EXPERIENCES IN SETTING PROTECTIONS OF SERIES CAPACITOR COMPENSATED LINES

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Abstract - **The protection of series compensated lines, in particular with capacitors located at the end of the line, present many difficulties. The satisfactory setting of line and capacitor protections requires time domain simulations including the protection model. In most complicated cases, the connection of the real protections to digital or analogical simulators becomes necessary. Using this approach, protections are settled as a system and not individually. Experiences of setting protections in high voltage systems with series compensation at line ends, using a Transient Network Analyzer (TNA), are shown in this paper. Some particular problems are examined, including main criteria used for setting of transmissions systems, which are nowadays in operation.**

Keywords: Line protections, capacitors, arresters, varistors, TNA, traveling wave relay, Impedance relay, resonance, transients.

I. INTRODUCTION

Series capacitor compensation (SCC) is included in transmission systems in order to reduce series reactance of lines. Capacitors increase the transmitted power and the transmission length. Inside the line, three protection schemes must work together, the series capacitor protections and the line protections at both ends. The operation of any of these relays changes the system configuration and the transient behavior detected by the other relays.

Additionally, the placement of capacitors at the end of the line reduces station costs but introduces particular difficulties [1] under fault states. Depending on fault location, resonant conditions are frequently obtained. Capacitors fully compensate inductances and only the losses of the system reduce fault currents. Resonant currents are dangerous not only for its magnitude but also for reducing the feeding of the non-resonant extreme. They create difficulties in the detection of the fault from this extreme and transform reclosing in a risky operation.

Traditional impedance relays are not very well suited to protect series compensated lines (SCL). Due to fault location and overcompensation of line reactance by the capacitor, the relay frequently misleads the fault position. Three principles had been used for SCL. Traveling wave relays were very popular and many systems are still using them. It is based on comparisons of current and voltage traveling waves generated in the fault location. Digital impedance relays, usually with its measurement points connected between the capacitor and the line, became usual. The flexibility of digital relays allow to consider many functions necessary to make it work correctly. Phase comparison principle, is also used for SCL. The phase of voltage signal at each end of the line is matched to detect abnormal changes introduced by line faults. This principle requires an elaborated communication system between line extremes and cannot be used in long lines.

In order to preserve capacitors and their internal insulation, a complex protection scheme is frequently used. Shown in fig. 1, arresters (usually of ZnO) are mounted in parallel arrangement with the capacitor bank. They reduce overvoltages due to the system faults. A fast-operated gap is frequently included in bypass capacitors and arresters. Finally a switch bypass capacitor, arrester and gap. These equipments are controlled by a microprocessor fed with internal signals from the arrangement. In most faults, only the varistor acts, but for critical faults (under risk of damage) gap and switch are triggered. Some functions of this relay have been successfully settled using a simulator.

When any of these protections operates, the wave forms detected by the others relays are changed. To find their proper settings, time domain simulations, including the logic of the relays, are necessary.

II. THE SIMULATORS AND THE SYSTEM MODELS

Traditionally, TNA have been used to study these systems [2]. Nowadays, the new generation of digital and hybrid simulators is replacing TNA [3], [4]. Parallel processing, expensive digital-analogical conversion (D/A), and model development are important factors that increase digital simulator costs. Real time TNA (where the frequency of the TNA is the same of the system) are very suitable to include many non-linear elements as well as control and protection equipment [5].

The time delay introduced by electronic interphases to connect protections is very low respect to delays of the D/A conversion and the computation time of digital simulators. The data acquisition system (DAS) of the TNA, usually used to record transients, can be used to detect the operation of the protection. The DAS can be connected not only to the simulated system but also to the protection terminals that provided the signalization of the operation. Thus, long statistical studies can be carried out where protection behavior can be evaluated in a probabilistic mode. The main advance in using a simulator respect the traditional off line EMTP simulation (using a portable D/A system), are the feedback of the protection response to the system and the major facilities to carry out probabilistic studies.

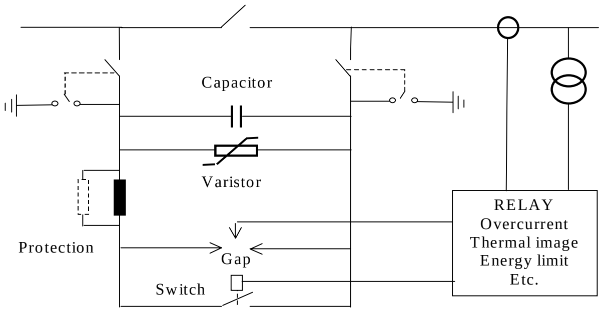

Fig. 1: Series Capacitor protection scheme

The pi cascade line model permits to consider multiple faults locations at the same time in order to study evolutive faults or fast detection of dangerous fault locations. Due to the natural filtering of measurement transformers and the protection filters, including frequency dependent representation of the earth return is enough to obtain a correct simulation of the phenomena. In some cases, especially when dc offset or sub harmonics frequencies have important effects over the simulation, the current and voltage transformers have to be included in the modelation.

