Switching overvoltages studies for Live Working on the Uruguayan 500 kV transmission network

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***Abstract*-- In order to obtain the distances required to perform live working maintenance on the Uruguayan transmission network under secure conditions, electromagnetic transient (EMT) studies are conducted to obtain the maximum switching overvoltage that can be found in 500-150 kV transmission network. Two different approaches were considered for these studies. On one hand, a simple approach is used, analyzing line switching transients on simplified two line network models. On the other hand, a detailed approach is considered, analyzing line switching overvoltage transients on a complete network model. This complete model considers 500 kV and 150 kV overhead lines, 500/150 kV transformers, cables, reactive power shunt compensation, hydraulic and thermal generators. Electromagnetic transient studies and the complete network model are performed in EMTP-RV software. Finally, a comparison between the results obtained considering each approach is performed.**

***Keywords*: switching overvoltage, EMT, grid modeling, live working**

I. Introduction

In the framework of the project for the consolidation of live working in the Uruguayan transmission network, the Uruguayan Transmission System Operator (UTE), with the consultancy of the French Transmission System Operator (RTE), has carried out studies to obtain the maximum switching overvoltages that can be found in the 500-150 kV transmission system. One of the main objectives of the project is to adopt the live working (LW) methods applied by the French Transmission System Operator (RTE) in their network. For this objective to be possible, new LW execution conditions must be developed as well as a special operation regime, to be applied during LW.

Current line switching overvoltage limits, and therefore security distances for LW in UTE, are based on the calculation methodology described in IEC 61472 Standard [1]. For RTE´s LW methods to be applied in UTE, the current security distances must be reduced. Therefore, line switching overvoltage limits must be revised, performing line switching overvoltage studies considering UTE´s network particularities. Two approaches have been considered for these studies, a simple one, which considers a simplified network model, and a detailed one, considering a complete network model. The objective of this paper is to compare the different approaches, and to analyze whether LW in the 500 kV system is possible in accordance with RTE's LW methods and security distances. Since these studies are specific to UTE´s network and RTE´s methodology for live working, to the authors' best knowledge such comparison between simple and detailed approaches has not been investigated in the literature.

For the development of the complete network model considered in the detailed approach, and for the performance of all line switching transient studies, the EMTP-RV simulation tool [2] and the Parametric Studio Tool [3] are used.

II. Methodology

Line switching overvoltage studies are performed applying two different approaches: a simple and a detailed approach.

A. Simplified methodology

The simple approach for LW is presented in [4]. It consists in simulating switching overvoltages per system voltage level considering a conservative simplified network model. This model is composed of two typical overhead transmission lines connected in radial configuration and a Thevenin equivalent representative of the system voltage level under study. See Fig. 1. Both typical lines are modelled considering frequency dependent parameters line models (Wide Band model [5]), based on the typical dimensions of high voltage towers and electrical data of conductors and shield wires. The Thevenin equivalent is calculated considering typical data which maximize the level of overvoltages. The equivalent was modeled taking into account the three phase short circuit power, the X/R and X_1/X_0 ratios.

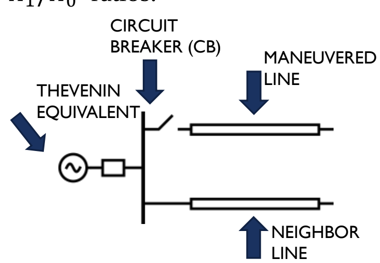

Fig. 1. Simplified network model.

Once the representative model for each voltage level is defined, different events are simulated in one of the lines (maneuvered line) and overvoltages on both lines' ends are monitored. A probabilistic approach is required for the simulations, in order to take into account the statistical nature of the phenomenon of overhead line switching. For this reason, N maneuvers of the CB are simulated in a 50 Hz cycle (including a discrepancy according to a typical CB Gaussian

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law). Thus, N values of possible maximum overvoltages for each event are obtained. From these values the U2% voltage is calculated, which represents the overvoltage having a 2 per cent statistical probability of being exceeded [1]. It has been demonstrated that for N≥500, the value for U2% is stable.

