Methodology Utilized in Black-Start Studies on EHV Power Networks

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Abstract - **This article presents the methodology developed in order to carry out black-start studies in Uruguay´s 500 kV electrical system. In relation to this, a detailed description of the following is given: a criterion in order to define black-start networks, types and order in which electrical studies should be made, which equipment ratings must be considered, equipment models for transient simulations. Some results obtained with the ATP (Alternative Transients Program) and their corresponding analysis are included. Finally, some alternative solutions to the problems detected are presented in order to restore the system operation as quickly as possible.**

Keywords: Electromagnetic Transients, Black-Start, Modelling, ATP.

I. INTRODUCTION

After a major disturbance that has led a system to collapse it is necessary to know how to restore the system operation as quickly as possible. In a black-start strategy two situations should be considered: a) If there is an interconnection with another power network, then the possibility of black-start from a neighbor system, which is under service, should be evaluated. b) If there isn´t an interconnection then the collapsed system must be recovered by means of power plants qualified for black-start.

Uruguay´s 500 kV electrical system is interconnected with Argentina´s electrical network in two points, so that the two situations presented above are likely to take place. In this work, for black-start purposes, Uruguay´s 500 kV electrical subsystem was studied as an isolated network, keeping in mind that this is the worst case.

In this paper, the black-start has been investigated by means of the energization from the hydroelectric power plant Palmar. The common practice in our country is to energize each equipment one by one, so the switching of a long transmission line was first studied and then the energization of a power transformer at no load condition was investigated. In our case the restoration of this radial network is crucial in order to get a fast reactivation of the complete system.

II. PROCEDURE DEVELOPED TO PERFORM THE ANALYSIS

This section focuses on a description of the methodology developed by the authors in order to conduct a black start study from the electrical transients standpoint.

A. Criterion in order to define black-start subsystems

In order to define some possible black-start subsystems the following questions must be answered: a) Which power plants are qualified for black start purposes? In Uruguay some power plants cannot start to generate during a blackout because they don´t have auxiliary energy (a diesel engine with a generator) for the station auxiliary bus. b) At what voltage level transmission network do they supply electrical energy? It is important to choose the highest voltage level for transmitting large amounts of bulk energy. c) What is the number of generators and which are the voltage control equipments necessary to reactivate the system operation? From an electromagnetic transients point of view, the minimum number of devices should be determined in such a way that switching overvoltages lie within acceptable limits. It´s important to know the minimun conditions because this is the best situation for the feasibility of the system recovery and it requires the minimun number of switchings resulting in a quick reactivation. d) Is it necessary to perform a frequency analysis? Inrush currents with significant harmonic content until frequencies around 750 Hz are created as a result of the switching of unloaded power transformer. In this frequency range it is important to look for the parallel resonant frequencies of the driving-point impedance, seen from power transformer terminals. If the frequency characterstic of this impedance shows resonance conditions inside the frequency range of interest, very high and weakly damped switching and temporary overvoltages may occur when the system is excited by a harmonic disturbance such as the switching of the power transformer. In this case, harmonic current components with frequencies around the parallel resonance frequencies are amplified, thereby creating higher voltages at the transformer terminals. This can happen particularly in lightly damped systems such as a black-start subsystem.

For the black-start networks resulting from items a), b) and c) it is still necessary to calculate the frequency characteristic of the driving-point impedance in order to analyze the values of the parallel resonant frequencies and their magnitudes as a final step for the preliminary acceptance.

B. Electrical studies

After the possible black-start subsystems have been determined the following electrical studies should be made in the sequence shown here.

Load Flow Analysis in pre-switching and post-switching conditions has to be performed in the different networks in order to verify that: the voltage profiles lie within operational limits and the active and reactive power generated by the machines must be inside the region defined by the reactive capability curves.

In applications involving the use of long distance transmission and EHV systems, the problem of load rejection might arise, giving rise to serious overvoltages, especially when the charging of the transmission line is excessive to the generation that remains connected. The so called self-excitation phenomenon could be developed, so Load Rejection Studies must be conducted.

Switching and Temporary Overvoltages caused by the energization of a transmission line and a power transformer must be calculated in order to verify that: the peak values of switching overvoltages don´t exceed the rated switching impulse withstand voltage (BSL) of the equipments, the temporary overvoltages in the transformer obey the duration of admissible short-term voltages given by the manufacturer and the temporary overvoltages in the ZnO surge arresters obey the temporary overvoltage capability given by the manufacturer. The energy absorbed by surge arresters must be less than the energy absorption capability. The 500 kV network has many gapped silicon-carbide (SiC) surge arresters and they have been in service for 25 years. They are considered not reliable and in order to minimize the risk of failures during restoration these equipments must not discharge.

