ATP modelling and Field Tests of the AC Voltage Regulator in the Palmar Hydroelectric Power Plant

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***Abstract* – This paper presents a detailed description of a synchronous generator excitation control system in the Palmar power plant, Uruguay. It also describes the most important aspects of the ATP modelling of the AC Voltage Regulator and Exciter. Some records of time response of the excitation control system to step change in input are included. Some results of ATP simulations of the field tests mentioned before are included. Finally a comparison was made between the obtained results from simulations and those obtained from field tests in order to validate the models developed.**

Keywords – excitation control system, modelling, TACS, field tests.

I. INTRODUCTION

The phenomenon of self-excitation of synchronous machines has been studied in the Palmar hydro power plant. Because of the non-linearities involved, the pole span of the circuit breakers and the travelling wave phenomenon presented in the transmission lines it was decided to use the ATP (Alternative Transients Program) as a tool for the analysis.

The over-voltage due to this phenomenon is a function of the amount of line charging, saturation of the iron, the over-speed characteristic of the turbine-generator set and the excitation response.

Palmar power plant has three hydro units of 111 MVA apparent power rating, voltage rating 15kV and the neutral of the armature winding is earthed through a 650 Ω resistance. The hydraulic turbine is a Kaplan type with nominal head 27m. The synchronous machines have been modelled using "Three-phase dynamic synchronous machine source(type- 59)", the speed governor and turbine models has been developed with TACS.

The step-up transformers have the following characteristics: voltage rating 15/500 kV, power rating 111 MVA, type of connection Dy11, neutral of the secondary winding is directly earthed. They have been modeled through the "Saturable transformer component".

The next sections are devoted to the description of the excitation control system, most important aspects of the ATP modelling, field tests description and ATP simulation of the time response to step change in input, showing that TACS is a powerful tool for solving real life problems at electrical utilities.

II. EXCITATION CONTROL SYSTEM

The basic requirement is that the excitation control system supply and automatically adjust the field current of the synchronous generator to maintain the terminal voltage as the output varies within the capability of the generator. From the power system point of view the excitation system should contribute to effective control of voltage and enhancement of system stability.

Figure 1 shows the block diagram of the Palmar excitation control system, where: the reference (Ref) represents the desired terminal voltage, the exciter provides DC power to the machine field winding, AC voltage regulator processes and amplifies input control signals to a level and form appropiate for control of the exciter, Power System Stabilizer (PSS) provides and additional input signal to the regulator to damp power system oscillations, load compensator (LD) holds constant voltage at some point electrically remoted from the generator terminal, over-excitation limiter (FCL) protects the generator field winding from overheating due to prolonged field over-current, underexcited reactive amper limit (URAL) prevents reduction of generator excitation to a level where the stability limit is exceeded. The Volts-per-Hertz limiter protects the generator and step-up transformer from damage due to excessive magnetic flux and it is disabled when the generator circuit-breaker is closed.

III. AC VOLTAGE REGULATOR AND EXCITER

Figure 2 shows the block diagram of the Palmar AC Voltage Regulator and the Exciter. Each generator has a

