Analysis of Self-Excitation in the Palmar Hydroelectric Power Plant

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Abstract - **This article presents a brief description of the phenomenon of self-excitation of synchronous machines, which is a problem detected in the Palmar hydro power plant in Uruguay. First, a comparison between the results obtained from the modelling of a Palmar generator unit utilizing the Three - Phase Dynamic Synchronous Machine model of the ATP (Alternative Transients Program) and the data supplied by the manufacturer is made. After simulating the phenomenon of self - excitation through ATP program in the Palmar hydro power plant, some results are presented. These results show how the automatic voltage regulator, the speed governor and the step-up transformer saturation influence this phenomenon. Finally, some corrective actions to be taken are presented in order to prevent serious overvoltage conditions (resulting from the full load rejection) from happening.**

Keywords: Electromagnetic Transients, Load Rejection, Self-Excitation, Modelling, ATP.

I. INTRODUCTION

The 500 kV voltage level Palmar substation (PAL), which belongs to the transmission system of Uruguay, bears the following characteristics: a) Three hydro units of 111 MVA apparent power rating are connected to it. b) Four transmission lines (PAL-A500, PAL-B500, PAL-SJ1, PAL-SJ2) connect the station to the 500 kV voltage level network c) It has an autotransformer of 200 MVA apparent power rating and voltage ratings 500/150/31.5 kV d) It has a scheme of one and a half circuit breaker. Fig. 1 shows the one-line single diagram of this substation.

Ever since the Palmar hydro power plant was put into service in 1981, it has not been possible to use the scheme one and a half circuit breaker due to the phenomenon of self-excitation of its generator units.

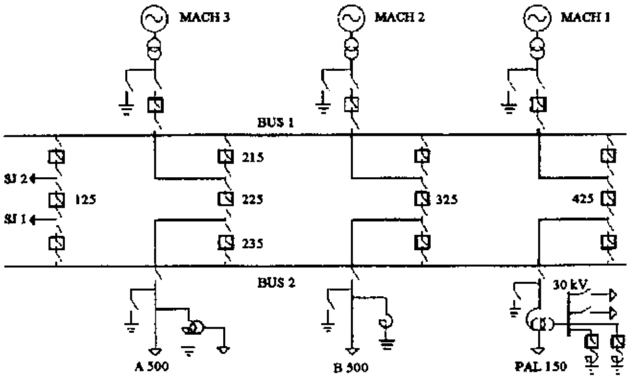

Fig. 1. Palmar Substation

The operation of the Palmar substation, with all equipments (switchgears and circuit breakers) in service or some of them out of service, is restricted when the power plant is generating because of the risk of self-excitation. In the first case the restrictions are: circuit breakers 125, 225, 325 are always open and the rest of them are always closed. In the second case the restriction consists of the prohibition for some generator units to come into service.

To set an example, the following situation can be considered (see Fig. 1): Circuit breaker 215 is in maintenance and machine 3 is generating. If a load rejection happens in the receiving end A 500 of the transmission line (first contingency) and opens circuit breaker 235, but does not open circuit breaker 225 at the same time (second contingency) the result will be that machine number 3 will be left connected to an unloaded transmission line. Therefore, that machine must not come into service. This example shows how unavailabilities promote additional costs associated with the deviation from the optimum dispatch and the loss of reliability. On the other hand, the transmission system of Uruguay has undergone some changes in its topology. Due to this fact it has become necessary to analyze how those changes influence the aforementioned phenomenon. Because of the previously stated reasons, a thorough analysis of the problem has been conducted.

II. SELF-EXCITATION [1] [2] [3]

In applications involving the use of long distance transmission and EHV systems the problem of load rejection might arise. One or more generators with some initial loadings are suddenly left connected to a transmission system disconnected from the loads and remaining power system. This condition can give rise to serious overvoltage conditions, especially when the charging of the transmission lines is excessive relative to the generation that remains connected. The so called self-excitation problem, is an electromagnetic phenomenon where the generators and transmission lines become in an unstable system, the voltage amplitude grows in an oscillatory manner and the frequency varies. The maximum overvoltage reached is a function of the amount of line charging, saturation of the iron, the overspeed characteristics of the turbine-generator set and the exciter response.