III. MODELLING OF THE SYSTEM

In the load rejection and switching studies, which are going to be presented in the next section, the ATP program was utilized. A brief description of how each element of the power system was represented is given.

The machines of Palmar were modelling through the "Three Phase Dynamic Synchronous Machine Source". Each generator unit has a static excitation system with negative field voltage capability and without negative field current capability. The automatic voltage regulator was implemented in TACS (Transient Analysis of Control Systems-ATP). The step-up transformers consist of three single units, which were modelled through the Saturable Transformer Component and whose iron losses, along with their saturation, were considered. The transmission line was simulated using the distributed parameters model and the shunt reactors were represented as lumped elements. During the simulation the power transformer was modeled through the matricial model $[R]-[L]^{-1}$ using the BCTRAN supporting program. The iron core losses were represented as lumped resistances placed across the terminal of the primary winding. The saturation effects were taken into account through the Pseudo-nonlinear reactor (Type 98) and the Pseudo-nonlinear hysteretic reactor (Type 96) placed across the terminals of the primary winding. In this last case, the residual fluxes in the core were assumed equal to: 0.7 p.u., 0.0 p.u. and –0.7 p.u. The ZnO surge arresters were represented through Exponential surge arrester model. The pole span of the closing circuit breaker without pre-insertion resistors was assumed to be 5 ms and 10 ms for those that have pre-insertion resistors.

IV. BLACK-START STUDIES

The single line diagram of the investigated 500 kV subsystem shown in Fig.1 bears the following characteristics: a) three hydro units of 111 MVA apparent power rating and voltage rating 15 kV b) step-up transformers voltage ratings 15/500 kV and power rating 111 MVA, type of connection Dy11 c) autotransformer (A1) voltage ratings 500/150/31.5 kV and power ratings 200/200/70 MVA, type of connection YNyn0d11. It has two shunt reactor banks of 30 MVAr each d) transmission line Palmar-MontA voltage rating 500 kV with length equal to 228.9 km.It has three shunt reactor banks of 50 MVAr each e) transformer bank (T1) voltage ratings 475/150/31.5 kV and power ratings 425/425/140 MVA f) transformer bank (T2) voltage ratings 475/150/13.8kV and power ratings 425/425/140 MVA. It has two shunt reactor banks of 30 MVAr each g) autotransformer bank (A2) voltage ratings 500/150/31.5 kV and power ratings 250/250/90 MVA. The type of connection YNyn0d5 is the same for all of them.

A. Energization of Transmission Line Palmar-MontA

The electrical studies mentioned above were carried out in the system shown in Fig.1 when the energization of the line from the sending end Palmar and the receiving end MontA unloaded. In order to minimize the number of switchings resulting in a quick first restoration step the following parameters were taken into account: number of machines, autotransformer (A1) with shunt reactors in (I/S) or out of service (0/S). Table I summarizes all the possible situations for the energization under study and their acceptance.

Table I – Alternative configurations

	A1(O/S)	A1(I/S)
one machine	NO (1)	NO (2)
two machines	YES (3)	YES (4)

