Design and Implementation of a Protection System against the Self-excitation Phenomenon in Punta del Tigre Thermal Power Plant

C.R. Saldaña, G. R. Calzolari, C.M. Sena

Abstract-- **A new thermal power plant denominated Punta del Tigre was built as a result of energy system planning in Uruguay. The electrical power generated by the power plant is supplied to the transmission network at 500 kV voltage level. In applications involving the use of long transmission lines and EHV systems, the problem of load rejection might arise, giving rise to the self-excitation phenomenon. As a result of a set of contingencies considered in the 500 kV transmission network, the self-excitation phenomenon in Punta del Tigre thermal power plant was studied with the ATP (Alternative Transients Program). One of the main conclusions from the study carried out, was the need to design a protection system against the self-excitation phenomenon to be installed in the power plant. This paper focuses on the most important aspects of the design of the protection system performed. In order to implement the solution commercial relays were chosen and some tests were carried out at the factory. In this work the values of the final settings, the operating time values of the relays and the trip logic are presented. Finally, from the test results it was concluded that the protection system fulfilled all the requirements. This protection system is in operation at present.**

***Keywords*: Self-excitation, Protection system, ATP.**

I. Introduction

A new thermal power plant denominated Punta del Tigre was built as a result of energy system planning in Uruguay. This power plant has six aeroderivative gas turbine units of 63.5 MVA apparent power rating, 11.5 kV voltage rating, nominal speed 3000 rpm, one pole pair and maximum power 50.8 MW. The electrical power generated by the power plant is supplied to the transmission network at 500 kV voltage level. Fig. 1 shows a schematic one-line single diagram of the electrical connection of Punta del Tigre power plant to the network. Each of the step-up transformers has 64 MVA apparent power rating, voltage ratings 11.5/150 kV and type of connection delta/wye.

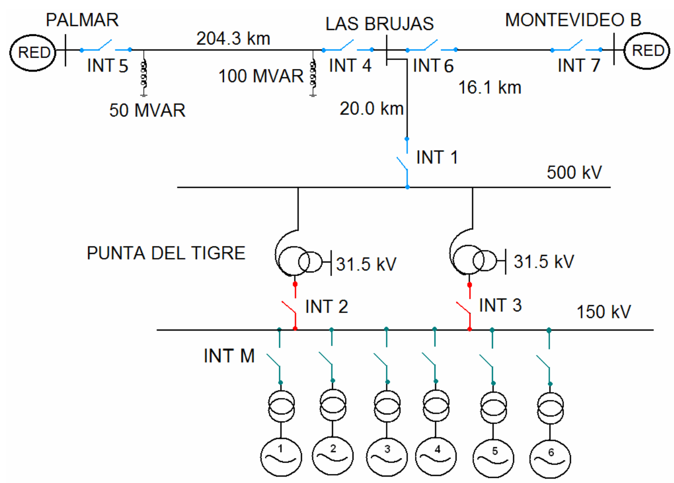

Fig. 1. Schematic electrical connection of the Punta del Tigre power plant

Each of the two autotransformers has 300/300/90 MVA apparent power rating, voltage ratings 500/150/31.5 kV and type of connection wye/wye/delta.

The generators are dispatched at full load due to economic reasons. As a consequence, the maximum value of the reactive power absorption is 20 MVAr, which is insufficient to control the voltage at 500 kV voltage level. For this reason there are three shunt reactors of 30 MVAr, each of them could be connected to the 31.5 kV bus bar.

In applications involving the use of long transmission lines and EHV systems, the problem of load rejection might arise, giving rise to serious overvoltages, especially when the charging of the transmission lines is excessive to the generation that remains connected. The self-excitation phenomenon could be developed under this situation [1], [2]. The overvoltage caused by this phenomenon is a function of the amount of line charging, saturation of the iron, the overspeed characteristic of the turbine-generator set, and the excitation response.

As a result of a set of contingencies considered in the 500 kV transmission network, the self-excitation phenomenon in Punta del Tigre thermal power plant was studied. The decision to use the ATP (Alternative Transients Program) was because of the non-linearities involved, the transient recovery voltage on the circuit breakers and the traveling wave phenomenon presented in the transmission lines, among other things.