For a strong and meshed Transmission system, as is usually the case for RTE´s 400 kV network, analyzing line switching overvoltages in this simplified network model, results in a worse case from the line switching overvoltages point of view.

B. Simple approach for studies in UTE´s 500 kV transmission network

UTE´s 500 kV network configuration is different from RTE´s 400 kV network. Overhead line lengths vary from 10 to 280 km, they have shunt compensation, and there are many lines in radial configuration. Therefore a generic simple approach is not sufficiently adequate to represent the whole 500 kV system. But, as the Uruguayan 500 kV network is relatively small, it was possible to apply RTE's methodology to each bus of the system. All possible combinations of two lines per substation were studied (as depicted in Fig. 1), resulting in a total of 25 simplified network models.

The particularities of the system in each bus were considered. The Thevenin equivalent of the network in each substation was calculated for the maximum and minimum short circuit power scenarios. The equivalent was modeled taking into account the three phase short circuit power, the X/R and X_1/X_0 ratios. Lines were modelled considering their specific tower geometry, conductor and shield wires parameters, shunt compensation and transpositions. Surge arresters were not included in the models, in order to obtain more conservative overvoltage values in substations.

For each simplified model considered, line switching transients were simulated, considering the probabilistic approach previously described. TABLE 1 details the events analyzed.

TABLE 1. LIST OF EVENTS STUDIED IN THE 500 KV SYSTEM.

Event	Fault	Number of simulations
Three phase reclosure	One phase fault (L-G)	500
One phase reclosure	One phase fault (L-G)	500
Energization and three phase definitive opening	Without fault One phase fault (L-G) Two phase fault, isolated or to ground (L-L, L-L-G) Three phase fault, isolated or to ground (L-L-L, L-L-L-G)	Energization: 500*6 Opening: 750*6

According to UTE's 500 kV protection scheme, there is no line re-closure for multi-phase faults. Additionally, the type of reclosure depends on the setting of the protection system. Currently, UTE's 500 kV lines are configured to perform only one-phase reclosure, with exception of one line, which has also the possibility of performing the three phase reclosure (MA5-MB5). For all simulations different fault locations were analyzed. All faults considered in the studies were solid, without fault resistance.

Parametric studies allowed to combine the different CB opening and closing times with both Thevenin equivalents.

For reclosure and energization maneuvers, taking into account the probabilistic approach, a sweep of a 50 Hz cycle every 0.04 ms is performed, which results in N=500 time domain simulations, as shown in TABLE 1.

For three-phase definitive line opening, a swept of one and a half 50 Hz cycle (from 40 to 70 ms covering the complete range of typical opening times for the 500 kV system) every 0.04 ms is performed, which results in N=750 simulations, as shown in TABLE 1.

For all maneuvers analyzed, the absolute maximum phase to ground voltage of the ends of both lines were registered for each simulation.

Between line energization, line opening and line reclosure of all 500 kV lines, and considering two different Thevenin equivalents, a total of approximately 425.000 possible overvoltage values were obtained. In Fig. 2 the flow diagram presenting all combination of cases studied is shown.

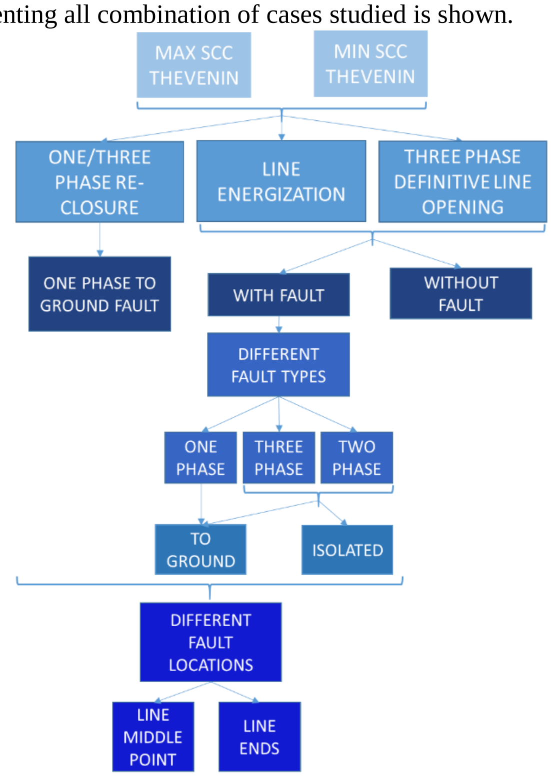

Fig. 2. Flow diagram representing all combination of cases analyzed.