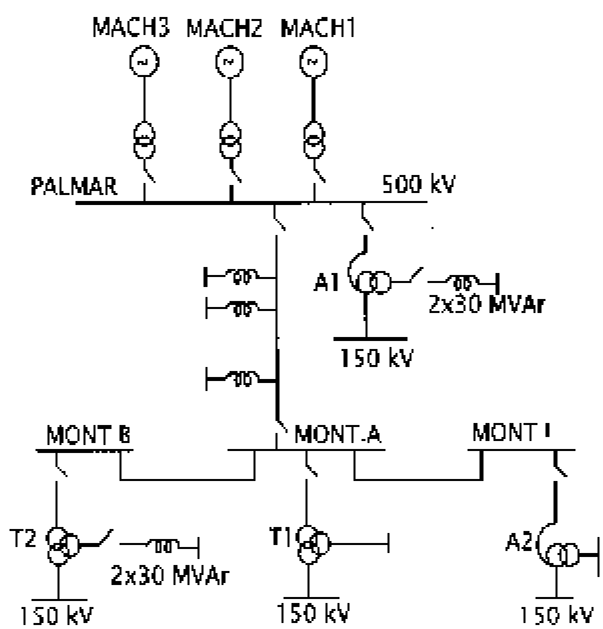

Fig. 1. Single phase diagram of 500 kV subsystem

A transient study had been carried out to calculate overvoltages following full load-rejection at MontA bus bar in Case (1). The network conditions before the load-rejection were chosen as if the machine were working in the overexcited region, this being the worst operating conditions for the machine since it has to go from the overexcited region to the underexcited region after the load-rejection. Fig. 2 shows voltage phase C-neutral at Palmar bus before and after the load rejection. From this figure it can be observed that: a) the voltage regulator controls the amplitude of sinusoidal voltage until 2.2 s b) after this instant of time the amplitude grows indicating the presence of self-excitation phenomenon c) the positive peak values grows monotonically and the voltage waveshape remains sinusoidal. The frequency of the sinusoidal voltage goes up due to the overspeed of the machine. The circuit breaker capability to interrupt was specified in 1.4 p.u. (base voltage 500 kV) and because any switching action will occur at levels beyond this capability, this case was rejected. Each energization study consisted of 100 statistic energizations in which circuit breakers poles were represented by a statistic switch model.The switching overvoltages obtained in Case (2) may result in the SiC surge arresters failures, so this case was discarded too. For Case (3) and Case (4) load rejection studies show the presence of the self-excitation phenomenon but there is enough margin to open the circuit breakers in relation to their capability. The switching overvoltages study was performed at lowest pre-switching voltage generator equal to 13.8 kV and the maximun overvoltages at MontA bus bar were 1.96 p.u. and 1.91 p.u. for Case (3) and Case (4) respectively. These values are less than the BSL of the transmission line equal to 2.26 p.u.; consequently, these cases were accepted as the first restoration step.

B. Energization of Transformer T1 at MontA bus bar (first attempt)

The energization of transformer T1 could be considered as the second restoration step starting from Case (3). The following pre-switching conditions were adopted: a) voltage at MontA bus bar equal to 0.99 p.u. b) the tap was positioned in order to give the highest number of turns to be excited c) the saturation effects were represented through Type 96 and Type 98 elements.

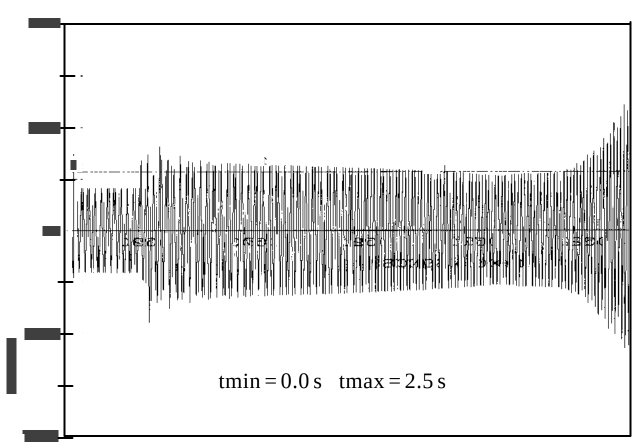

Fig. 2. Voltage Phase C-Neutral (Palmar bus)

Each energization study consisted of 100 statistic energizations in which circuit breakers poles were represented by a statistic switch model. Table II summarizes the maximum overvoltages reached.

Table II – Maximum overvoltages

	Type 96	Type 98
Palmar 500	2.57 p.u.	2.38 p.u.
MontA 500	2.60 p.u.	2.61 p.u.

These values are greater than the BSL of the transmission line and less than the BSL of the power transformer equal to 2.88 p.u. These values were unexpected and the wave shapes were too oscillatory as shown in Fig. 3, compared with the normal situation (all the electrical system in service).

From these results it is impossible to reach the second restoration step, as a consequence, this system configuration for restoration plans was discarded. At this point it was very important to investigate what the cause of too high transient overvoltages was. During the early stages of the restoration procedures the system is ligthly loaded and weakly dumped; therefore, resonance conditions which are different from the ones at normal operation might arise. The authors considered that this might be the source of the problems detected; thus, the ATP Frequency Scan feature was utilized to calculate the driving-point impedance at MontA bus bar for the desired frequency range. Fig. 4 and Fig. 5 show the magnitude of the sequence impedances in the frequencies from f =0.0Hz to f =1kHz.