This paper is organized as follows. Section II presents the

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Paper submitted to the International Conference on Power Systems Transients (IPST2015) in Cavtat, Croatia June 15-18, 2015.

self-excitation case studies and some simulation results. Section III focuses on the protection system design against self-excitation phenomenon. Section IV describes the protection system tests carried out at the factory. Finally, Section V presents the conclusions.

II. Self-Excitation Case Studies

Supposing that the transmission line Las Brujas – Montevideo B is out of service, circuit breakers INT6 and INT7 opened, the following contingencies are considered: a) a load rejection happens: circuit breaker INT5 opens at the Palmar end of the transmission line Palmar – Las Brujas (first contingency) b) a direct transfer trip is initiated in order to open circuit breaker INT4, but it does not open (second contingency). As a result, the power plant will be left connected to an unloaded transmission network, giving rise to the self-excitation phenomenon. Considering that the transmission line Las Brujas – Montevideo B is in service, circuit breakers INT6 and INT7 closed, another set of contingencies should be analyzed, leading to the same situation. In order to define the case studies, a different number of machines and autotransformers were considered in service. Each of the machines was simulated through the “Three Phase Dynamic Synchronous Machine Source”. The Excitation System, the Automatic Voltage Regulator with the Under Excitation Limiter and the Speed Governor were modeled in TACS [3], [4].

Some results associated with the case of one machine and two autotransformers in service are going to be presented in order to characterize the self-excitation phenomenon. Fig. 2 shows the time variation of the rotor speed after the simulation of the load rejection at t=1.5 s. The overspeed limit of 11.7 % was achieved 375 ms after the load rejection and the generator will be tripped out by the overspeed relay.

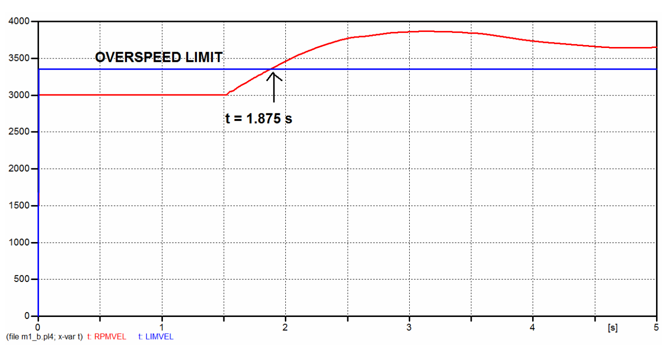

Fig. 2 Generator speed (rpm)

Fig. 3 shows the time variation of the stator voltage in pu. A quick increase and very high values in the voltage could be observed.

Fig. 4 shows the field current time response. It could be observed that after the load rejection the generator changes from the over excited region to the under excited region in order to control the terminal voltage, but without success.

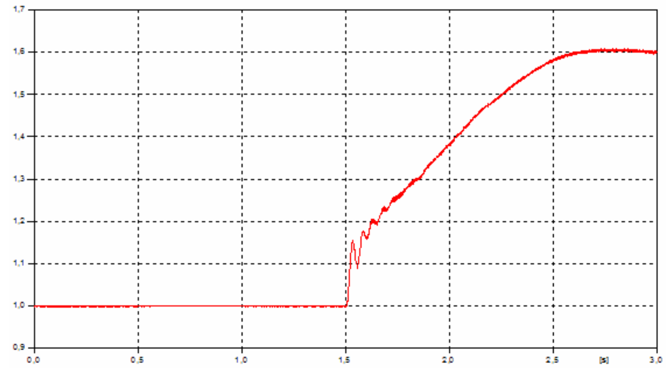

Fig. 3 Stator voltage in pu

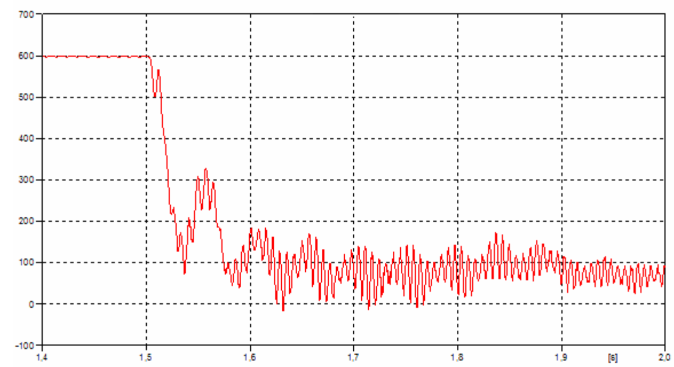

Fig. 4 Field current (A)