In order to avoid its occurrence in electrical systems the power plant must be operated in such a way that the number of generators, the number of transmission lines connected to it and the shunt reactors banks are enough to compensate the charging of the transmission line rejected.

In some publications on the problem of self-excitation, in order to obtain practical results through analytical analysis

(Park's theory), considerable simplifications were assumed, such us neglecting the transformatory terms of the synchronous machine and a.c. transients in the load, etc . If all of these factors are taken into account and symetrical load and constant speed are assumed a characteristic equation (polynomial of the seventh order) is obtained. From this fact the authors think that ATP program or similar tools are more appropiate to analyze the problem.

III. NETWORK REPRESENTATION

The power network resulting from the double contingency described in the introduction is schematically indicated in Fig. 2, where:

G - One generator, voltage rating 15 kV and power rating 111 MVA and the neutral of the armature is earthed through a 650 Ohms resistance
T - Step-up transformer voltage ratings 15/500 kV and power rating 111 MVA, type of connection Dyll, neutral of the secondary winding is directly earthed
L - Transmission line Palmar-A 500 voltage rating 500 kV with length equal to 228.9 km
R - Reactor bank of 50 MVAr

The ATP program is the tool that was used to both simulate the full-load rejection at receiving end A 500 and detect the existence or nonexistence of self-excitation.

A. Generator

The methodology employed was to model a machine at Palmar using the "Three Phase Dynamic Synchronous Machine Source" of the ATP following the rules of the Rule Book [7].

After that, the ATP was used as a "laboratory" in order to simulate different tests. Based on those tests, and through measurements made in the graphics obtained from the simulations, the values of some machine parameters were determined. Those parameters were later on compared with the ones supplied by the manufacturer. This allowed to test the quality of the modelling performed.

The negative-sequence, zero-sequence and the short-circuit tests were simulated. Negative-sequence test: three negative-sequence current sources (the same value as the rated armature current) were connected across node pairs Phase A- Ground, Phase B- Ground and Phase C- Ground, and the field voltage was set equal to zero.

Zero-sequence test: three zero-sequence current sources (the same value as the rated armature current) were connected across node pairs Phase A- Ground, Phase B- Ground and Phase C- Ground, and the field voltage was set equal to zero.

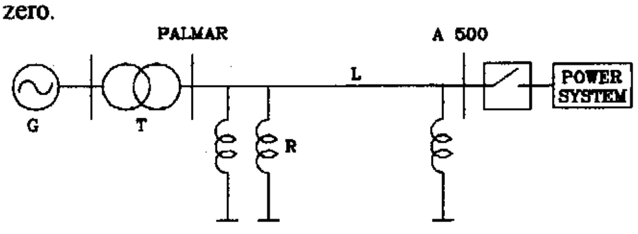

Fig. 2. Power Network Configuration

Short-circuit test: the machine is in a no-load condition at rated armature voltage and a three-phase short circuit is applied to its terminals.

The results of the simulations, as well as the data from the manufacturer, and the corresponding errors are presented in Table I.

From Table I, it can be concluded that the modelling performed is a good representation of the synchronous machine.

It is worth pointing out that the saturation curve of the machine was included in the model mentioned above.

B. Excitation System

Each generator unit of the Palmar hydro power plant has a static excitation system with negative voltage capability and without negative field current capability. The implications of having or not having negative field current capability are explored in connection with the problem of protective system equipment against the possibility of self-excitation. Fig. 3 shows the block diagram of the excitation system where:

VF - Exciter output voltage
VL - Generator terminal voltage
VREFPU - Regulator reference voltage setting
URAL - Underexcited reactive ampere limit
Current Limit - Rotor current limit
SALID6 - Regulator output voltage
VFMAX, VFMIN - Maximum and Minimum values of regulator output voltage

The excitation system shown in Fig. 3 was implemented in TACS (Transient Analysis of Control Systems - ATP). The ATP program was used to simulate the closed-loop time response to a step change in input with the generator in a no-load condition. This response was compared to the one found in the Report on Excitation System Commissioning Test for Palmar Units. The conclusion that this comparison brought about is that the wave shapes are the same. The Underexcited Reactive Ampere Limit (URAL) is used to restrict the operation of the generator in the underexcited region. If operation in the underexcited region exists, and a decrease in excitation occurs, the generator may fall out of synchronism. The function of the URAL is to set a limit in the underexcited region in which the generator may safely operate. This device has two independent operational states and it is nonlinear. Due to this, it cannot be represented through a block diagram. Nevertheless, a model whose parameters were set so as to reproduce the reactive capability curve in the underexcited region given by the manufacturer, was constructed in TACS.