C. Detailed approach for studies in UTE´s 500 kV transmission network

Another possible approach for the analysis of line switching overvoltage implies a detailed network model. As the Uruguayan high voltage network is not sufficiently meshed to consider only two busbars back from the energizing bus [7], the complete network model is used as a reference model, performing line maneuvers and analyzing the propagation of overvoltages throughout the complete network. The same hypothesis made for the simple approach regarding CB closing and opening times and fault characteristics, are considered for the detailed approach. Hydraulic and thermal generators connected to the 150 kV and 500 kV are modelled as Thevenin equivalent, considering active and reactive power and zero, positive and negative sequence impedances.

The computational time involved in performing EMT simulations with the complete 500-150 kV network model is 20 times the time involved in simulations with the simplified model. For this reason, two simplifications were considered, based on the results obtained in the simple approach: only one fault location (which maximizes the overvoltage) and only a typical load and generation scenario.

A total of 270 different line maneuvers were simulated in the 500 kV system:

- 120 line openings
- 120 line energizations
- 20 one phase line reclosures
- 10 three phase reclosures

This results in 165.000 possible overvoltage values (see TABLE 1).

Additionally, a total of 2057 different line maneuvers were simulated in the 150 kV system:

- 726 line openings
- 726 line energizations
- 605 three phase reclosures

This results in 1.210.000 possible overvoltage values (see TABLE 2).

TABLE 2. LIST OF EVENTS STUDIED IN THE 150 KV SYSTEM.

Event	Fault	Number of simulations
Three phase reclosure (*)	One phase fault (L-G) Two phase fault, isolated or to ground (L-L, L-L-G) Three phase fault, isolated or to ground (L-L-L, L-L-L-G)	500*5
Energization and Three phase definitive opening	Without fault One phase fault (L-G) Two phase fault, isolated or to ground (L-L, L-L-G) Three phase fault, isolated or to ground (L-L-L, L-L-L-G)	Energization: 500*6 Opening: 750*6

(*) According to UTE's 150 kV protection scheme, three phase reclosure for multi-phase faults is enabled for all lines.

III. COMPLETE NETWORK MODEL DEVELOPMENT

A. Model description

The entire Uruguayan 500 kV and 150 kV network has been modeled in EMTP-RV in the framework of this project. The 500 kV network consist of 10 substations and 11 overhead lines (see Fig. 3). On the other hand, the 150 kV network has 82 substations, 4250 km of overhead lines and 95 km of underground cables. The Uruguayan system is interconnected to Argentina trough SU5, which has been selected as the Slack bus.

All 500 kV and 150 kV lines were included in the model, considering for each one the specific tower geometry, conductor and shield wires parameters, shunt compensation and transpositions. Frequency dependent parameters models (Wide Band model [5]) were considered. As the time step selected for the simulations was 20 µs, all 150 kV lines shorter than 6 km are considered as a PI-model, because the propagation delay is lower than the time step. Underground cables were modelled considering conductors, semiconductor and insulation layers. Regarding 500/150 kV transformers, short circuit and magnetization impedances, stray capacitances and saturation were included based on the type test datasheets. In particular, stray capacitances were modeled as lumped capacitors between transformer terminals and ground and between terminals [6]. Only 500 kV and 150 kV voltage levels were included in the model. Distribution network is not considered in this analysis (63 kV, 31.5 kV and 22 kV) which implies a more conservative approach. Loads were modelled connected directly to 150 kV substations, consisting of R-L-C impedances (shunt impedances consisting of R, L and C in parallel) [7] which consume a specific P-Q power at 150 kV. Reactive power compensation connected to transformer tertiaries are also modelled as L-C impedances that consume or inject the nominal reactive power at nominal bus voltage. Only conventional generators (hydraulic and thermal) connected to the 500 kV and 150 kV networks were modeled, considering active and reactive power and zero, positive and negative sequence impedances. No renewable generation (wind, solar, biomass) were considered in this stage of the studies. HVDC converter stations connected to the 500 and 150 kV systems were not included either.