In order to decrease the excessive injection of reactive power on the generator, the connection of two shunt reactors of 30 MVAr each, 200 ms after the load rejection was simulated. Fig. 5 shows a decrease in the terminal voltage, but the overvoltage can not be controlled.

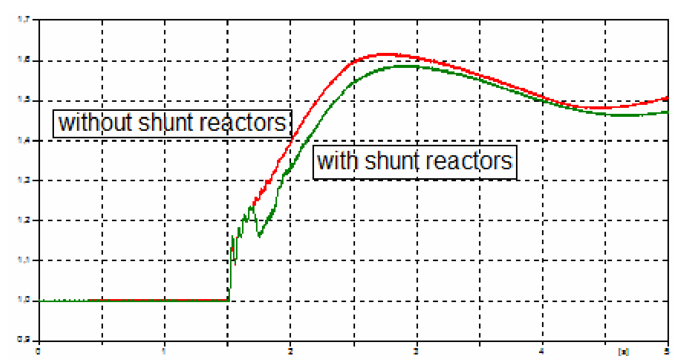

Fig. 5 Stator voltage in pu

The scenarios with a higher number of generators in service showed similar results.

Due to the severity of the results and the low number of contingencies considered, a protection system against the self-excitation phenomenon to be installed in the power plant was designed.

III. Protection System Design

In order to separate the power plant from the network a trip signal could be sent to INT1, or INT2 and INT3, or INTM circuit breakers. It was decided to open INT2 and INT3, at

150 kV voltage level, due to economic reasons and less complexity in the implementation of the protection system. These circuit breakers do not have opening and closing resistors, so they were modeled as ideal switches.

A. Transient Recovery Voltage

The first stage in the design was to analyze if the circuit breakers can open the capacitive currents under overvoltage conditions. To do this, the transient recovery voltage (TRV) across circuit breakers was calculated. Reference [5] gives for the case of Capacitive Current Switching Test with Specified TRV, the peak recovery voltage u_c, as indicated by (1), which constitutes the limit of the prospective TRV which the circuit breaker shall be capable of withstanding.

$$u_c = U_r * \sqrt{2}/\sqrt{3} *k_c *1.95 \ \ [\text{kV}] \qquad (1)$$

where: U_r _ rated voltage, k_c _ capacitive voltage factor

In relation to k_c, the values 1.2 and 1.4 were taken into account, which leads to u_{c1} = 325 kV and u_{c2} = 370 kV, being U_r = 170 kV. Two values of the time (t_1) between the load rejection and the opening of the circuit breakers were considered: a) 200 ms as a typical value resulting from the trip relay time and the opening time of the circuit breakers b) 400 ms as a limit value coming from the trip overspeed relay time.

Fig. 6 shows the TRV for the case of one machine and two autotransformers in service and t_1= 200 ms. In this case, the two values of the k_c are adequate. From the results of the rest of the cases with a different number of machines and autotransformers in service, it was concluded that the k_c must be specified equal to 1.4 in order to allow the opening of the circuit breakers.