Table I - Tests results

Parameter	Manufacturer	Calculated	error %
$X_2(\Omega)$	0.48649	0.46929	3.53
$X_0(\Omega)$	0.20270	0.20276	0.03
$X_d(\Omega)$	1.459	1.445	0.96
T_a(ms)	210.00	275.49	31.00
T'_d(s)	2.7	2.8	3.70
$X'_d(\Omega)$	0.5473	0.5485	0.20
T''_d(s)	40.0	35.5	11.00
$X''_d(\Omega)$	0.4257	0.4072	4.30
T'_{do}(s)	7.10	7.38	4.00
T''_{do}(s)	0.0500	0.0478	4.40

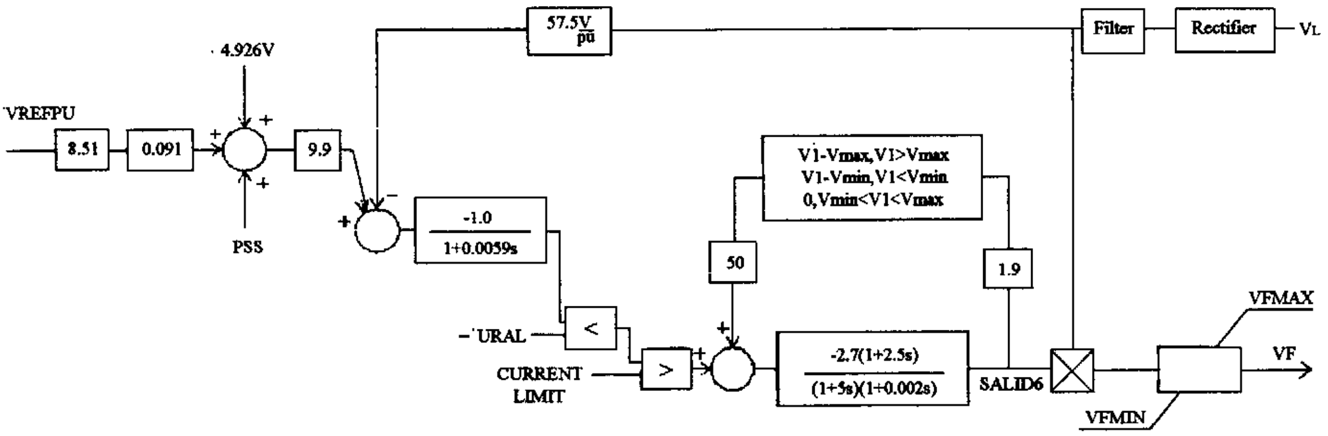

Fig. 3. Block diagram of the excitation system

C. Speed Governor

The speed governor type is mechanical-hydraulic. Fig. 4 shows the block diagram of the speed governor and the Kaplan turbine, where:

CF - Regulator reference power setting
Pe - Generator active power output
PN - Rated active power
Δf - Frequency error
fo - Nominal frequency (50 Hz)
ΔY - Gate position
Yo - Maximum gate position
Δ Pm - Mechanical power
e - Speed droop
Tw - Water starting time

The hydrogovernor-turbine shown in Fig.4 was implemented in TACS.

D. Transmission System

The step-up transformer consists of three single units and was modelled through the Saturable Transformer Component. The iron losses, along with its saturation, were considered. The transmission line was modelled through the trasposed distributed-parameter transmission line model. The reactors were modelled as lumped elements.

IV. SYSTEM STUDIES

In order to analyze the self-excitation problem in the network shown in Fig.2, a number of transient studies have been carried out to calculate overvoltages following full load rejection at A 500 bus bar. The network conditions before the load rejection shown in Fig.5 were chosen as if the machine were working in the overexcited region. This being the worst operating condition for the machine since it has to go from the overexcited region to the underexcited region after the load rejection.