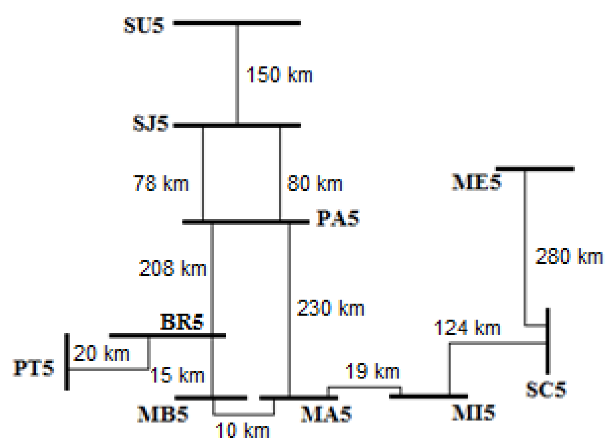

Fig. 3. 500 kV one line diagram.

B. Model validation

As a validation process for network configuration, load flow and short circuit results obtained running simulations with the detailed model, were compared with the same simulations performed in another network model developed in phasor domain in PSS/E Software. UTE develops, keeps up to date and systematically validates (by comparing short circuit currents and load flows though specific strategic lines with real measurements) the PSS/E model.

With the objective of validating the EMTP-RV complete network model developed, the same generation and load scenario were configured both in EMTP-RV and PSS/E models. Short circuits in all 500 kV substations were simulated. Results obtained with both models are shown in TABLE 3. Additionally, the voltage in each 500 kV substation and the active power flow through all 500/150 kV transformers is compared between models. Results obtained are shown in TABLE 4 and TABLE 5.

TABLE 3. Short circuit current for three phase faults in 500 kV substations. EMTP-RV vs PSS/E.

500 kV Substation	Short circuit current (kA)	
	EMTP-RV	PSS/E
MA5	6.8	6.5
MB5	6.9	6.5
MI5	6.5	6.1
SC5	4.5	4.4
ME5	2.6	2.6
BR5	6.7	6.4
PT5	6.2	5.9
PA5	9.3	8.8
SJ5	10.0	9.5
SU5	19.1	19.1

TABLE 4. Voltage in 500 kV substations. EMTP-RV vs PSS/E.

500 kV Substation	Voltage (kV)	
	EMTP-RV	PSS/E
MA5	514.9	513.0
MB5	514.6	512.2
MI5	516.0	514.8
SC5	520.5	522.1
ME5	515.6	518.4
BR5	514.2	511.7
PT5	514.3	511.9
PA5	509.6	506.5
SJ5	507.7	505.7
SU5	510.0	510.0

TABLE 5. Active power flow through secondary winding of 500/150 kV transformers. EMTP-RV vs PSS/E.

500 kV transformer	P (MW)	
	EMTP-RV	PSS/E
SU5	162	146
SJ5	74	65
PA5	84	75
MA5	400	383
MB5	292	291
MI5	399	359
SC5	164	150
ME5	28	-4

Results obtained in EMTP-RV are quite close to PSS/E results, validating the model developed in EMTP. Internal investigations has shown that the main differences are due to the 150 kV network modeling. In fact, in PSSE, the lines are modeled with PI-sections and without transpositions, whereas a frequency dependent model and transpositions were considered in EMTP-RV. Also, in PSSE the system is modelled as perfectly transposed and equilibrated, whereas a detailed 3 phase model was considered for EMTP.

IV. RESULTS

A. Overvoltage limits for LW

In order to adopt the LW methods applied by RTE in their network, new limits for the security distances were establish, which translates into new limits for switching overvoltages.

