

Control of unsymmetrical overvoltages during open pole condition on overhead transmission lines compensated at one end

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Abstract—Different types of overvoltage phenomena are found in the power systems and each one of them requires a particular study because of its nature, features and impact on equipment. The influence of such overvoltages in the power system could have drastic consequences. This paper describes the analysis and provides a methodology for understanding a particular unsymmetrical overvoltage phenomenon based on real power system cases and its mitigation method using protection schemes. The power network under analysis includes overhead transmission lines compensated at one end with three-phase reactors among other elements. According to the relays' DFR (Digital Fault Recorder), the phenomenon appeared on these lines when one phase was opened as a result of single pole tripping of circuit breakers, and after the secondary arc was extinguished. Consequently, an unsymmetrical overvoltage appeared in the phase that was opened. The modeling of three-phase reactor compensation and the whole system was done using ATPDRAW, which is also explained through the paper with transformer model combined with real equipment data. Numerous simulations were considered until finding that the zero sequence impedance of the reactors had the main influence upon this problem. After this, other studies were conducted. They were aimed to analyze the single pole tripping and reclosing of the lines and reactors during the first arc. Finally, some studies' recommendations were done and were also implemented into the protection schemes. These actions consisted of not only keeping single pole tripping and reclosing for circuit breakers of the lines, but also applying these actions to the reactor circuit breakers. All of them were validated by real single fault disturbances on the power lines assisted with fault records.

Keywords: EMTP, ATPDRAW, unsymmetrical overvoltages, single pole tripping, impedance, DFR records.

I. SUMMARY OF BENEFITS OF THIS WORK

THE particular development of this work helped to reduce the impact on the line equipment regarding overvoltage signal when one pole is opened in presence of three-phase reactor compensators at one end of the overhead transmission line. Furthermore, the self-maintained secondary arc was reduced in comparison to the previous condition. Hence, whole recommendations derived from this work led to issue

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the single pole reclosing successful on the lines compensated at one end with this type of inductive elements. In this sense, this application has been suggested in other places where this type of compensation was considered for the lines. One additional benefit expected is the possibility to diminish insulation impacts on line equipment such as reactors, surge arresters and potential transformers. Another advantage is the reduction of the commercial fees because of having successful reclosing every time there is a disturbance on the power line, would avoid paying for the time the asset remains unconnected. In general, the contributions of this work are significant for overhead transmission lines with these features.

II. INTRODUCTION

Different electromagnetic problems of power equipment can be emerged during their service life, and although they are frequently known and classified as overvoltage and overcurrent disturbances, their origins and controls not necessarily are clearly identified. Therefore, this paper works on the electrical studies to understand the unsymmetrical overvoltages on the overhead transmission lines with three phase reactors compensated in one end. Furthermore, it treats the mechanisms used to control the phenomenon by taking advantage of the line's protection and recloses schemes, which allow mitigating the overvoltages and other struggles generated on these kinds of lines. Moreover, comparisons between studies and the responses of the application of studies' recommendations will be presented, and effectiveness of the implementation and conclusions will be also described.

III. HISTORICAL BACKGROUND

Approximately nine years ago, three long overhead transmission lines compensated were put into operation within the electrical power system at 230 kV in a South American country. The three lines were compensated as follows: 53.7% for L1, 67% for L2 and 93.9% for L3. They involved one or two reactors at one end as shown in the Figure 1.

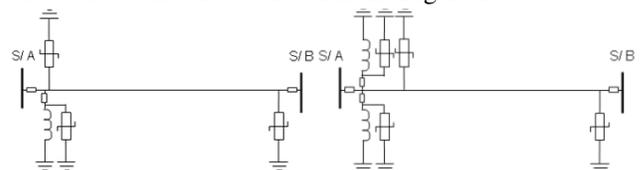


Fig. 1. Lines configurations: L1 (164 km long) left, L2 (247 km long) and L3 (177 km long) right

During disturbances on the lines concerning single pole tripping at both ends of the faulted lines, two opposite phenomena were identified: The long-lasting secondary arc and the unsymmetrical overvoltage in the line after extinguishing of this arc. Therefore, it will be necessary to explain the effect of the secondary arc condition when the unsymmetrical overvoltage phenomenon is present. Both cases happened during open pole condition after tripping.

When a single pole tripping is issued by distance protection, the first interesting thing detected was the duration of the secondary arc which was longer than the dead time of the reclosing in some cases. This caused three-phase trip after reclosing on to fault. However, in some faults, the auto-extinguishing of secondary arc occurred before the dead time setting, and unsymmetrical temporary overvoltage (about 1.6 per unit - pu) occurred in the open phase of the line. Both phenomena brought negative effects against the electrical system and equipment supportability. All this represented rising costs for the lines operation and an increased the risk of breaking the line equipment's insulation. The results found led the technical staff to take different actions in order to solve those problems. As a result it was necessary to investigate the cause of the problems and use EMTP-ATPDRAW to analyze and understand both phenomena. The software was used to model the network as well. Nevertheless, it did not have a three-phase reactor model. Hence, this equipment had to be implemented on this program using the transformer subroutines. Finally, the solution alternatives were derived from this model, and they were proposed and applied in order to address the problem.