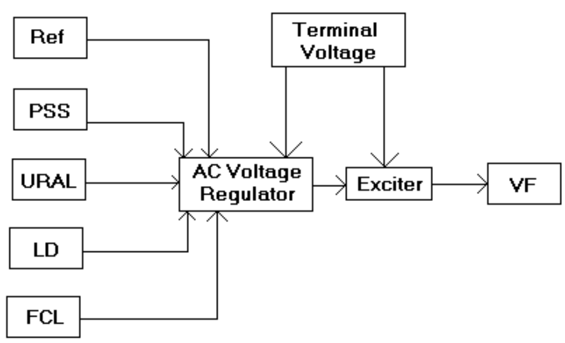

Fig. 1 Excitation control system

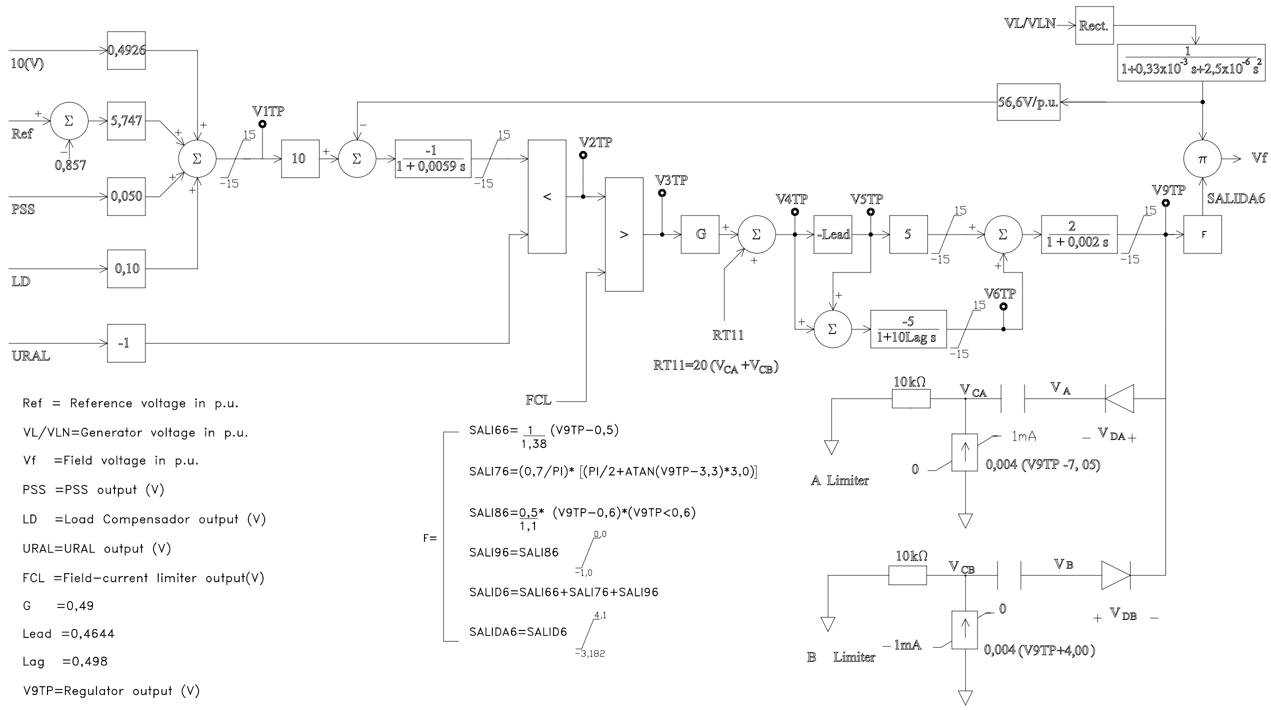

Fig. 2 Block diagram

static excitation system, in this system the excitation power is supplied through a transformer from the generator terminals and is regulated by a controlled rectifier.

A. Feedback of Generator Stator Voltage

The generator voltage (VL) is reduced through step-down transformers as shown in Figure 3. It is rectified through full-wave diode bridge and filtered through a second-order low-pass filter, their elements and values are shown in the same figure and the transfer function is also indicated in Figure 2. For rated terminal voltage the output filtered signal is equal to 56.6 V and it is compared with the set-point reference signal.

B. Comparators

The first comparator showed in Figure 2 allows the URAL to take the control of the excitation system when its output signal value it is less than the other input, in order to prevent the generator operation beyond its stability limit.

The second comparator in Figure 2 allows the FCL to take the control of the excitation system when the field current is greater than 900 A in order to limit the field voltage.

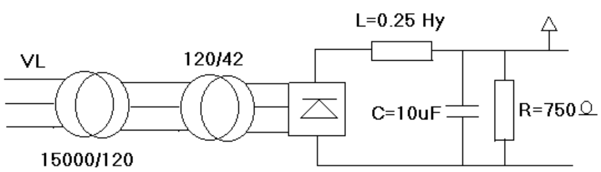

Fig. 3 Rectifier and filter

C. Gain G

Gain G is an adjustable value and it allows to regulate the overshoot of the AC voltage regulator time response.