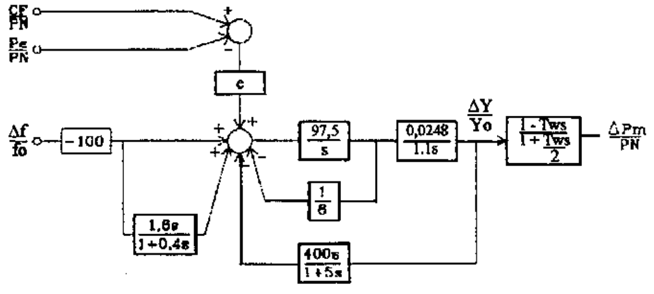

Fig. 4. Block diagram of the speed governor and the turbine

A. Worst case

In this case, the load rejection phenomenon was simulated by an opening of the circuit breaker 15 cycles after the simulation had been started. The excitation control system, speed governor and step-up transformer saturation were not taken into account, in this way, only the saturation of the machine limits the overvoltages. Therefore, the worst voltage rise and the worst voltage rate of rise are expected. The obtained results will be compared with the ones obtained when the elements formerly mentioned were included in the simulation. In this manner, it will be possible to know their effectiveness in the control of the problem. Fig.6 shows the voltage wave shape, Phase C-Neutral, in the high voltage side because the circuit breakers are placed at 500 kV voltage level. For instants of time 313 ms and 322 ms, the overvoltages reached values 1.66 pu and 2.19 pu respectively. Such values are considered too high. It is also observed that the voltage amplitude grows in an oscillatory manner indicating the presence of self-excitation.

B. The effect of the excitation control system (Closed-Loop)

In this case the closed-loop of the excitation control system was modelled.

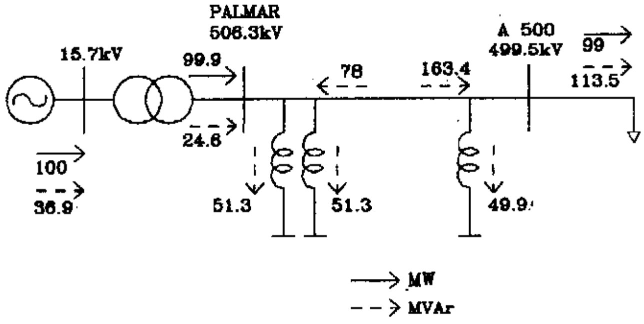

Fig.5. Network conditions

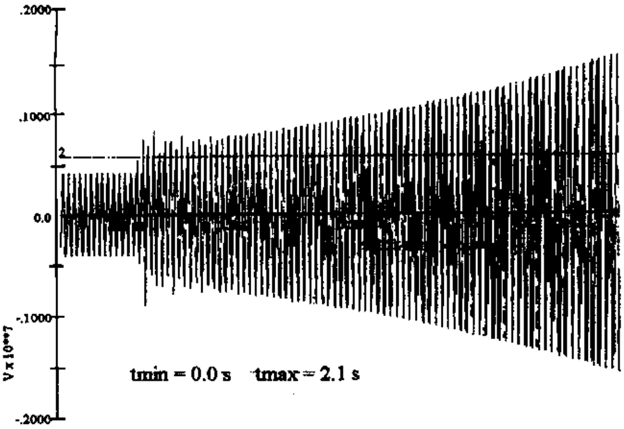

Fig.6. Voltage Phase C-Neutral (Worst Case)

The same load-rejection phenomenon (Case A) was simulated again.

The excitation system was designed in such a way that the voltage applied to the field winding lies within values -701 V and +750 V.

Fig. 7 shows the voltage wave shape, Phase C- Neutral in the high voltage side.

For instants of time 313 ms and 322 ms the overvoltages reached the same values as in Case A. The overvoltages are characterized by an almost instantaneus rise at the instant of rejection follow by a more gradual rise so that the first peaks can not be controlled by the excitation control system.

It can be concluded that the excitation control system effectively controlled the overvoltage magnitudes between 0.4 and 2.1 seconds.

It's important to remark that, in the event of self-excitation, the excitation control system postpones for a time the inevitable rise of terminal voltage thereby providing additional time to take corrective actions [3].

