Proceedings of Electrical Power Applications. Vol.145, No.3, pp.206-216, May 1998.

[5] Mello, F.P.de, Anderson John ,"The control of a synchronous machine using optimal control theory, Proceedings of the IEEE vol 59 nr 1 pp 25 – 35 1970.

[6] Kilyeni, St. - Numerical methods, vol. 1 şi 2, ediţiile 1 şi 2, Editura Orizonturi Universitare Timişoara, 1997, 2000.

[7] ***PE 509/1984 **-** Instructions for functional tests of systems voltage and speed automatic regulation for power units.

[8] ***IEEE Std.421.1-1986 - IEEE Standard Definitions for Excitation Systems for Synchronous Machines

[9] ***IEC 60034-16-1 : 2011- Rotating electrical machines - Part 16-1: Excitation systems for synchronous machines - Definitions

[10] ***IEC 60034-16-2 : 2012 - Rotating electrical machines Part 16: Excitation systems for synchronous machines.

[11] ***IEC/TS 60034-16-3: 1996 - Rotating electrical machines - Part 16-3: Excitation systems for synchronous machines - Section 3: Dynamic performance

[12] Herisanu, A., Cicirone, C., Dumitrescu, S., Zlatanovici, D., Method in determination of parameters of hidrogenerators voltage regulators, Journal of Sustainable Energy, Univ. Oradea , vol 3, nr.1, 2012,pag.60,