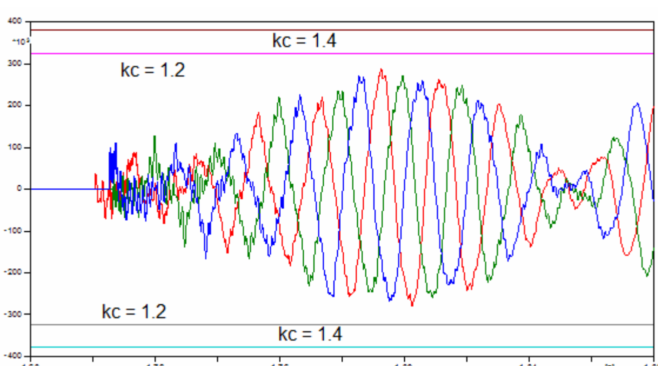

Fig. 6 Transient Recovery Voltage (V)

B. Trip Logic Function

The second stage in the design was to characterize the phenomenon under study. From the ATP results, it was possible to identify two main characteristics: a) a high overvoltage at the different voltage levels b) the subexcitation of the generators. As a consequence, a trip logic function based on ANSI device numbers 40 (loss of excitation) and 59 (overvoltage) was devised, as shown in Fig. 7. It is important to remark that the field failure protection function will be implemented in a new relay, not using the loss of excitation relay of the generator.

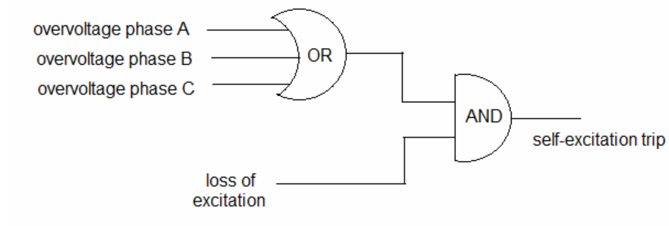

Fig. 7 Trip Logic Function

C. Non conventional settings of Loss of Excitation Protection Function

The loss of excitation protection consists of two offset mho characteristics as shown in Fig. 8, [6]. The conventional relaying approach to detect a loss of excitation condition is to supervise the variation of the apparent impedance as seen from the generator terminals. If there is a field failure, the apparent impedance locus will enter the mho circles depending on the initial generator loading and system impedance. The conventional settings are: a=1.0 pu, b=0.5*X'd pu, c=Xd pu, d=0.5*X'd pu, being Xd=2.51 pu and X'd=0.263 pu the synchronous and transient direct axis reactance of the machine. Some external time delay could be added for both characteristics.

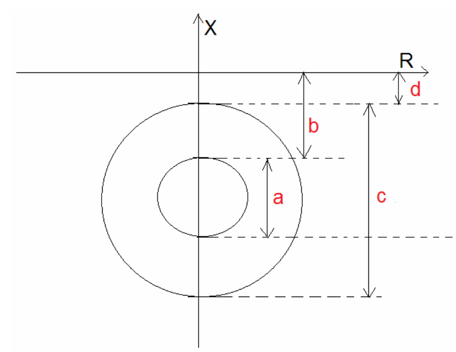

Fig. 8 Mho operating characteristics

In order to set "a", "b", "c" and "d" the apparent impedance locus was calculated with the ATP for each of the case studies mentioned earlier. After this, the mho circle was located on the R-X plane in such a way that it encompassed all the loci. The time delay was set to instantaneous.

D. ATP modeling [3], [4]

The input signals of the loss of excitation relay are one phase instantaneous current and one phase-to-ground instantaneous voltage, which are obtained from ATP simulations.

The Discrete Fourier Transform was used to estimate the fundamental frequency (50 Hz) components of the current (I) and voltage (E). The recursive form of the sliding full-cycle algorithm, described in reference [7], was implemented with device Type 69 of the TACS.

The apparent impedance measured by the relay is given by (2), which was implemented in TACS.

$$Z_{apparent} = \frac{E}{I} \qquad (2)$$

From this model, it is possible to derive an apparent impedance locus in the R-X plane during a self-excitation condition. The performance of Function 40 was analyzed by plotting its operating characteristics and the apparent impedance locus on the same R-X plane. This procedure was applied to all the phases in order to see the shape of each locus and be sure that the settings are adequate for all of them.

In order to determine the overvoltage relay setting value, the voltage time response in pu was calculated with ATP.

E. Implementation with two digital relays

The third stage in the design was the implementation of the Trip Logic Function utilizing two digital relays.