D. Gain-Lead-Lag Transfer function

The lead-lag block is designed in order to obtain optimum damping of the voltage regulator time response, without repeated oscillations and over-damping. The transfer function, in Laplace domain, from V3TP to V9TP signals of the block diagram of Figure 2 is:

$$\frac{V9TP}{V3TP} = -G * 5 * \frac{1 + 10Lead * Lag * s}{1 + 10Lag * s} * \frac{2}{1 + 0,002s} \qquad (1)$$

The Lead and Lag parameters are derived from the values of the adjustable knobs. The last term in equation (1) is designed to amplify the input signal and filter the noise.

E. Limiter

This device has two functions: a) it ensures that the regulator output signal (V9TP) will be within a band defined by the values -4.0V and 7.05V b) it limits the rate of increase of V9TP signal in order to avoid sudden changes on it. This braking effect has a duration of 120 ms for the full range of the band. These functions are carried out through two limiter circuits, one of them (B Limiter) for the lower limit -4.0V and the other (A Limiter) for the upper limit 7.05V, as shown in Figure 4. Basically each circuit is made out of one transistor, one capacitor , one diode and resistances. When V9TP signal is within the band the transistors are turned off and the capacitor volt-

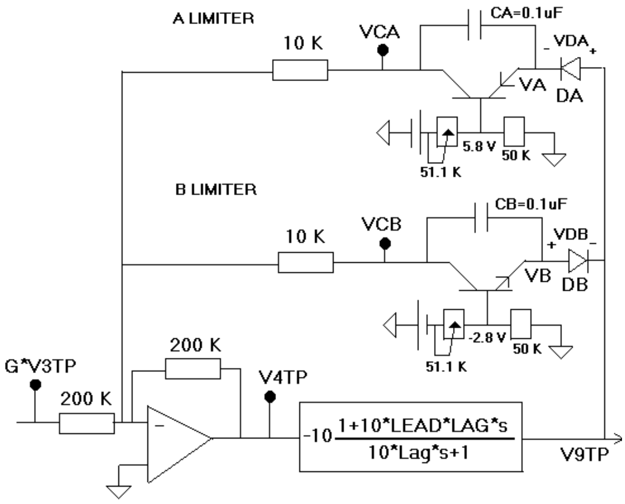

Fig. 4 Limiter

ages are equal to V9TP in steady state conditions. During transients conditions one of the diodes begins to conduct and the associated capacitor provide slow changes in V9TP. If V9TP signal exceeds the upper limit for example, the transistor turns on and injects a current in the resistance (10kΩ). The voltage VCA across this resistance is added into the closed loop in such a way that V9TP goes back inside the band. The same operating principle is valid for B Limiter.

F. Exciter

The field voltage (Vf) is the output of the controlled rectifier (full-wave thyristor bridge) fed through a power potential transformer from the generator terminals. The field voltage value in per unit is defined from the following relationship:

$$Vf = SALIDA6*(VL/VLN) \qquad (2)$$

where SALIDA6, Vf and VL/VLN are indicated in Figure 2. The regulator output signal (V9TP) controls the firing angle of the thyristors and because of the complexity of this firing circuit it was decided to find a mathematical relationship between SALIDA6 and V9TP from field tests data. The procedure developed by the authors will be described now. At the beginning it was supposed a linear relationship between V9TP and SALIDA6, some simulations were carried out in order to reproduce some records of time response to step change in input of the control system. It was founded that the simulation results did not fit accurately the field tests.

Figure 5 shows V9TP values and their corresponding Vf/(VL/VLN) values resulting from field test data (curve1).

Three operating regions were defined: a)V9TP< 0.5 V (Region 1) b) 0.5V<V9TP<2.5V (Region 2) c) 2.5V < V9TP (Region 3). Region 1 represents an unstable state of the exciter because negative field voltages can be stand during a short time before the thyristors turn-off.

Region 2 represents an stable state of the exciter and could be observed a linear relationship between the variables.