IV. SINGLE PHASE FAULTS

Single-phase faults were the typical disturbances occurring on these lines, and although single pole auto-recloses were only successful in some occasions at one end, equipment such as line potential transformers (PT), reactors and surge arresters connected to the faulted phase of the line were exposed to severe overvoltages during auto-reclose cycle. Some events are explained to show what was found.

Event on December 20th, 2005: The Fault was caused by a flashover on line L2. The single pole tripping at both ends was issued by zone 1 of distance protections. Then, the secondary arc was kept for 400 ms and unsymmetrical overvoltage (about 1.6 pu) emerged for 300 ms until circuit breakers reclosed as shown in the following figures:

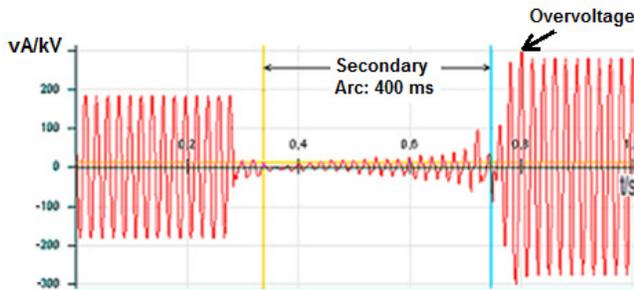


Fig. 2.1. Voltage signal during the event on 12/20/2005 at end A for L2

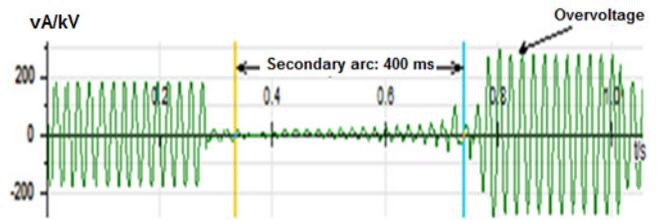


Fig. 2.2. Voltage signal during the event on 12/20/2005 at end B for L2

In this event, a successful single-phase auto-reclose was done at both ends of the line. This is produced after 1 second, see Figure 2.2.

Event on January 1st, 2006: The fault was caused by flashover on line L3. Distance protections issued trips in zone 1 circuit breakers at both ends opened one pole. After the reclosing was done, SOTF (Switch On To Fault) function tripped as the secondary arc time was longer than the dead time setting. Figure 3 shows the current and voltage signals for this event.

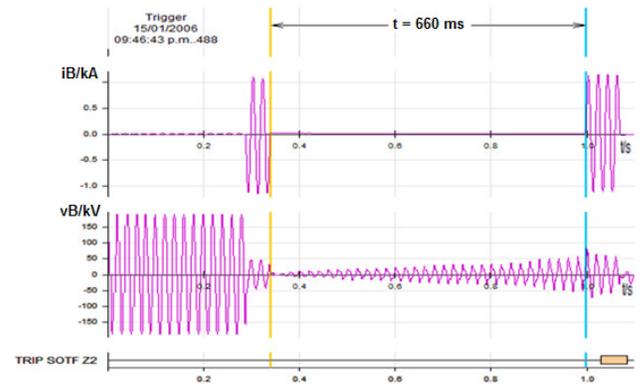


Fig. 3. Current and Voltage signals registered during the event of 01/15/2006 over line L3 detected in S/B end

Event on December 18th, 2005: A similar event occurred on line L1 with the same causes mentioned above. However, after one pole was opened, the secondary arc was kept during 365 ms and overvoltage was achieved. The Figure 4 illustrates the event (DFR record).

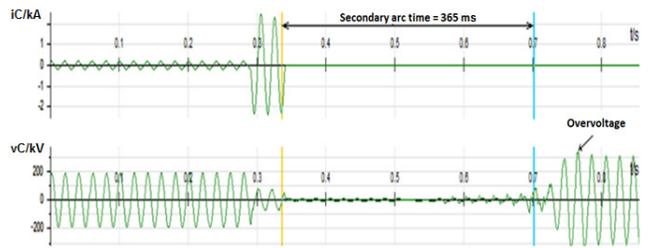


Fig. 4. Current and Voltage signals recorded for the event on 12/18/2005 on line L1 detected at end B

Voltages signals for this event are similar to those shown in figures 2.1 and 2.2. This kind of event was frequent, and the line equipment such as PTs, surge arresters and reactors suffering the effects.