Fig. 4 shows two parallel resonance peaks: 40 kW at 88 Hz and 20 kW at 623 Hz which are too high and lie within the frequency range associated with the transient under study.

With the system in normal operating conditions the same calculation was performed in order to compare the parallel resonance values.The differences were dramatic: the positive sequence highest value was 1 kΩ at 700 Hz. Fig. 6 shows the magnitude of the positive sequence impedance in the same frequency range in normal operating conditions.

Voltage phase C- neutral at MontA bus bar reached the highest value (2.6 p.u.) during the energization of transformer T1 and in order to know the significant harmonic content Fast Fourier Transform (FFT) was taken of this voltage.

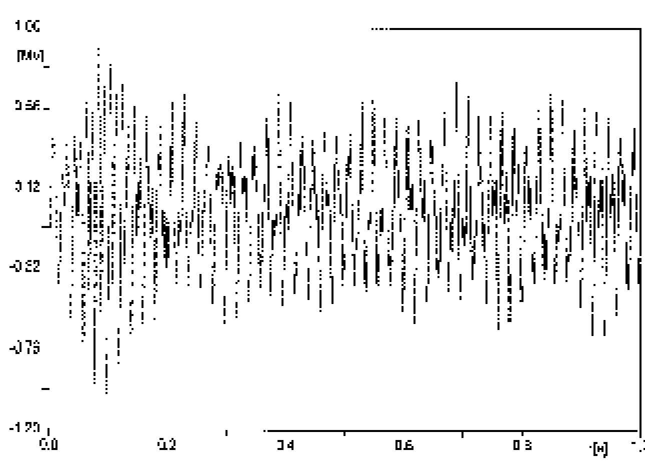

Fig. 3. Voltage Phase B – Neutral (MontA bus)

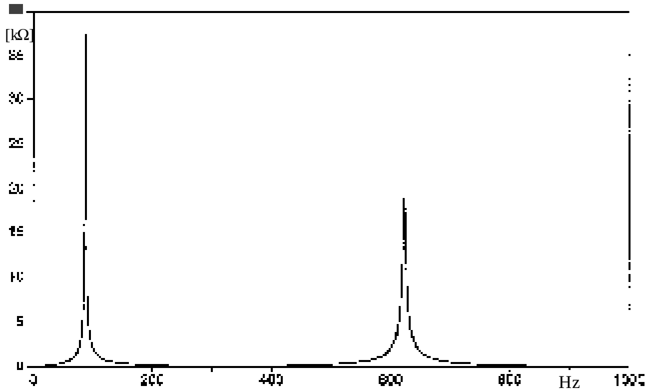

Fig. 4. Positive sequence impedance

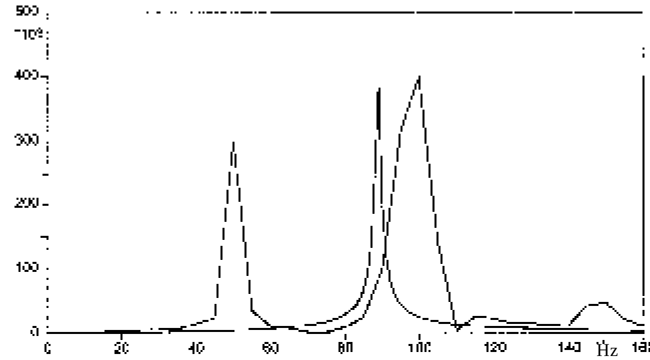

Fig. 7. Harmonic spectrum (0 –160 Hz)