For each voltage level there are two different limits for the security distances, which depend on the type of LW to be performed. The limits are shown TABLE 6.

TABLE 6. NEW LIMITS FOR SWITCHING OVERVOLTAGES.

Voltage level	**Base voltage**	**Low limit**	**High limit**
500 kV	550 √2/√3 kV	2.0 p.u.	2.2 p.u.
150 kV	170 √2/√3 kV	2.1 p.u.	2.3 p.u.

B. Maximum overvoltages in 500 kV substations, simple approach

For each simulated event (described in TABLE 1), the U2% overvoltage value was obtained for each 500 kV substation.

TABLE 7 shows the maximum U2% overvoltage value per substation, from studying all possible simplified network models.

TABLE 7. MAXIMUM OVERVOLTAGE IN 500 KV SUBSTATIONS, SIMPLE APPROACH, WITHOUT SURGE ARRESTERS.

500 kV Substation	Max. U2% (p.u.) per substation
MA5	2.8
MB5	2.2
MI5	2.3
SC5	2.6
ME5	2.5
BR5	2.2
PT5	2.3
PA5	2.6
SJ5	2.5
SU5	2.8

The maximum overvoltage obtained in the 500 kV network applying the simple approach is 2.8 p.u., without surge arresters. The obtained values are higher than the allowable limits in TABLE 6.

Further analysis was performed including the surge arresters at the ends of the maneuvered and neighbor lines. The maximum overvoltage obtained for the 500 kV substations with surge arrester was 2.0 p.u. On the other hand, when including surge arrests in the model, the middle of the lines must be measured in the simulations. A value of 2.3 p.u. was obtained in the middle of SU5-SJ5 line. In conclusion, when surge arresters are considered, the maximum overvoltage obtained are close to the allowable High limit. Nevertheless, this is not sufficient to perform LW. Therefore, the detailed approach is used, in the next section, for further investigation.

C. Maximum overvoltages in 500 kV substations, detailed approach

When considering the complete network model, to obtain the maximum overvoltage in the 500 kV system, the maneuver of all lines in the system (150 kV and 500 kV) was simulated. For each simulated event (described in TABLE 1 and TABLE 2), the U2% overvoltage value was obtained for each 500 kV substation.

TABLE 8 shows the maximum U2% overvoltage value per 500 kV substation caused by maneuvers in 500 and 150 kV lines.

TABLE 8. MAXIMUM OVERVOLTAGE IN 500 KV SUBSTATIONS, DETAILED APPROACH.

500 kV Substation	Max. U2% (p.u.) Maneuvers in 500 kV	Max. U2% (p.u.) Maneuvers in 150 kV
MA5	1.3	1.1
MB5	1.4	1.1
MI5	1.3	1.1
SC5	1.5	1.2
ME5	1.8	1.3
BR5	1.3	1.1
PT5	2.0	1.1
PA5	1.5	1.1
SJ5	1.7	1.1
SU5	2.3	1.0

On one hand, overvoltages in the 500 kV substations caused by events in the 150 kV system are negligible. On the other hand, overvoltages caused by events in the 500 kV systems are more significant, but lower than 2.0 p.u. for all substations, with the exception of SU5 substation in which a value of 2.3 p.u. arises. This overvoltage is obtained in a particular case of an energization of SJ5-PA5 with a two phase isolated fault in SJ5. The one line diagram indicating the maneuver is presented in Fig. 4. The maximum overvoltage of 2.3 p.u. arises in SU5, a substation connected in radial configuration from SJ5.

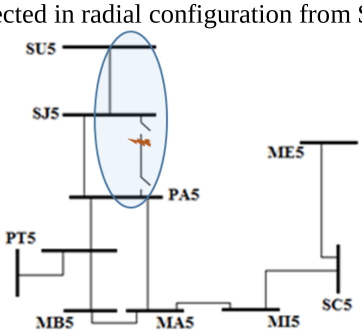

Fig. 4. One line diagram for the 500 kV network.