As mentioned before, INT2 and INT3 circuit breakers at 150 kV voltage level will be opened. Therefore, the simplest way to implement the Trip Logic Function is to consider one digital relay for each circuit breaker, containing Functions 40 and 59.

In order to supply the input signals of Functions 40 and 59, the current transformers (CT) were located at the secondary windings of the autotransformers and the voltage transformer (VT) was located at the 150 kV bus bar (blue color), as shown in Fig. 9. The VT ratio is 150/0.1 kV and the CT ratio is 1500/1 A. Table I shows the secondary values of “a”, “b”, “c” and “d” for the conventional setting and their maximum values given by the manufacturer.

TABLE I

	Conventional setting (Ω)	Maximum values (Ω)
a	354.3	325.
b	101.5	40.
c	889.4	325.
d	101.5	40.

The setting values were chosen as the maximum secondary values given by the manufacturer, corresponding to 1A input. The setting value of Function 59 was 1.15 pu.

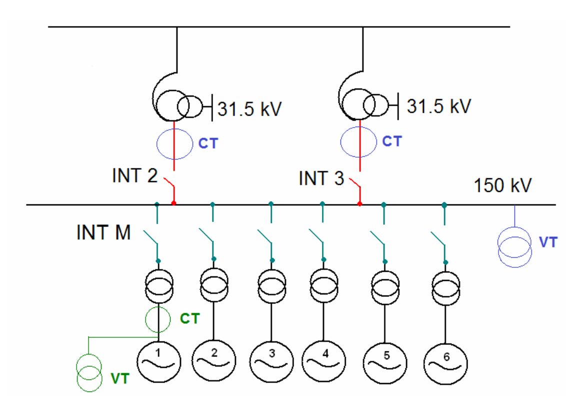

Fig.9 Current and Voltage transformers locations

Fig. 10 shows the apparent impedance locus (primary values) for the case of one machine and one autotransformer in service, during the first two cycles after self-excitation initiation, for each phase. In this case the loci did not enter the mho characteristic and then the alternative option was discarded. The overvoltage attained the set value of 1.15 pu.

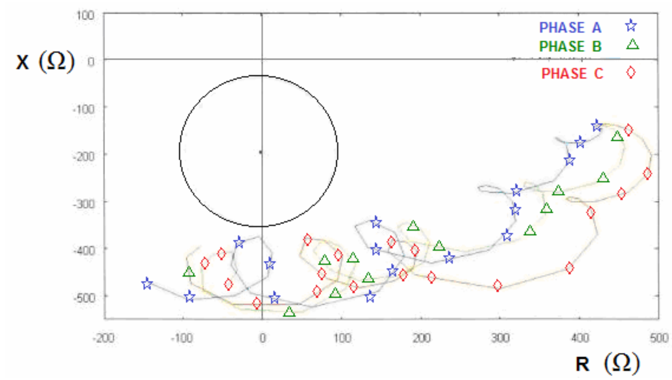

Fig.10 Apparent impedance loci – 1 machine and 1 autotransformer

F. Implementation with six digital relays

The fourth stage in the design was the implementation of the Trip Logic Function utilizing six digital relays.

One digital relay for each generator was considered, which contained Functions 40 and 59 and which would send trip signals to INT2 and INT3 circuit breakers. In order to supply the input signals of Functions 40 and 59, the CT and VT were located at the generator terminals (green color), as shown in Fig. 9. The VT ratio is 11.5/0.115 kV and the CT ratio is 4000/1 A.

Table II shows the secondary values of “a”, “b”, “c” and “d” for the conventional setting and their maximum values given by the manufacturer.

TABLE II

	Conventional setting (Ω)	Maximum values (Ω)
a	83.3	325.
b	11.0	40.
c	209.1	325.
d	11.0	40.

The setting values were chosen as the maximum secondary values given by the manufacturer, corresponding to 1A input. The setting value of Function 59 was 1.15 pu.

Fig. 11 shows the apparent impedance locus (primary values) for the case of four machines and two autotransformers in service, during the first two cycles after self-excitation initiation, for each phase. In this case two loci entered the mho characteristic, but one did not enter and then the alternative option was discarded. The overvoltage did not reach the set value of 1.15 pu.