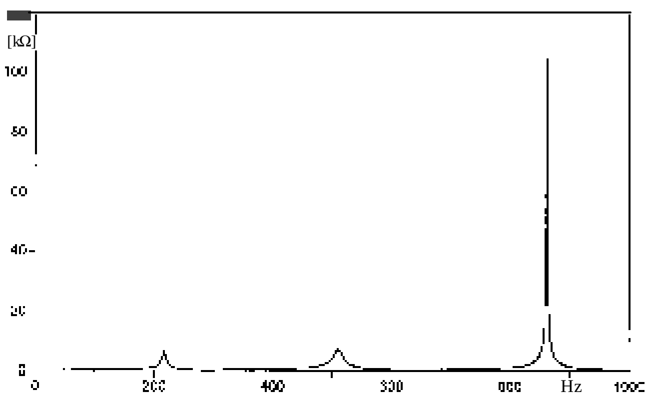

Fig. 5. Zero sequence impedance

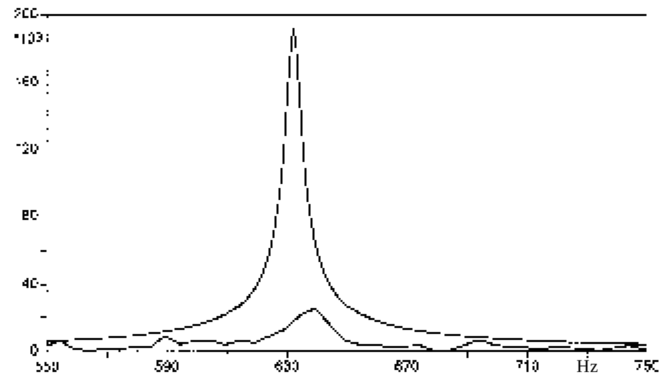

Fig. 8. Harmonic spectrum (550-750 Hz)

Fig. 7 and Fig. 8 show together the magnitude of the harmonic spectrum for the voltage mentioned above and the positive sequence driving-point impedance at MontA bus bar.

From these figures, some overlaping between the spectrums around the parallel resonance frequencies could be observed. Although one of them it is in phase coordinate and the other in sequence components from a qualitative point of view, this is a coherent result. Taking the FFT of phase C inrush current, we could observe same thing happened. Finally Fig. 9. shows the magnitude of the harmonic spectrum for the inrush current when the system is all in service and while the system is recovering. It could be observed that in normal situations the peaks values are monotonically decreasing but in abnormal conditions they do not show this behaviour. It can be concluded, then, that the parallel resonance conditions are responsible for the high overvoltages when the system is excited by an harmonic disturbance.

C. Selection of System Configurations

The topology of the network shown in Fig. 1 suggests three possible ways in order to achieve the second restoration step which entails the energization of transformers T1 or T2 or A2 respectively. A way to avoid a large number of time-domain simulations is to define a selection criterion of the possible system configurations for black-start purposes.

The transmission line, number of machines at Palmar power plant, number and locations of shunt reactor banks (SRB) and autotransformer A1 have a strong influence on the frequencies and magnitudes of the parallel resonances. For all configurations resulting from the parameters mentioned

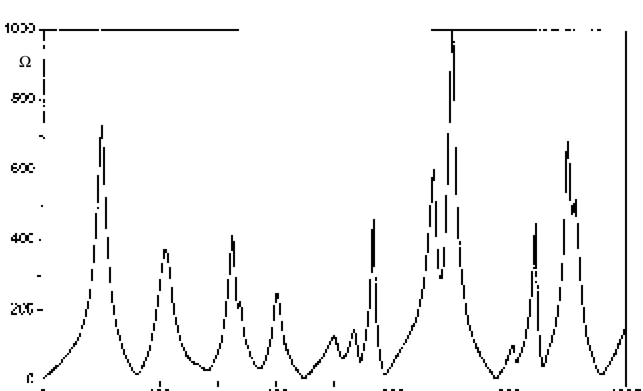

Fig. 6. Positive sequence impedance (normal operation)

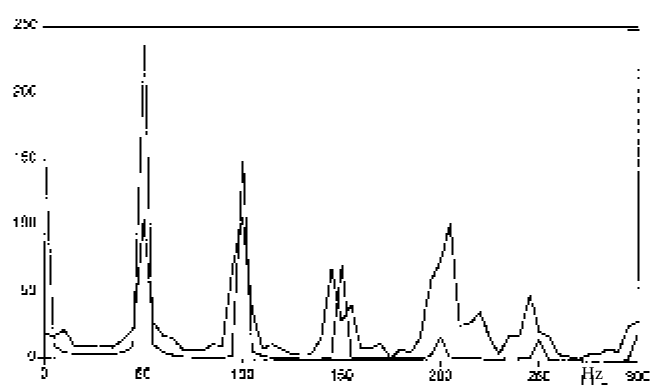

Fig. 9. Inrush currents harmonic spectrum

above the driving-point impedances at MontA, MontB and MontI bus bars in the frequency range 0-1000 Hz were calculated. Taking into account the results and conclusions of item B, only system configurations with parallel resonance peaks lower than the values obtained in item B were preliminary accepted.