Furthermore, according to reference [3], after secondary arc extinction, the recovery voltage appears because of direct dependence on degree compensation. Therefore, the maximum

values expected on the lines affected would be around 0.3 pu for L1, 0.5 pu for L2 and 2.5 pu for L3. These values can be reached from 25 to 150 ms on these lines. Obviously, these voltage levels do not have any problem and real cases demonstrated that something had to be reviewed. Consequently, it was necessary to investigate an appropriate model form of three-phase reactors to understand every kind of phenomenon that was happening. Several questions were formulated to different transformer manufacturers and consultants so as to know the state of the art on this topic, but the answers were not satisfactory. Particularly, EMTP program [1], [2] does not present any especial model for this type reactor. Then, it was necessary to develop it. Next chapter describes the reactor model generation.

V. THREE-PHASE REACTOR MODEL

According to reference [4], three-phase reactor could be modeled in EMTP as an YnYn transformer connection. However, this reference is not very detailed. So, this suggestion was solved by BCTRAN routine of EMTP [1], which was considered to model the transformer with the following considerations and technical data [2].

A. General Features

- Three limb core reactors
- Rated power of three-phase reactor: 12 Mvar
- Rated voltage: 230 kV
- Rated current: 30.12 A
- Rated reactance of positive sequence: 4408 Ω
- Rated reactance of zero sequence: 1700 Ω
- Knee point of magnetization curve: 1.7 pu
- Surge Arresters nominal voltage: 192 kVp. Maximum Energy of surge arresters: 1.6 MJ. This equipment is the same of the lines.

B. Model Considerations

The three-phase reactor model in the ATPDRAW was considered as a three phase transformer with 12 MVA and two sides of voltages: 230 kV/230 kV. Technical data required by BCTRAN and SATURATION routines.

1) Excitation current of positive and zero sequence

According to Figure 5 the excitation current to rated voltage (1 pu) correspond to rated current, i.e., 30.12 Amps.

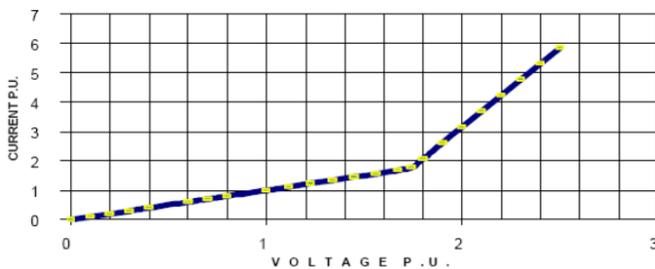


Fig. 5. Three-phase reactor magnetization curve [8]

The manufacturer was asked for zero sequence current data. Nevertheless, it was not possible to obtain it. Only zero sequence impedance (mutual coupling between phases) was

available, which is 1700 Ω . From this value it is possible to achieve the zero sequence current excitation. Next figure illustrates how currents are distributed around the zero sequence tests in order to find the required current.

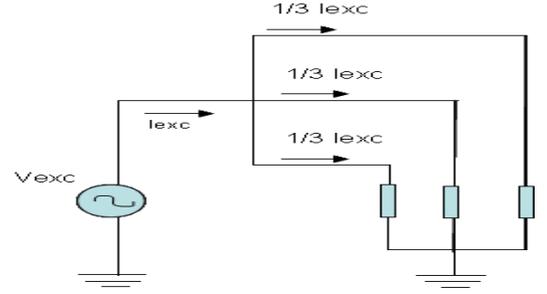


Fig. 6. Measurement of zero sequence impedance of a three phase system

V_{exc} corresponds to rated voltage ($V_{LL-nom}/\sqrt{3} = 230 \text{ kV}/\sqrt{3}$) and zero sequence impedance is $Z_0 = 1700 \Omega$. So, it is possible to obtain zero sequence current (I_{EXZERO} in the EMTP) as follows:

$$I_{exczero} = \frac{1}{3} * I_{exc} * \sqrt{3} * \frac{V_{LL-nom}}{S_{ZERO}} \quad (1) \text{ from [2]}$$

with,

$$I_{exc} = \frac{3 * V_{exc}}{Z_0} = \frac{3 * (V_{LL-NOM} / \sqrt{3})}{Z_0} \quad (2) \text{ from Figure 7}$$