Fig. 12 shows the generator terminal and 150 kV bus bar voltages in pu for this case. It can be observed that the bus bar voltage presents a higher rate of rise than the generator voltage, and it has achieved the set value.

As a result, the 150 kV bus bar voltage as an input signal of Function 59 was chosen.

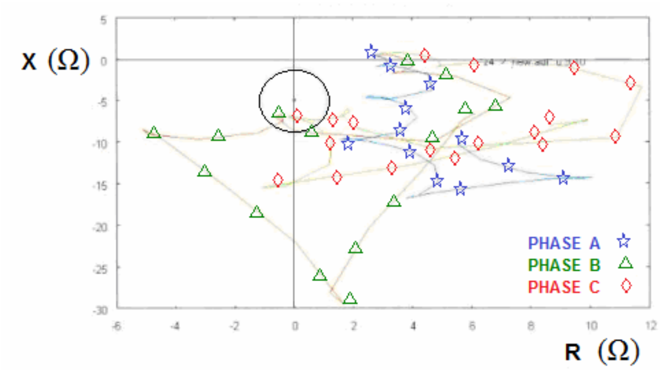

Fig.11 Apparent impedance loci – 4 machines and 2 autotransformers

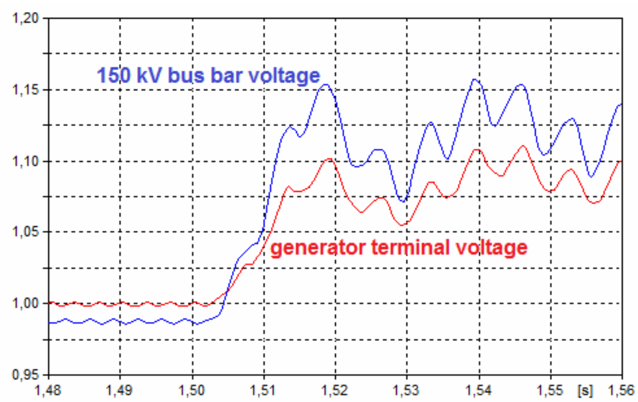

Fig.12 Generator terminal and 150 kV bus bar voltages in pu

G. Implementation with seven digital relays

The fifth stage in the design was the implementation of the Trip Logic Function utilizing seven digital relays.

One digital relay for each generator was considered, which utilized Function 40 only. In order to supply the input signals of the relay the CT and VT were located at the generator terminals. The VT ratio is 11.5/0.115 kV and the CT ratio is 4000/5 A. The setting values were chosen as the maximum secondary values given by the manufacturer, corresponding to 1A input.

The idea was to keep the same mho characteristic in secondary values, corresponding to 1A input, and increase its size in primary values. To do this, the CT ratio was decreased from 4000 to 800 with the same VT ratio. As a result, the currents from the CT of 5A nominal current were injected into 1A input of the relay. From the thermal withstand point of view, the manufacturer reported that the relay can withstand four times the nominal current continuously. The nominal current of the generator is equal to 3.99 A secondary value.

The seventh relay only uses Function 59, having the 150 kV bus bar voltages as input signals. The VT ratio is 150/0.1 kV. The setting value of Function 59 was 1.15 pu.

Fig.13 shows the apparent impedance locus (primary values) for the case of one machine and one autotransformer in service, during the first two cycles after self-excitation initiation, for each phase.

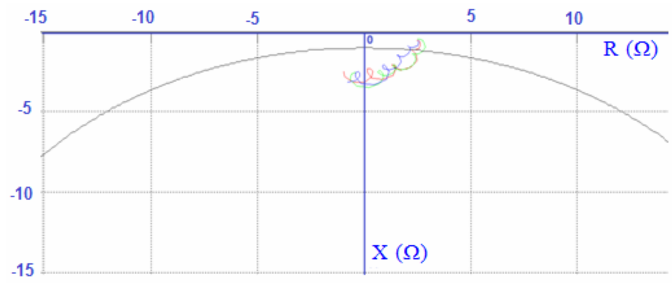

Fig.13 Apparent impedance loci – 1 machine and 1 autotransformer

Unlike in Fig.10, in this figure all the loci entered the mho characteristic.