Tables III , IV and V show the results obtained applying this criterion for each alternative.

Table III – Transformer T1

	two machines	three machines
A1(O/S)	NO	YES
A1(I/S)	NO	NO

Table IV – Transformer T2 with or without SRB

two machines		
	SRB(O/S)	SRB(I/S)
A1(O/S)	NO	NO
A1(I/S)	NO	YES(1)
three machines		
	SRB(O/S)	SRB(I/S)
A1(O/S)	YES(2)	NO
A1(I/S)	YES(3)	NO

Table V – Autotransformer A2

	two machines	three machines
A1(O/S)	YES(1)	YES(2)
A1(I/S)	YES(3)	YES(4)

D. Energization of Transformer T1 at MontA bus bar (second attempt)

The only case previously accepted was then studied in detail. The pre-switching voltage at MontA bus bar was equal to 0.97 p.u. Table VI summarizes the maximum overvoltages reached.

Table VI – Maximum overvoltages

	Type 96	Type 98
Palmar 500	2.06 p.u.	1.97 p.u.
MontA 500	2.25 p.u.	2.14 p.u.

These values are less than the BSL of the equipments, but they may cause SiC surge arresters failures at MontA substation. The manufacturer gave a table with the duration of admissible short-term voltage exceeding during the operation of the transformer. From the comparison of these values with the temporary overvoltages resulting from the simulations it can be concluded that they may lead to damage to the transformer with a probability equal to 0.21. Consequently, it is impossible to reach the second restoration step through this alternative. Nowadays, ZnO surge arresters are not expensive, so the authors have considered to exchange SiC surge arresters for ZnO surge arresters as a possible solution to the problem detected above.Table VII summarizes the maximum overvoltages reached with ZnO surge arresters.

Table VII – Maximum overvoltages (ZnO)

	Type 96
Palmar 500	1.85 p.u.
MontA 500	1.78 p.u.

From the results obtained, it can be observed: the maximum switching overvoltage decrease 21% at MontA bus bar, the temporary overvoltages can be withstood by transformer T1, the energy absorbed by the surge arresters is less than their energy absorption capability (3MJ), and the temporary overvoltages in surge arresters obey the temporary overvoltage capability. Finally, this corrective measure will allow this second restoration step to be reached.

E. Energization of Transformer T2 at MontB bus bar

Case (1) indicated in Table IV was rejected because the maximum switching overvoltages exceeded the BSL of the equipments and they may cause SiC surge arresters failures at MontA, MontB and Palmar substations.

A full load rejection study at MontB bus bar was performed for Case (2) indicated in the same table. Fig. 10 shows voltage phase A-neutral at Palmar bus bar before and after the switching load (instant of time t_1), instants of time t_2 and t_3 corresponding to the opening of the first and the second machine circuit breakers. The third machine circuit breaker will not open because the voltage exceeds, their capability to interrupt (1.4 p.u.) immediately after instant t_3 . As a consequence of that, Case (2) was discarded. Case (3), indicated in Table IV, was rejected because the maximum switching overvoltages may cause SiC surge arresters failures at Mont A and Mont B substations in spite of the fact that those overvoltages are lower than the BSL of the equipments. From these alternatives it is impossible to reach the second restoration step.

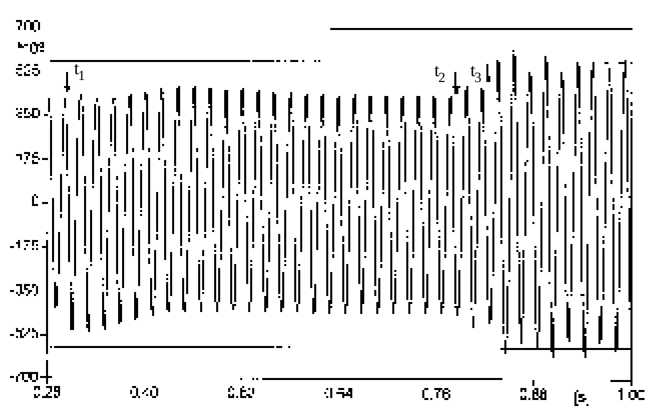

Fig. 10. Voltage Phase A-Neutral (Palmar bus)

F. Energization of Autotransformer A2 at MontI bus bar

A full load rejection study at MontI bus bar was performed for Case (1) and Case (2) indicated in Table V. After the switching load, the last machine circuit breaker will not open because the voltage exceeds, their capability to interrupt (1.4 p.u.), so these cases were also discarded. Case (3), indicated in the same table, was rejected due to the fact that the maximum switching overvoltages not only exceeded the BSL of the equipments but also they might cause SiC surge arresters failures at MontA and Palmar substations.