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$$I_{exczero} = \frac{1}{3} * \frac{3 * (V_{LL-NOM} / \sqrt{3})}{Z_0} * \sqrt{3} * \frac{V_{LL-nom}}{S_{ZERO}}$$

$$I_{exczero} = \frac{V_{LL-NOM}^2}{Z_0 * S_{ZERO}}; \text{ with } S_{ZERO} = S_{NOM}$$

$$I_{exczero} = \frac{230kV^2}{1700\Omega * 12MVA}$$

$$I_{exczero} = 2.6 \text{ pu} \Rightarrow I_{exczero} = 260\%$$

2) Short circuit test

Short circuit impedance, losses and other data are required for this routine. However, the transformer model would be connected to one side only and this information is not reported by the manufacturer. Consequently, this data would be replaced for:

$$z_{12} = 100\%, \text{ Losses : } 10 \text{ kW}, S_{base} : 12 \text{ MVA}$$

3) Magnetization curve

As it was previously mentioned, the reactor manufacturer gave its magnetization curve and it was used for SATURATION routine of EMTP and the relationship of current vs. flux was obtained. This curve has two regions: lineal and saturated. Although the lineal part was considered in the BCTRAN routine, it was omitted in the transformer model. Therefore, the SATURATION routine contained the whole magnetization curve.

Other parameters considered were: Bergeron's model of the line and surge arresters' curves which are modeled in the EMTP's 92 routine using the manufacturer's curve. The Figure 7 shows characteristic curve of surge arresters.

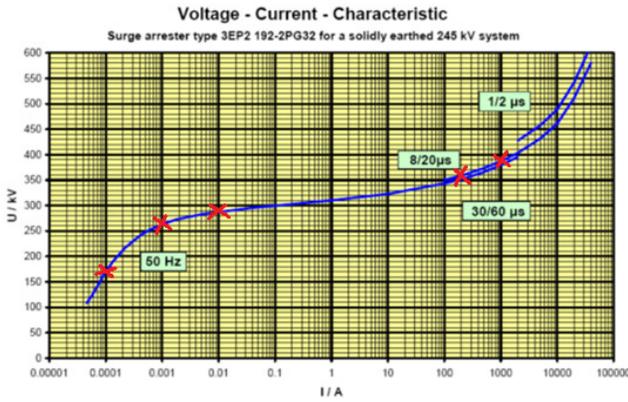


Fig. 7. Characteristic curve of surge arrester and region considered (crosses in red color) [9]

After generating these elements and including them in the network, events were reproduced properly. However, voltages and currents waveforms became rippled. Therefore, to soft waveform voltages, bushing capacitances were considered in the model: 0.01 μF for each one. Next figure illustrates the model considered with all described elements (without these capacitances).

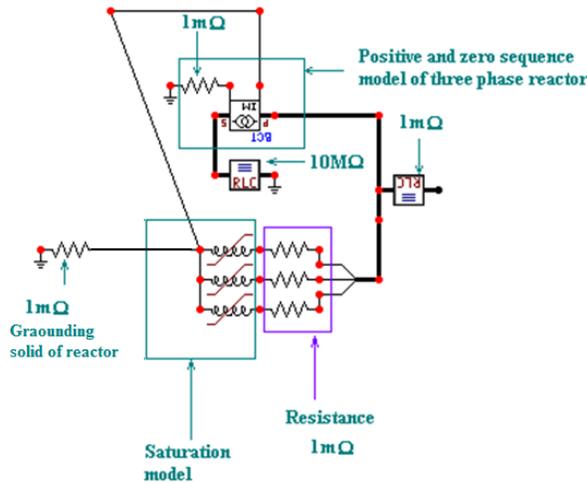


Fig. 8. Three-phase reactor model implemented in the EMT-ATPDRAW program

Particular data of this model is illustrated in the next figure:

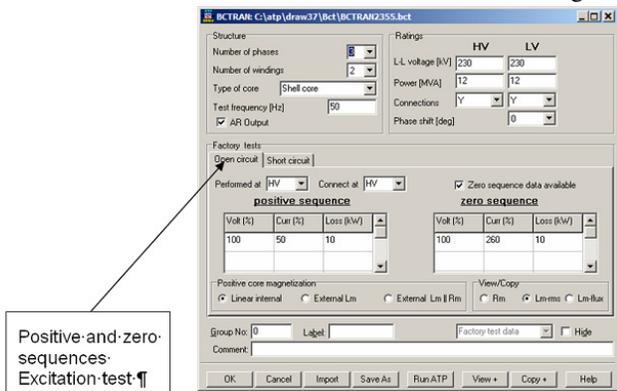


Fig. 9. Three-phase reactor model (BCTRAN routine transformer)

C. Measurements of voltage and current signals

According to unsymmetrical overvoltage events, after poles are opened, reactor currents and line voltages were measured by protection systems at the points illustrated in the Figure 10.

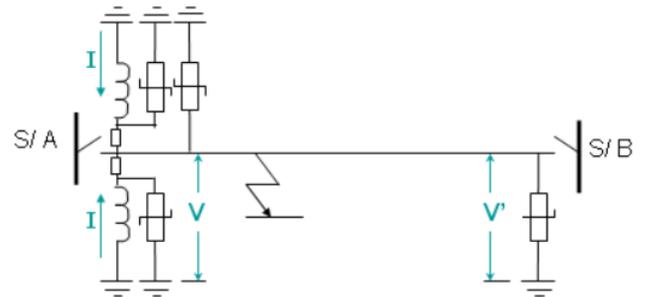


Fig. 10. Measurement points of current and voltage signals in the simulations

It is important to note that the model was used to simulate the phenomena in the whole configurations of the lines. However, line L1 was reconfigured at that time, and its reactor was withdrawn. Thus, the study focuses on lines L2 and L3.