For the Palmar substation, the circuit breaker capability to interrupt was specified in 1.4 pu (base voltage 500 kV), represented as a horizontal line in Fig. 7. Reference [3] established having negative field current capability as a very important fact because it allows the control of the voltage rate of rise and permits corrective measures. Assuming that negative field current is allowed to circulate, there is a little margin to open between 1.75 and 2.1 seconds as shown in Fig. 7.

Unfortunately, the excitation system under consideration does not have the characteristic just pointed out. For instant of time 1.02 seconds the field current goes through zero thus any switching action up to this time will occur at levels beyond the circuit breaker capability to interrupt.

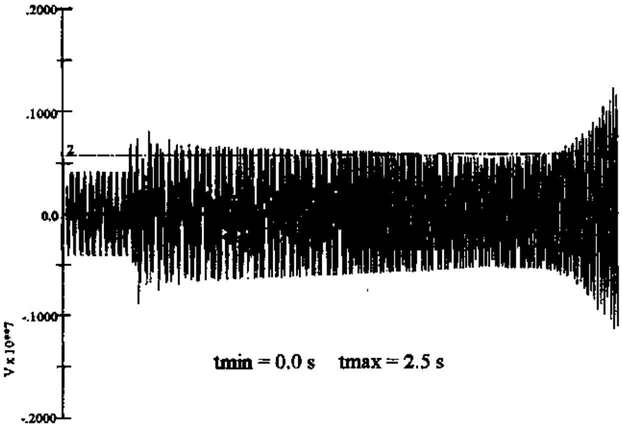

Fig. 7. Voltage Phase C-Neutral (Closed-Loop)

C. The effect of the speed governor

In this case the closed-loop of the excitation control system and the speed governor were taken into account. The same load-rejection phenomenon (Case A) was simulated again.

Fig. 8 shows the voltage wave shape, Phase C- Neutral in the high voltage side.

In the former cases the speed governor was not taken into account, thus the ATP logic held the external mechanical power applied to the mass on the shaft constant [8]. In fact it doesn't have physical meaning because there is an initial power surge which is oppositive to that of the direction of change in gate position. This is because, when the gate is suddenly closed, the flow does not change inmediatelly due to water inertia, however, the pressure across the turbine is increased, causing the power to increase. As shown in the block diagram of Fig. 4 the speed droop, gate position and transfer function of the turbine were modelled, therefore the turbine power output changes (due to the load rejection) were simulated.

From Fig. 8 it can be observed that the voltage amplitude increased in relation to Case B because of a greater change in the frequency. For cases B and C, the deviations from the nominal frequency achieved values 15.8 % and 18.9% respectively. The speed governor controls the speed after 2.3 seconds, so that it doesn't have any influence on the phenomen under study.

It is important to remark that in this case the circuit breakers can not open after the load rejection.

D. The effect of the step-up transformer saturation

In this case the closed-loop of the excitation control system, the speed governor and the step-up transformer saturation were taken into account. The same load-rejection phenomenon (Case A) was simulated again.

Fig. 9 shows the voltage wave shape, Phase C- Neutral in the high voltage side.

The manufacturer did not supply the value of air-core

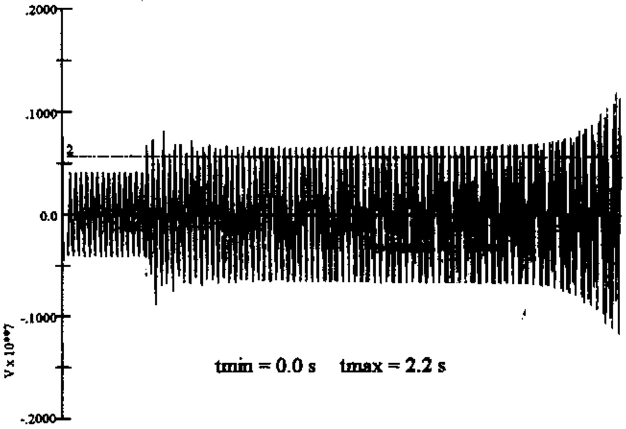

Fig. 8. Voltage Phase C-Neutral (Speed Governor)