Fig.14 shows the apparent impedance locus (primary values) for the case of four machines and two autotransformers in service, during the first two cycles after self-excitation initiation, for each phase.

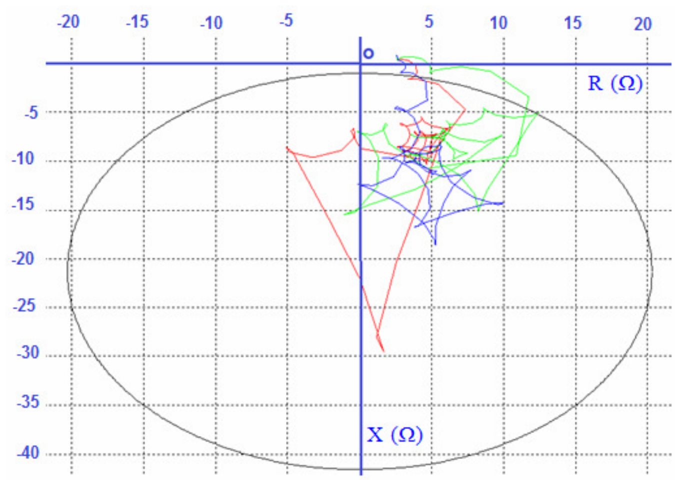

Fig.14 Apparent impedance loci – 4 machines and 2 autotransformers

Unlike in Fig.11, in this figure all the loci entered the mho characteristic.

With reference to the rest of the cases, all the loci entered the mho circle and the overvoltage attained the set value of 1.15 pu.

From the ATP simulation results, it was concluded that the Trip Logic Function implementation with seven digital relays fulfilled the loci and overvoltage requirements.

This alternative option was selected as a preliminary solution to the protection system design against the self-excitation phenomenon. The final acceptance depended on the test results, carried out at the factory.

IV. Protection System Tests

The main goal of the tests, carried out at the factory, was to validate the preliminary solution described above. To do this, the manufacturer selected two digital relays, one for the loss of excitation function and the other for the overvoltage function.

Fig. 15 shows the layout used for the tests. For all the scenarios associated with a different number of generators and autotransformers in service, the input signals of Functions 40 and 59 were obtained with ATP simulations in COMTRADE format. Two COMTRADE files were created for each scenario; one contained the input signals of Function 40, and was loaded into Laptop 2, and the other contained the input signals of Function 59, and was loaded into Laptop 1.

Two secondary injection relay test sets injected the input signals of Functions 40 and 59 from the COMTRADE files into the relays. Each pair of COMTRADE files were obtained from one ATP simulation, so that all the variables were synchronized. Therefore, it was necessary to synchronize the two secondary injection relay test sets in order to perform the tests. This was done by two GPS (Global Positioning System).

The logic gate AND of Fig. 7 was implemented inside the Function 40 relay, being one of the inputs the Function 59 output contact, as shown in Fig. 15.

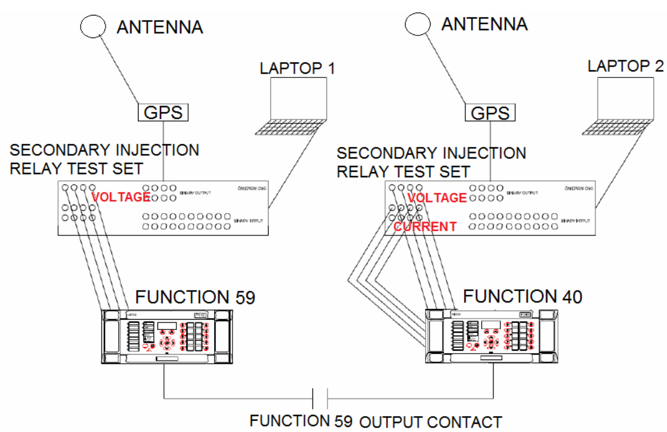

Fig.15 Test layout

The tests were planned in order to verify two aspects: a) whether or not Functions 40 and 59 actually detected the self-excitation phenomenon in all the scenarios b) if affirmative, the operating times of the different parts of the Trip Logic were recorded, in order to determine the global operating time of the protection system. Fig. 16 shows the different times t_1, t_2, t_3 and t_4 recorded during the tests.