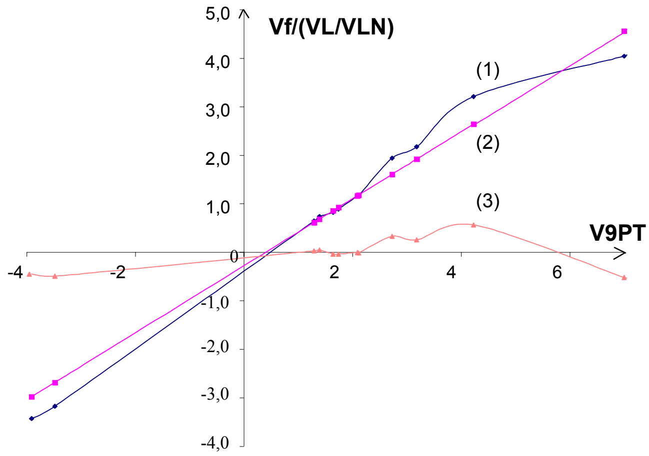

Fig. 5 SALIDA6 x V9TP

Region 3 represents a transient state of the exciter and could be observed a nonlinear relationship.

The mathematical expressions, equation (3), that define all the regions were developed in such a way that simulation results fit accurately field test data and them will be present in item V.

$$SALIDA6 = \frac{V9TP - 0{,}5V}{1{,}88V - 0{,}5V} + F1(V9TP) + \frac{0{,}7}{\pi}\left(\frac{\pi}{2} + Arc\,\mathrm{tg}\left[3*(V9TP - 3{,}3)\right]\right)$$

$$F1 = \begin{cases} 0 & V9TP \geq 0{,}6V \\ 0{,}5/1{,}1*(V9TP - 0{,}6V) & -1{,}6V < V9TP < 0{,}6V \\ -1 & V9TP \leq -1{,}6V \end{cases} \qquad (3)$$

Region 2 is defined analytically by the first term of the equation (3) as shown in Figure 5 (curve2), whereas Region 1 is defined through the addition of the first and second terms and Region 3 is represented through the addition of the first and third terms. The addition of the second and third terms is shown in Figure 5 (curve3) and the third term has negligible effect in Regions 1 and 2, for values of V9TP greater than 5V it reaches an upper limit of 0.7 pu. The values of SALIDA6 varies between -3.182 pu and 4.1 pu because of the limits imposed in the firing angles.

IV. ATP MODELLING

In this section the most important aspects of the ATP modelling of the excitation control system are going to be presented.

A. Feedback of Generator Stator Voltage Modelling

The generator voltage reduction and rectifier stages were modelled through a mathematical equation (4) and it was implemented utilizing Fortran expressions in TACS. In this equation VLN is the rated generator voltage and Va, Vb and Vc are the instantaneous phase-neutral generator voltages, passed into TACS through Type 90 Sources.

$$Vrect = \frac{ABS(Va) + ABS(Vb) + ABS(Vc)}{\frac{VLN * \sqrt{2}}{\sqrt{3}}} * \frac{\pi}{6} \qquad (4)$$

B. Comparators modelling

The comparators used for URAL and FCL protection functions were modelled in TACS through Device Code=63 (instantaneous minimum/maximum).

C. Gain-Lead-Lag Transfer function modelling

The transfer function of equation (1) was represented in TACS with S-blocks.

D. Limiter modelling

"A Limiter" circuit was modelled as a network made out of passive elements, sources, and a diode as shown in Figure 6. The network is fed by V9TP TACS signal as a Type 60 Source. The transistor was represented as a controlled current source and it injects current (transistor turns on) when V9TP signal exceeds the upper limit 7.05V. The value of the current source is calculated in TACS and is passed to the network as a Type 60 Source. In ATP program a diode can be represented as a switch wich closes when the voltage from anode to cathode becomes positive, however operation below reverse blocking region can not be simulated. One of the diodes of the limiter circuit shown in Figure 4 allows the charging of the capacitor through their inverse resistance. In order to simulate this phenomenon the authors decided to model the diodes as nonlinear resistances utilizing Type 92 "4444" nonlinear element. The non-linearity is represented by a piecewise-linear characteristic of current and voltage as shown in Figure 7. The VCA output signal of the network of Figure 6 is passed into TACS in order to build the RT11 output signal of the Limiter circuit and it is added to the closed-loop. If the capacitors are not adequately initialized then long simulation times up to reach steady state conditions are expected. The steady state initialization of the capacitors were performed through Near-DC sources in the phasor solution using a f=0.0001 Hz. In the time domain simulation these sources were connected to the network during three time steps.