All these models were represented in ATPDRAW program through distributed parameters model of lines (Bergeron model), equivalent sources for busbars, secondary arc model, three-phase reactor models, time controlled switches and surge arrester curve models. Figures 11 to 14 illustrate the line voltage and the reactor current signals recorded on the protection and the ones obtained using the ATPDRAW model, respectively.

1) Line overvoltages comparison

Overvoltage phenomenon was reproduced on the phase opened as shown in the following figures:

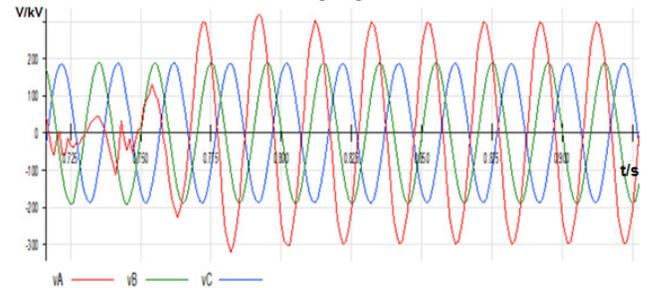


Fig. 11. Voltage waveforms recorded on distance protection

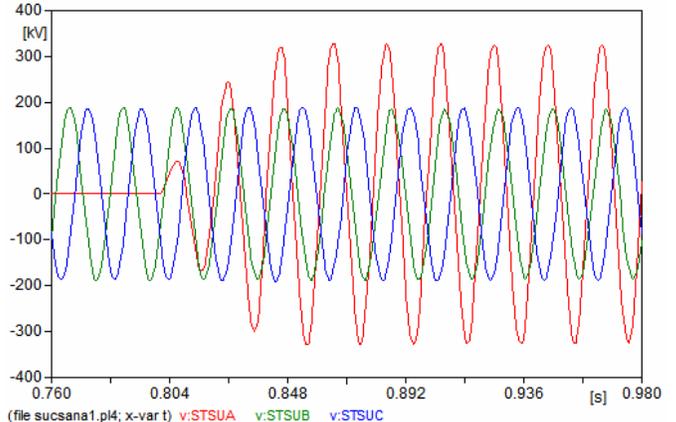


Fig. 12. Voltage waveforms from simulation

According to these figures, the voltage waveforms simulated were adequate.

2) Reactor signal overcurrent comparison

Next figures show the current signals obtained by overcurrent protection and ATPDRAW model, respectively.

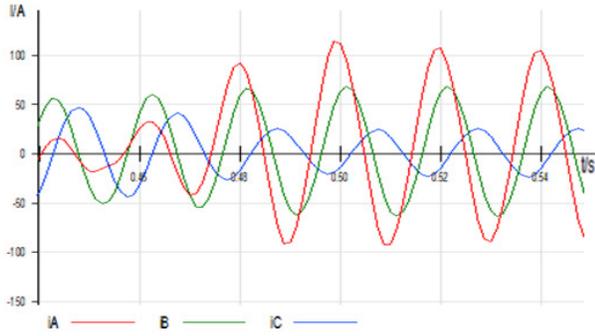


Fig. 13. Reactor current signals recorded on overcurrent protection

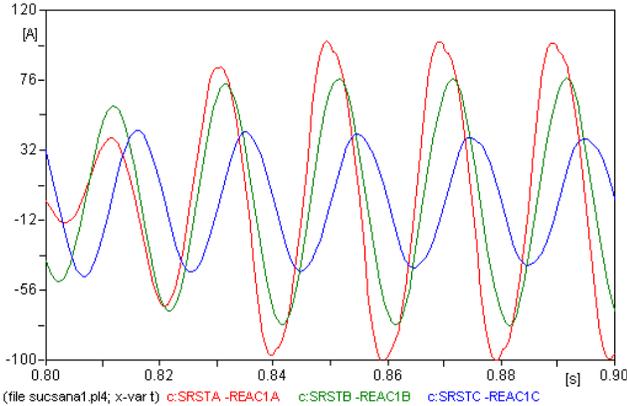


Fig. 14. Current simulations in ATPDRAW program

These simulations were considered with a simple model of the secondary arc using a timer controlled switch. Later, more simulations included a special model for the secondary arc according to references [6, 7].