The test results confirmed that Functions 40 and 59 detected the self-excitation phenomenon in all the scenarios. Table III shows the values of t_1, t_2, t_3 and t_4 for all the scenarios.

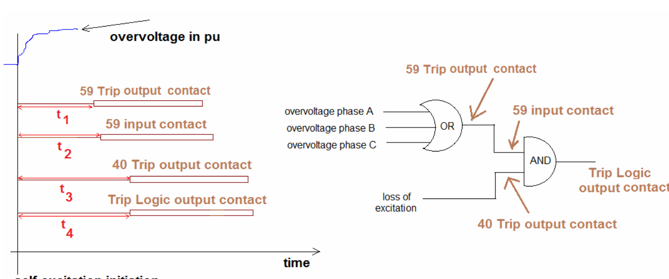

Fig.16 Times recorded

TABLE III

	t_1 (ms)	t_2 (ms)	t_3 (ms)	t_4 (ms)
1G_1T	12.2	27.5	31.4	31.4
1G_2T	17.3	33.7	38.7	38.7
2G_1T	13.0	32.0	71.8	71.8
2G_2T	18.7	33.9	63.7	63.7
4G_1T	18.2	34.8	89.1	89.1
4G_2T	21.4	40.6	75.3	75.3
6G_1T	19.7	38.1	72.8	72.8
6G_2T	14.9	33.1	117.2	117.2

where: G generator T autotransformer

Taking into account that the opening time of the circuit breakers will be in the range of three to four cycles, the total time required to separate the power plant from the network will be 200 ms in the worst case.

When the generator overspeed reaches its limit value of 11.7 %, the overspeed relay will send a trip signal to the generator circuit breaker. From the ATP simulations the minimum time value to reach this limit was 336 ms.

Due to the fact that the generator circuit breaker was not specified to open capacitive currents under overvoltage, it is important to open INT2 and INT3 circuit breakers before the overspeed reaches its limit value. The total time of 200 ms required for the protection system fulfills this constraint.

Finally, from the test results it was concluded that the protection system design implemented fulfilled all the requirements. This protection system is in operation at present.

V. Conclusions

As a result of a set of contingencies considered in the 500 kV transmission network of Uruguay, the self-excitation phenomenon in Punta del Tigre thermal power plant was studied.

The hypothesis used to define the case studies, some comments about ATP models and user models are presented. Some results obtained with the ATP and their corresponding analyses are included.

One of the main conclusions from the study carried out was the need to design a protection system against the self-excitation phenomenon to be installed in the power plant.

This paper describes the steps followed in order to design the protection system:

a) It was analyzed if the circuit breakers could open the capacitive currents under overvoltage conditions. To do this, the transient recovery voltage (TRV) across circuit breakers was calculated.

b) From the ATP results it was possible to identify the main characteristics of the self-excitation phenomenon. As a consequence, a trip logic function based on ANSI device numbers 40 (loss of excitation) and 59 (overvoltage) was devised.

c) In order to supply the input signals of Functions 40 and 59, different alternatives for voltage and current transformers were considered.

d) For each alternative the settings of Functions 40 and 59 were calculated. Also, the overvoltage and the apparent impedance loci during the first cycles after self-excitation initiation were derived in the time domain with the ATP program. The Function 40 performance was analyzed by plotting its mho characteristic and the apparent impedance loci on the same R-X plane for all the case studies.

The main conclusion drawn from the design stage is that only one alternative fulfilled the loci and overvoltage requirements.

This alternative option was tested at the factory. The values of the final settings, the layout diagram of the equipment utilized in the tests and the operating time values of the relays and the trip logic are presented.

Finally, from the test results it was concluded that the protection system design carried out fulfilled all the requirements.

This protection system is in operation at present.

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