E. Exciter modelling

The mathematical expressions of equation (3) were implemented in TACS through Fortran expressions and order-zero blocks with static limiters in order to take into account the saturation levels.

IV. FIELD TESTS AND SIMULATIONS

During the development of the block diagram of Figure 2 several field tests were carried out at Palmar power plant in order to calculate and adjust several parameters (gains, time constants,etc) of the control system. Two of them were considered very important because the time response of the generator terminal voltage to a step change in input of the excitation control system was registered. In this section the field test conditions and some records are presented. The ATP Program was used to simulate these two field tests in order to validate the mathematical models developed and also the simulation results are included.

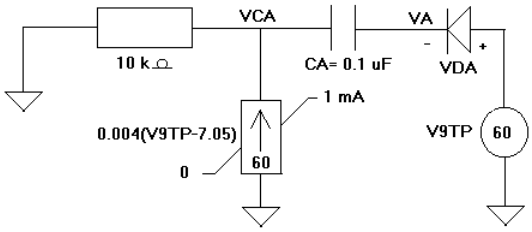

Fig. 6 A Limiter

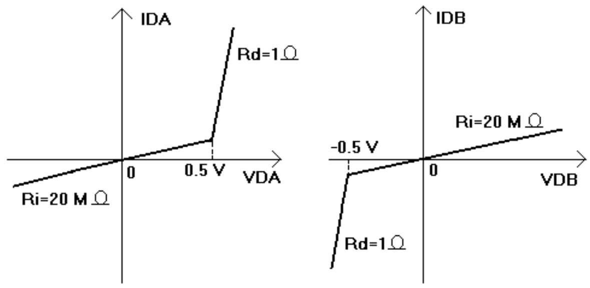

Fig. 7 Diode models

A. Field Test Conditions

In order to get the time response to step change in input in the excitation control system two field tests were carried out in Generator 3 of Palmar power plant. The tests were performed with the generator in a no-load condition and the set-point reference signal was changed in order to obtain a desired terminal voltage of 16 kV starting from rated voltage 15 kV and inversely. The sampling rate in the records was equal to 50 samples per cycle. During the tests the voltages on pins V3TP, V9TP, RT11 on the AC regulator board were recorded. It was also registered a DC voltage signal proportional to the generator terminal voltage, named TGEN.

B. ATP Simulations of Field Tests

The AC voltage regulator and the exciter described in item III and modelled according to item IV were implemented in ATP program with the goal to reproduce the field tests mentioned above. The generator was modelled with "Three-phase dynamic synchronous machine source (type- 59)" in order to simulate the whole time response of the set generator and excitation system, this is very important for self-excitation phenomenon and other transient disturbances.

C. Simulations and Records of Field Test I

If an adequate positive step change is applied in the set-point reference then the generator voltage varies from 15 kV to 16 kV (Field Test I). In practice it was implemented through a reduction of the feedback gain value from 56.6 to 52.65 (V/pu). In Table I the initial and final values of the generator terminal voltage (VL) and field voltage (Vf), resulting from the field test and ATP simulation are shown. From the results presented in Table I it can be concluded that there is a good agreement between field

Table I Test and ATP results

	Field Test	ATP
Initial VL (kV)	15.12	15.12
Final VL (kV)	16.245	16.25
Initial Vf (V)	190.0	193.6
Final Vf (V)	218.0	218.1

tests and ATP simulations.