D. Measurements of Other Electrical Parameters

On the contrary, the energy consumed by surge arresters was taken into consideration. Hence, the results given by ATPDRAW, after running the first simulations, became critical for surge arrester capability. According to the simulations, if unsymmetrical overvoltage signal had remained on the line for more than 1 second, the maximum energy dissipated (1.6 MJ) especially for surge arresters of the line L2 would be reached. Consequently, the equipment would be at risk. This situation needed to be solved.

VI. UNDERSTANDING THE PHENOMENON AND ALTERNATIVE SOLUTIONS TO MITIGATE THE OVERVOLTAGE AND THE SECONDARY ARC

After reactor compensation was successfully represented in the ATPDRAW program, the most important feature was to understand the special behavior of the unsymmetrical overvoltage. Then, several parameter variations in the reactor were considered taking away one by one. For example: the first parameters removed were the magnetization component, surge arresters and one of two reactors, but none of them showed variability. However, when the zero sequence current was removed from the reactor model, unsymmetrical overvoltage had disappeared, and the time of secondary arc became shorter as it is shown in Figure 15.

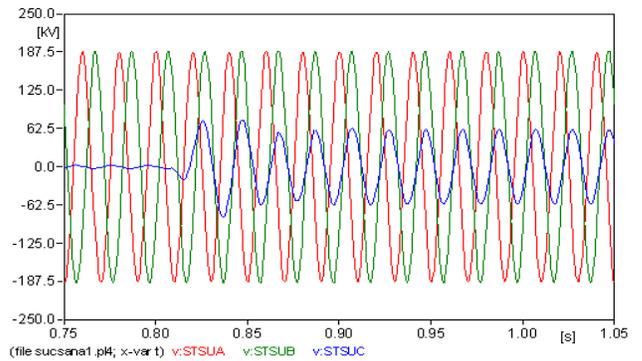


Fig. 15. Recovery voltage (blue signal) after removing zero sequence current (IEXC ZERO) from the reactor models

One last conclusive proof was determining in order to make later decisions to minimize the phenomena. At that moment only three-phase tripping with auto-reclosing for any kind of fault was initially implemented on each line as a measurement to control the long-lasting secondary arc and the unsymmetrical overvoltages. However, the country's electrical regulations demanded that two of the three lines (L2 and L3) have the single-phase auto-reclosing scheme in service. Thus, it implied to continue with technical analysis in order to put into operation the single-pole reclosing scheme again, regardless overvoltages and recloses on to faults problems. Therefore, with the results found from the simulations, zero sequence parameter was removed from the reactor model. In this case, the possibility to open not only the faulted phase both line ends, but also open the corresponding circuit breaker poles of reactors was now considered. The results were very suitable and satisfactory because the simulations clearly reproduced the same behavior of recovery voltage picture in the Figure 15. As a consequence of the simulated conditions, single pole tripping for line's and reactors' circuit breakers were proposed, including single-pole auto-reclose for all of them. Hence, several simulations were done and the results demonstrated that this recommendation mitigated both phenomena and the reclosing would be possible. To this end, it was necessary to acknowledge that the protection systems of those lines such as zone 1 of distance protection, POTT (Permissive overreach transfer trip) and 67N Directional Comparison (67NDC) teleprotection schemes could command both single and three pole trips with auto-reclose. Any other protection schemes must issue three pole definitive trips. Thus, the subsequent analysis was considered as a consequence of tripping by these protections. In Figure 16 it is shown a simulation of single-pole tripping at both ends, including reactors' circuit breakers, after a single-phase fault.

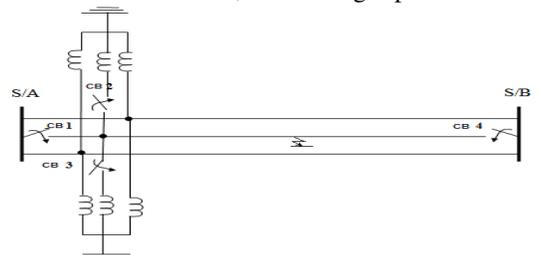


Fig. 16. Simulations of single-pole tripping and auto-reclosing of every circuit breakers of the line and reactors

After the dead time was completed, the reclosing was successful. The final results of these simulations are shown in the following figures:

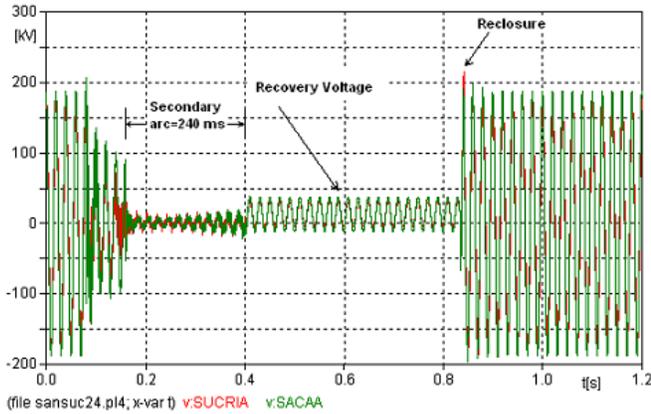


Fig. 17. Voltage signals evolution at both ends: end A and end B of line L2 during the simulated event of single-phase fault at 50%

With one pole opened in four circuit breaker at the same time the secondary arc (240 ms) did not last for as long as in the previous conditions. Thus, the overvoltage achieved disappeared as well. Finally, a recovery voltage signal appeared and then a single-phase auto-reclosing for all four circuit breakers were also successful. The same simulation was generated for line L3 and the results were also satisfactory.