Further analysis was performed, considering a metal oxide surge arrester connected to SU5 substation. Considering the influence of the surge arrester, the overvoltage in SU5 decreases to 1.9 p.u., being admissible for LW. When including the surge arrest in the simulation, the voltage in the middle of the lines was also measured. No overvoltage exceeded the allowable Low limit of 2.0 p.u. The time domain simulations for this case (with and without surge arrester) are shown in Fig. 5.

Regarding overvoltages in overhead lines, when considering surge arresters, the maximum overvoltage is found in the middle point. For the particular case of the lines connected to PT5 and ME5, simulations with surge arresters were also performed for the worst cases. These substations were selected because the maximum overvoltages exceeded the residual voltage of the 500 kV surge arrester. The analysis showed that the overvoltages found in the middle point of the lines PT5-BR5 and SC5-ME5 are admissible according the limits for LW.

It is important to highlight that the maximum overvoltages take place in substations at the end of lines connected in radial configuration.

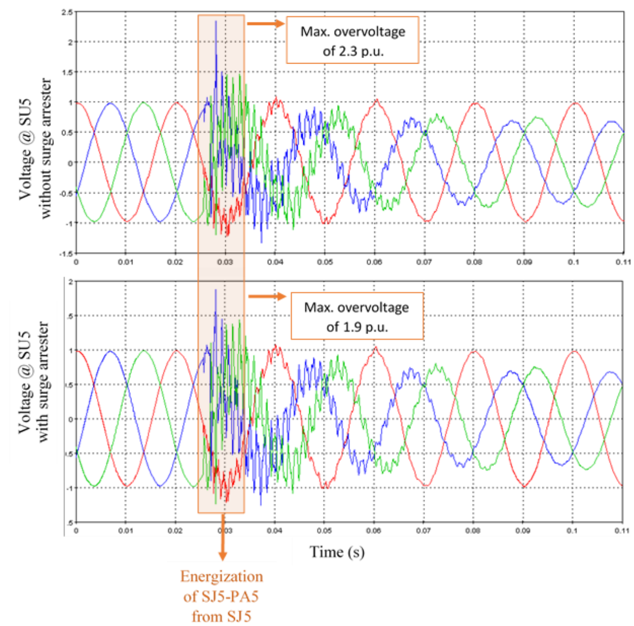

Fig. 5. Time domain simulation of an energization of SJ5-PA5, with a two phase isolated fault in SJ5.

In addition to analyzing overvoltages in the 500 kV system when simulating possible events in this voltage level, overvoltages transferred to the 150 kV through the 500/150 kV transformers were also registered. For approximately 15% of the simulations performed, inadmissible overvoltages were found in the 150 kV system, varying from 2.1 p.u. to 3.1 p.u. Only KIY 150 kV substation presents inadmissible overvoltages due to maneuvers in the 500 kV system.

KIY is connected to the secondary winding of PT5 500/150 kV transformer by a short overhead line of around 25 km. The substation KIY is in radial configuration, open at the end of KIY. See Fig. 6.

The maneuver of BR5-PT5, MB5-BR5, PA5-BR5, MA5-MB5, MA5-MI5 and PA5-MA5 originates overvoltages in KIY.

The time domain simulation for the worst overvoltage in KIY, due to maneuvers in the 500 kV system, is presented in Fig. 7. This case corresponds to the energization of MB5-BR5, with a three phase isolated fault in BR5. The line is energized from BR5 end at approximately 30 ms and MB5 end closes 100 ms later. As it can be seen in the simulation, an overvoltage of 3.1 p.u. arises in KIY as a consequence of the line energization. The impact of not considering stray capacitances in the model of transformers connected to PT5 substation was studied, resulting in a maximum overvoltage of 3.03 pu instead of 3.1 p.u.