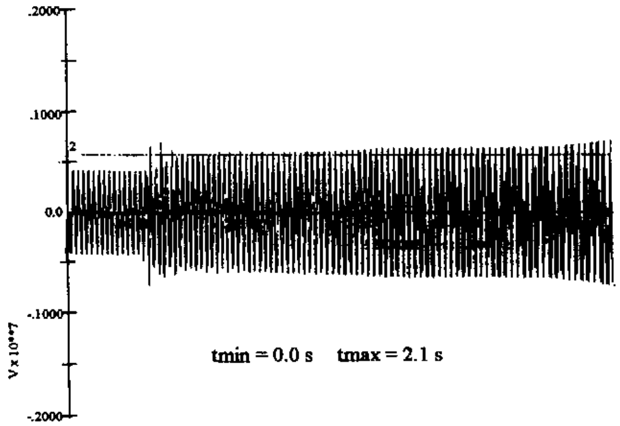

Fig. 9. Voltage Phase C-Neutral (Transformer Saturation)

inductance, so that a typical value equal to 2 times short-circuit inductance was selected [8].

In relation with the former case, the transformer saturation caused a reduction of 8.3% in the overvoltage values. It is also observed that self-excitation voltages do not rise too fast, but the circuit breakers can not open after the load rejection.

E. The effect of the excitation control system (URAL)

In this case, the closed-loop of the excitation control system, the speed governor, the step-up transformer saturation and the URAL were taken into account. The same load-rejection phenomenon (Case A) was simulated again.

Fig. 10 shows the voltage wave shape, Phase C- Neutral in the high voltage side.

The function of the URAL is to increase the voltage applied to the field winding in order to prevent the generator from operating in an unsafe portion of the underexcited region. As a result, the generator terminal voltage increases and this leads to a rise in the reactive power generated by the unloaded transmission line. The generator has to absorb this excess of reactive power, therefore, the URAL operates again. The terminal voltage increases even faster as the excitation control system is now under conditions of positive feedback. Fig. 10. shows this undesirable effect.

V. CORRECTIVE ACTIONS

The problem is not guaranteeing the impossibility of self-excitation, but ensuring that if self-excitation conditions arise, the phenomenon can be detected, and consequently, adequate corrective measures can be taken before hazardous conditions develop.

Keeping this in mind, the authors have considered the following corrective actions up to now: either to change all circuit breakers at Palmar power plant, or to add a bank of shunt reactors to the 500 kV side of each step-up transformer.

In relation to the first corrective action, the circuit breaker capability to interrupt must be specified equal to 1.7 pu (base voltage 500 kV). Any switching action at safe voltage levels should occur between 6.5 and 34 cycles after the load rejection.

In relation to the second corrective measure, some preliminary load-flow studies were conducted. The voltage profile in the power network under heavy load condition and for different megavar values of the shunt reactor bank was calculated. Two cases were selected: a) without URAL and a reactor bank of 30 MVAr b) with URAL and a reactor bank of 40 MVAr.

In case a), the URAL was disconnected due to its negative effect. It is necessary to design a protection to remove URAL when the generator and transmission line are disconnected from the load and remaining power system.

Fig. 11 shows the voltage wave shape, Phase C- Neutral in the high voltage side.

From this figure it can be concluded that any tripping should occur between 40 and 60 cycles after the load rejection. A security margin of 10% was adopted.

Fig. 12 shows the voltage wave shape, Phase C- Neutral in the high voltage side from case b).

This figure shows that any switching action should occur between 31 and 51 cycles after the load rejection. The same security margin was adopted.

It is important to remark that in both cases the self-excitation phenomenon did not disappear. As a result, the philosophy of protection against self-excitation should be designed in order to allow necessary switching actions at safe voltage levels.