Removing zero sequence impedance from reactor models by tripping one pole of circuit breakers, both problems the long-lasting secondary arc and unsymmetrical overvoltage were solved. With these results, several operative conditions were simulated for lines L2 and L3 in order to predict its performance among different fault conditions as follows:

1) Variation of impedance fault

Location: 50% from end A (Figure 18). After running a lot of single-fault simulations, the longest time of the secondary arc (150 ms) was reached at the middle of the line with low impedance (0.1Ω).

2) Pole discordance time

Despite it is suggested to trip one pole for all circuit breakers simultaneously, some pole discordances were also analyzed in order to evaluate the maximum time for the secondary arc in this condition. In this case, the maximum value obtained was 140 ms with 20 ms of pole discordance time. In general, all extinction times of secondary arc were reduced considerably which increased the probability to obtain successful auto-recloses.

Furthermore, different types of tripping conditions of circuit breakers were also simulated. Among others, it can be mentioned:

- Simultaneous Single-pole trips of reactors' and lines' circuit breakers. No problems were detected in this simulation.
- Single pole trip of the reactors' circuit breakers including the same trip at end A of the line, although, three-phase tripping at end B after 400 ms (tripping by zone 2 time). No problems were detected here.
- Statistical switching simulations in ATPDRAW. This study permitted getting transient overvoltages after reclosing

every circuit breaker pole. The maximal value obtained was 345 kVp, with surge arrester energy of 45 kJ. Therefore, no critical condition was considered in these cases.

- Single pole tripping at end B of the line, three-phase tripping at end A of the line after 400 ms (zone 2 time of distance protection) and no single-pole tripping for reactors' circuit breakers. Self-maintaining secondary arc and recovery overvoltage became visible again, as shown in Figure 18.

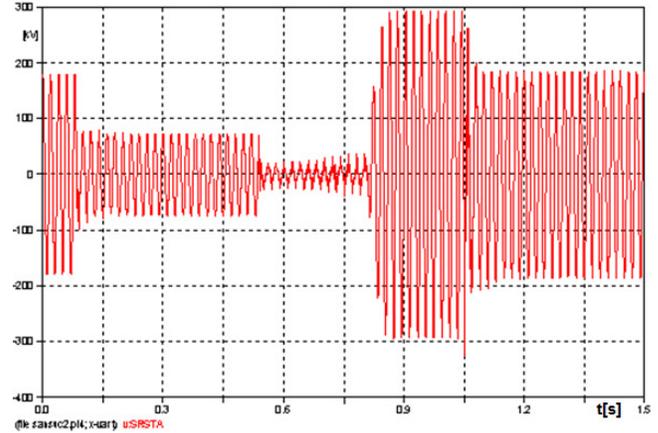


Fig. 18. Three-pole trip at end A with auto-reclose

The recovery overvoltage lasted 250 ms because of the successful reclosing at end B. In this condition, the surge arresters consumed 220 kJ. Finally, the impact was reduced in comparison to the previous state (without any mitigating action taken).

After all, the decision to put into operation single-pole tripping and auto-reclose schemes of reactors was made and it required a study, which first evaluated requirements at each substation for lines L2 and L3. The application was oriented to the settings of protection schemes, and the connections for single-pole tripping and close command for reclosing of reactors' circuit breakers. It means, the distance protection tripping at the line end, nearest to the reactors' circuit breakers had to be implemented to this equipment (end A in Figure 16). Additionally, auto-reclose relays for reactors had to be implemented with its settings. Some of these values were: dead time in 650 ms which must be the same for every auto-reclose relay (reactors' and both line ends' circuit breakers); evolving fault dead time for the reactors' auto-recloses relays was set to 200 ms; the pole discordance time function for line circuit breakers was reduced from 1200 to 900 ms in order to get three pole trips of the lines and reduce exposition times to overvoltages after reclosing circuit breaker pole of reactors. The pole discordance time function of the reactors' circuit breakers was set to 1 second.

All these facts were implemented at the beginning of 2007, and it was only at the end of that year when events began taking effect in L2 and L3 lines. DFRs were obtained from the line protection systems and the results were the expected. One of them can be seen in the next figures.