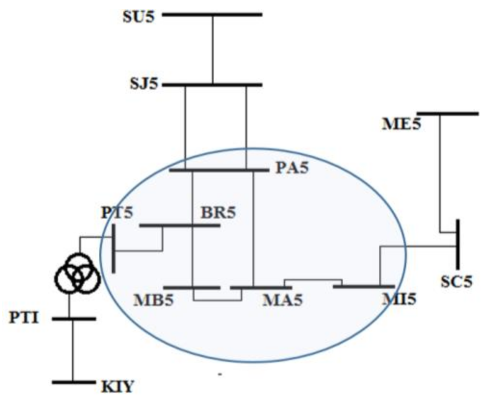

Fig. 6. One line diagram for 500 kV network and 150 kV line connected to 500/150 kV PT5 transformer. Line maneuver originating overvoltages in 150 kV.

Although the probability of occurrences of this event is low, further analysis was performed considering a metal oxide surge arrester connected to KIY. The maximum overvoltage obtained is 1.8 p.u., being admissible for LW. The time domain simulation is also shown in Fig. 7.

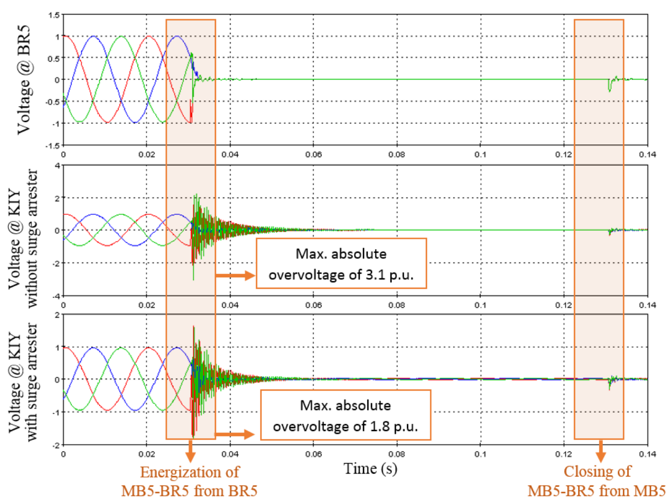

Fig. 7. Time domain simulation of an energization of MB5-BR5, with a three phase isolated fault in BR5.

V. Conclusions

When comparing maximum overvoltages in the 500 kV network obtained with the simple approach versus the detailed approach, it can be seen that, on the Uruguayan transmission network, the simple approach results always in worst values.

For LW to be performed for security distances, a limit of 2.0 p.u. is required for overvoltages in the 500 kV system (see TABLE 6). As shown in TABLE 7, all values obtained are higher than 2.0 p.u. so no conclusion can be obtained from these “worst case” values regarding viability of LW. Therefore, the simple approach is a fast procedure to obtain general, but conservative results for maximum overvoltages present in the system, increasing further more the safety level. The results obtained are not sufficiently detailed to verify whether LW is in fact possible. Thus, a detailed approach is required to obtain a more realistic set of maximum line switching overvoltage values, which can be considered for the development of the LW execution conditions, in compatibility with RTE´s LW methods. Overvoltages in the 500 kV system considering this approach are lower than 2.0 p.u. for all substations, with the exception of SU5 substation in which a metal oxide surge arrester is required to decrease overvoltages.

From analyzing the results obtained, it can be concluded that the propagation of overvoltages in the 150 kV network due to maneuvers in the 500 kV network, are low. Particular situations arise when 150 kV substations are connected in radial configuration, in close connection to 500/150 kV transformers, when maneuvers take place in the vicinity of the mentioned transformer. This amplification of overvoltages is due to the radial configuration of 150 kV line that leads to high frequency resonance circuit, and it is not related to stray capacitances of transformers.

VI. Future Work

Studies applying both the simple and detailed approach are being currently performed over the 150 kV network, in order to obtain the maximum line switching overvoltage values for this voltage level. Additionally, once this first stage is finished, a sensitivity analysis considering variations over load and generation scenarios, fault location and duration will be performed for the worst cases obtained.

Finally, studies performed with the detailed approach will be revised considering wind generation and HVDC converter stations, in order to analyze the impact of this equipment on line switching overvoltages. Nevertheless, the results obtained are currently being taken into account for live working activities when HVDC converter stations are not transferring and the wind farms are disconnected. The final objective is for live working to be performed without these restrictions over HVDC and wind generation.

VII. References

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