Figure 8 shows V3TP voltages from test I (1) and from the simulation (2). It can be observed a good agreement in the decreasing region and in the peak value, the simulation presented a time delay of 20 ms in the increasing region.

Figure 9 shows V9TP voltages from test I (1) and the simulation (2). The peak value of the simulation presented an error of 5.3% when compared with the field test value.

Figure 10 shows RT11 voltages from test I (1) and the simulation (2). The peak value of the simulation gave an error of 13.3% and the simulated decreasing region presented a delay of 12ms.

Figure 11 shows TGEN voltages from test I (outer curve) and simulation (inner curve). This figure shows the whole time response of the set generator and excitation system and it could be observed a very good agreement between the curves. The generator voltage takes 350ms to reach the desired value of 16 kV.

Figure 12 shows the field voltage resulting from the simulation. The step applied led SALIDA6 signal to its upper saturation value and then from equation 2 the field voltage must increase linearly.

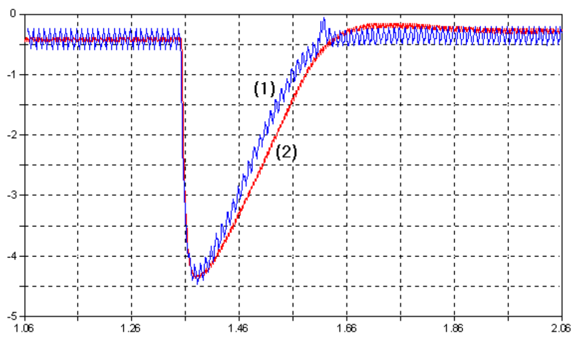

Fig. 8 V3TP voltage

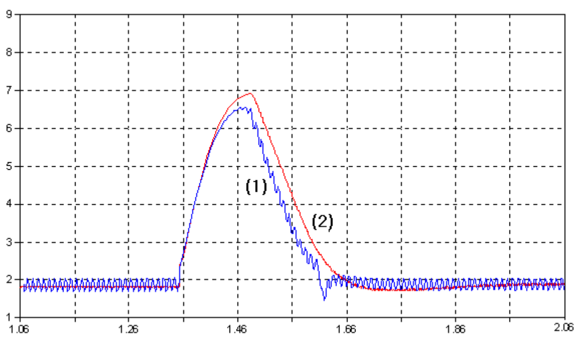

Fig. 9 V9TP voltage

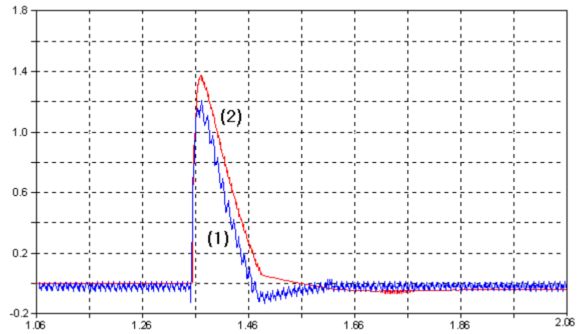

Fig. 10 RT11 voltage

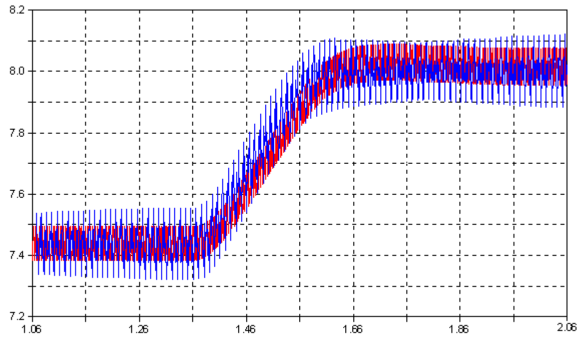

Fig. 11 TGEN voltage

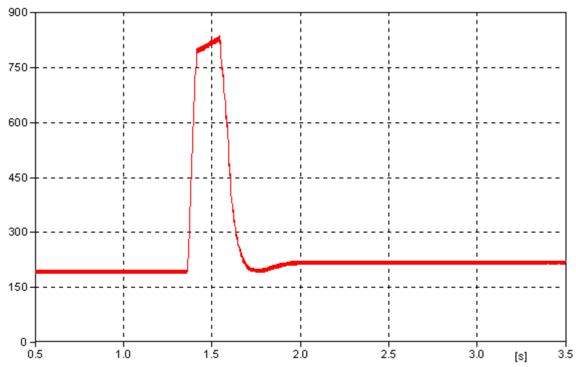

Fig. 12 Vf voltage

D. Simulations and Records of Field Test II

If an adequate negative step change is applied in the set-point reference then the generator voltage varies from 16 kV to 15 kV (Field Test II). In practice it was implemented through a raise of the feedback gain value from 52.65 to 56.6 (V/pu).