Event of 19/11/2007: Single fault phase C on the line L2, location 27.9% from S/B end. As it can be seen in the next figures, the fault was opportunely cleared by single pole trip of distance protection systems in zone 1 and successful single

auto-recloses of circuit breaker poles of line and reactors were accomplished.

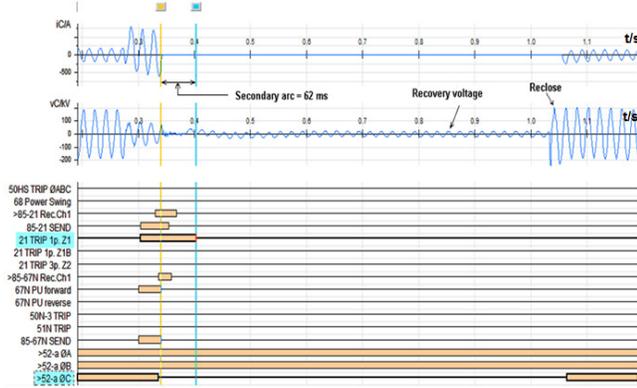


Fig. 19. Fault record of the event 19/11/2007 detected by end A's distance protection of the line L2

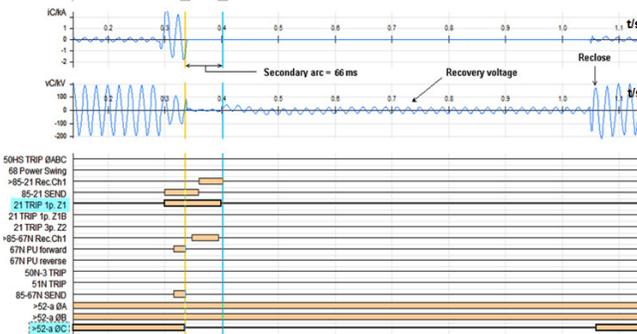


Fig. 20. Record of the event 19/11/2007 detected by end B's distance protection of the line L2

In this event, there was not an overvoltage signal and the secondary arc time was very short (less than 70 ms).

Several events similar to this on lines L2 and L3 presented the same performance confirming the prior simulations showed in the Figures 15 to 17 and demonstrating the appropriate three-phase reactor model as well. Finally, this implementation produced successful auto-recloses without any overvoltage phenomena which avoided investing of money in other equipment and additional resources. Next chapter describes the study developed for the single pole auto-reclose in these lines before and after this recommendation.

VII. STATISTICAL PERFORMANCE OF THE SINGLE POLE AUTO-RECLOSE ON LINES L2 AND L3

The owner company of these lines has taken the statistical behavior of the auto-recloses since they were put into operation. The Figure 21 illustrated a summary of this study.

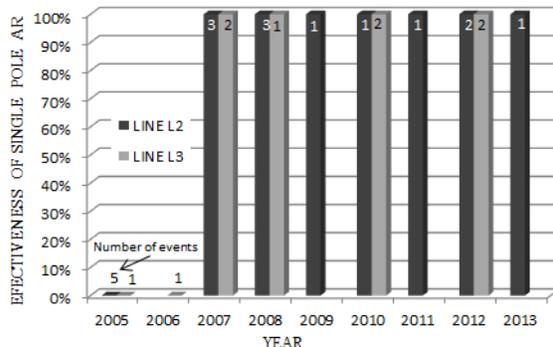


Fig. 21. Statistical study of Auto-recloses on both ends of the lines L2 and L3

Before the implementation was done, the single pole auto-recloses were not successful in any event. It was only since 2007 until today that the events of single phase fault on both lines have come being successful as a consequence of this application.

VIII. CONCLUSIONS

Three-phase reactor model obtained by technical manufacturer data and implemented in EMTP-ATPDRAW program permitted to reproduce the overvoltage phenomena and the self-maintaining secondary arc contributions after single fault phase and during single auto-reclose cycle in an appropriate way.

Moreover, this model was helpful to study other alternatives related to the reduction of the unsymmetrical overvoltage with the condition of one pole opened such as single-pole tripping of the reactors' circuit breakers, and the behavior analysis of the single phase auto-reclose cycle which was later implemented with satisfactory results.

All in all, the actions described through this paper represent alternatives to improve the operation of power systems and reduce impacts on equipment. These facts can be seen during the design stage and should be supported by other studies in order to decide if three limb reactors are an adequate solution or perhaps five limb reactors could be a better option, or using single-phase units would be more appropriate as it is said in reference [5]. Therefore, it is strongly recommended to explore alternatives available related to technical solutions so as to face engineering practical problems properly. Combining software and research experiences of other people before deciding to install new power equipment; it will make more confident the final outcome and reduce the risks of damaging due to electromagnetic problems.

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