The same load rejection study was carried out for Case (4) in the same table. Fig. 11 shows, voltage phase A-neutral at Palmar bus bar before and after the switching load (instant of time t_1), instants of time t_2 and t_3 corresponding to the opening of the first and the second machine circuit breakers. The third machine circuit breaker will open because the voltage does not exceed its capability to interrupt (1.4 p.u.)

The pre-switching voltage at MontI bus bar was equal to 0.97 p.u. for switching studies. Table VIII summarizes the maximum overvoltages reached with and without ZnO surge arresters.

Table VIII – Maximum overvoltages

	With ZnO	Without ZnO
Palmar 500	1.89 p.u.	2.18 p.u.
MontI 500	1.75 p.u.	2.43 p.u.

From the results obtained, it can be observed that the maximum switching overvoltage decreases 28% at MontI bus bar. Fig. 12 shows the voltage waveshape at MontI bus bar with and without ZnO surge arresters. The maximum switching overvoltages do not exceed the BSL of the equipments, and the energy absorbed by the surge arresters is less than their energy absorption capability (3MJ).

As a result of the comparison of the temporary overvoltages with the duration of admissible short-term voltages given by the manufacturer, it can be concluded that they may be withstood by autotransformer A2. The temporary overvoltages in surge arresters obey the temporary overvoltage capability.

Finally, from the results stated above, it can be concluded that this case allows the second restoration step at 500 kV voltage level to happen.

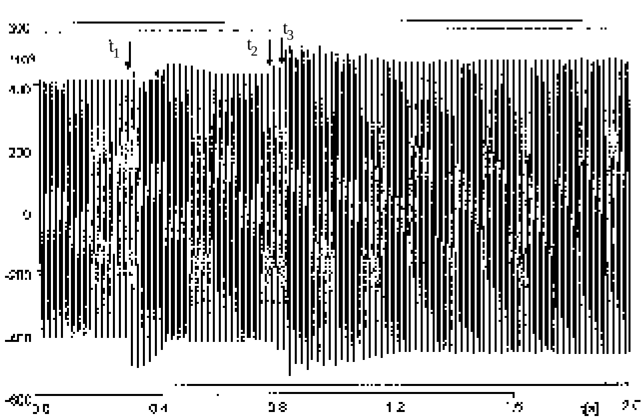

Fig. 11. Voltage Phase A-Neutral (Palmar bus)

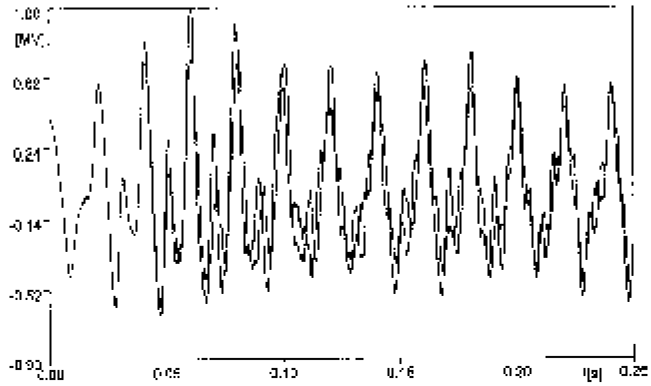

Fig. 12. Voltage Phase A-Neutral (MontI bus)

V. CONCLUSIONS

In the present work a procedure developed in order to carry out black-start studies in Uruguay´s 500 kV electrical system was presented. This methodology allows one to limit the number of time-domain simulations, discarding a number of them and; therefore, reducing the overall calculation time.

Three possible ways to promptly reactivate the system operation were analyzed, and some results obtained with the ATP Program were included. Some cases were discarded due to the self-excitation phenomenon. The authors will conduct research in this problem in order to make some of those cases feasible (as a second restoration step) with a fewer number of machines than the number of machines required for the already accepted case. Other cases were discarded due to the possible failures of the SiC surge arresters, so the authors proposed to exchange them for ZnO surge arresters in order to get some new alternatives.

At the moment, there is only one way to restore the system through the powerful 500 kV system for the isolated Uruguay´s network.

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