Figure 13 shows V9TP voltages from test II (1) and the simulation (2). It can be observed a good agreement between the curves and the peak value of the simulation presented an error of 2.2% when compared with the field test value. Figure 14 shows RT11 voltages from test II (1) and the simulation (2), it can also be observed a good agreement between the curves. Figure 15 shows TGEN voltages from test II (outer curve) and the simulation (inner curve).

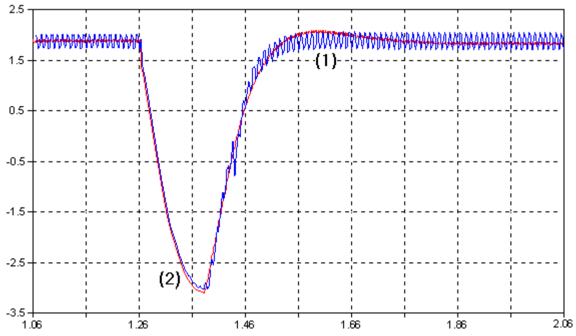

Fig. 13 V9TP voltage

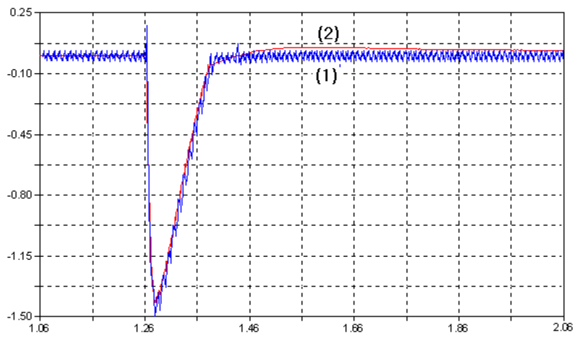

Fig. 14 RT11 voltage

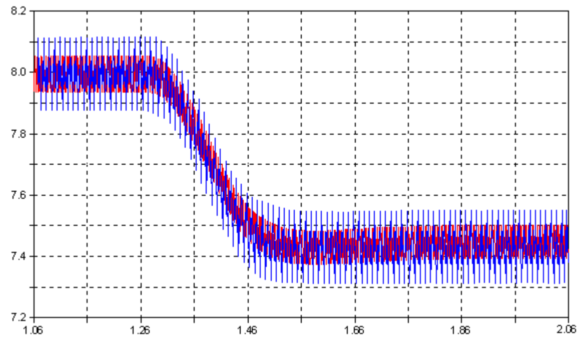

Fig. 15 TGEN voltage

It could be observed a very good agreement between the curves. The generator voltage takes 350ms to reach the desired value of 15 kV.

VI. CONCLUSIONS

In the present work the AC Voltage Regulator and the Exciter of the generators of the Palmar hydro power plant were described.

The mathematical model of the AC Voltage Regulator and the Exciter was presented as a complete block diagram in Laplace domain.

The mathematical models were implemented mainly in TACS routine of ATP program and it was explained in detail how this implementation was made.

From the comparison between field test records and simulation results it can be concluded that the models developed and their implementation are very accurate.

At this time these models are being used in the investigation of the self-excitation phenomenon in the Palmar power plant by the authors.

During the development of this work the authors verified that TACS is a powerful tool for solving real life problems at electrical utilities in the sense that it permits to improve the models until their responses fit the field test records accurately.

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