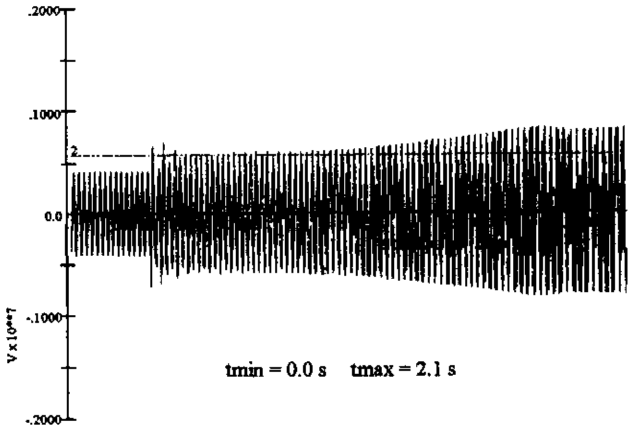

Fig. 10. Voltage Phase C-Neutral (URAL)

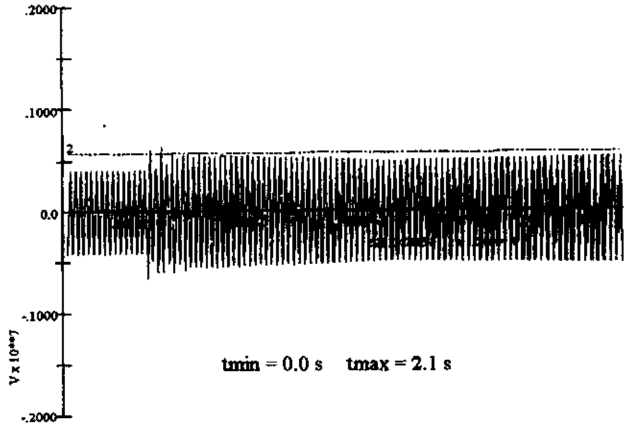

Fig. 11. Voltage Phase C-Neutral (30 MVAr)

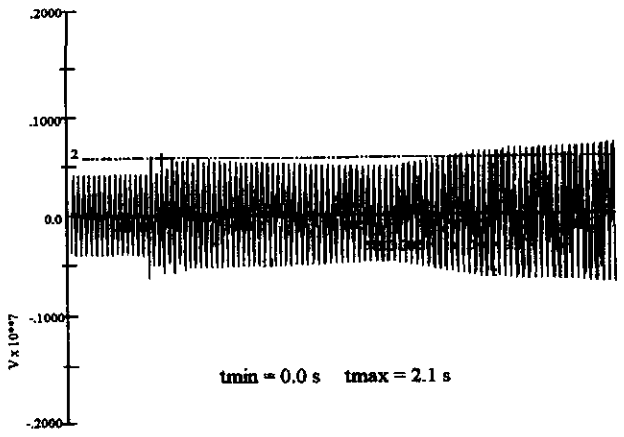

Fig. 12. Voltage Phase C-Neutral (40 MVAr)

VI. CONCLUSIONS

In the present work the first results related to the phenomenon of self-excitation in the Palmar hydro power plant are presented.

The Three-Phase Dynamic Synchronous Machine Source of the ATP program is a good representation of the synchronous machine at Palmar power plant.

TACS is a very suitable tool for the simulation of the excitation control system and the speed governor associated with rotating machinery.

The influence of the excitation control system, the speed governor, the step-up transformer saturation and the URAL were analyzed in relation to the phenomenon under study.

The closed-loop of the excitation control system reduced and controlled the overvoltage magnitude resulting from the full load rejection. In the event of self-excitation, negative current capability has a little effect on the control of the overvoltages.

The voltage amplitude increased due to the mechanical dynamics of the speed governor and turbine.

The step-up transformer saturation caused a reduction in the overvoltage values and the self-excitation voltages do not rise too fast.

Corrective actions such as changing all circuit breakers at Palmar power plant or adding a bank of shunt reactors to the 500 kV side are necessary in order to allow any switching action before dangerous conditions develop.

The authors will conduct more research in this problem in order to improve the operation of Palmar substation. The following studies will be carried out in order to know what is going to happen when:

a) two or three generators are left connected to the unloaded transmission line Palmar - A 500
b) an autotransformer with a reactor bank of 60 MVAr connected to its tertiary winding (see Fig. 1.) is in or out of service during the load rejection
c) a full load rejection occurs at the receiving end of the transmission line Palmar - B 500
d) a full load rejection occurs at the receiving ends of both lines, A 500 and B 500
e) the interconnection lines Palmar- SJ 1 and Palmar- SJ 2 are in or out of service during the load rejection

VII. ACKNOWLEDGMENT

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