Fig. 2 shows the scheme of protection connections to a TNA. It can be seen the feedback of the protections to the simulator through the operation of the switches, as well as the communication channel between protections.

The process of simulation involves the uses of multiple fault position and impedances [6], and a set of statically defined times for fault insertion. In case of three-phase and two-phase faults, the probability of fault insertion is uniform in one nominal frequency period. In a cycle of nominal network frequency, there is always a high voltage difference between phases or a phase and neutral to breakdown the isolation distances and to maintain an arc.

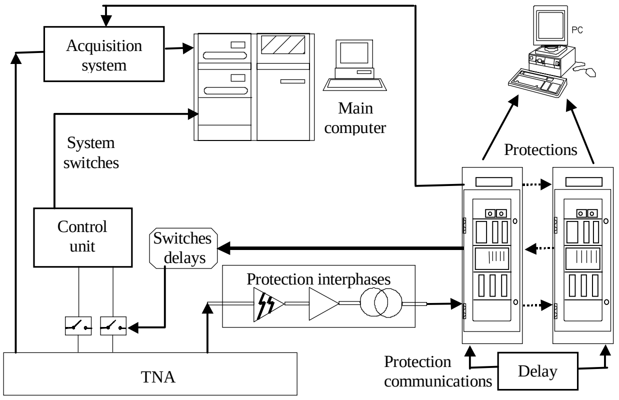

Fig. 2 Simulator and protections connection scheme

On the contrary, for single-phase faults due to external causes like fire, tornados or tower fall, a mechanical phenomenon is involved with a very slow time constant respect to the frequency period. That means, faults are more likely to ocurr when the voltage is close to its peak, i.e. the angle of fault insertion respect to zero crossing voltage is close to 90 degrees. An exception of this is backflashover-originated fault. The voltage required to start a fault is significatively bigger than the voltage required to maintain it. The atmospheric discharges that start the fault in backflashover have uniform probability of occurrence in one period. Since an small voltage is necessary to maintain the fault, it is possible to find small angle insertion faults in this case. Thus in single phase fault, two zones of different likelihood of fault insertion can be defined, considering data from Isoceraunic levels.

III. CAPACITOR PROTECTIONS

Faults in the system are a very important strength of the insulation inside the capacitor. The combination of high currents, rising internal temperatures, with high terminal overvoltages could easily damage them. From the many and complex functions included in the relay that command the protection scheme of fig. 1, two settings are very important. They are incorporated in the dynamic setting of the protection carried out with simulations.

An instantaneous overcurrent relay trigger the gap and the switch when current inside the varistor overcome its setting. Additionally, a thermal image relay control temperatures inside key points of varistors. The relay computes the varistor energy dissipation and triggers the gap and the switch when this magnitude reaches its limit. Overcurrent relay setting is used to obtain selectivity in the operation of parallel lines. Thermal image settings are defined from the energy capabilities of the varistor. Its operation usually requires the block of both, the reclosing and the fast reconnection of the arrester.

During a fault, most of the highly distorted current due to the non-linear behavior of the varistor is short-circuited through the capacitor low impedance. Only, the fundamental component of the harmonic currents flows to the system. Since the circuit is non linear, any kind of faults excite the three sequences, i.e. it is not valid to analyze three phase faults by considering direct sequence circuit alone. It has consequences over the severity of faults used in the system design.

Fig. 3 shows part of the 500 kV Argentine system. The varistor protections and the line protections were intensively studied in a TNA. Fig. 4 shows a 50 Hz equivalent of the circuit that could be used for any of the buses with four capacitors connected.

Under fault conditions, the protection level and the slope of the varistor characteristic have big influence over the energy dissipated inside the varistor. For each system there is an optimum protection level, usually ranged between 2 and 3 pu. Extensive transient simulations were carried out to obtain energy levels and to define the optimum protection level of the system. The relation between the varistor characteristic and the energy absorption during a fault is different, depending on the position of the fault. If the protection level of varistor D in fig.4 is increased, the absorbed energy is bigger, increasing the voltage difference between capacitor terminals. On the contrary, in varistors A, B and C the increase of the protection levels reduces the dissipated energy. In those varistors, the circuit imposes the voltage across the capacitors, while, in varistor D the capacitor voltage is strongly influenced by the varistor characteristic. A higher protection level in bank D also means more investment in insulation of the capacitor bank.

Fig. 4 lets to understand others particular behaviors of the system. Most of dangerous faults, with high currents and absorbed energies occur inside the line and not in bus faults. Equivalents of branches A, B and C are inductive at nominal frequency, since the system is under-compensated. As these branches are in parallel, the total inductance is reduced and easily compensated by the capacitance of bank D. Thus it is very easy to find fault locations inside the line involving resonant configurations and very high currents.

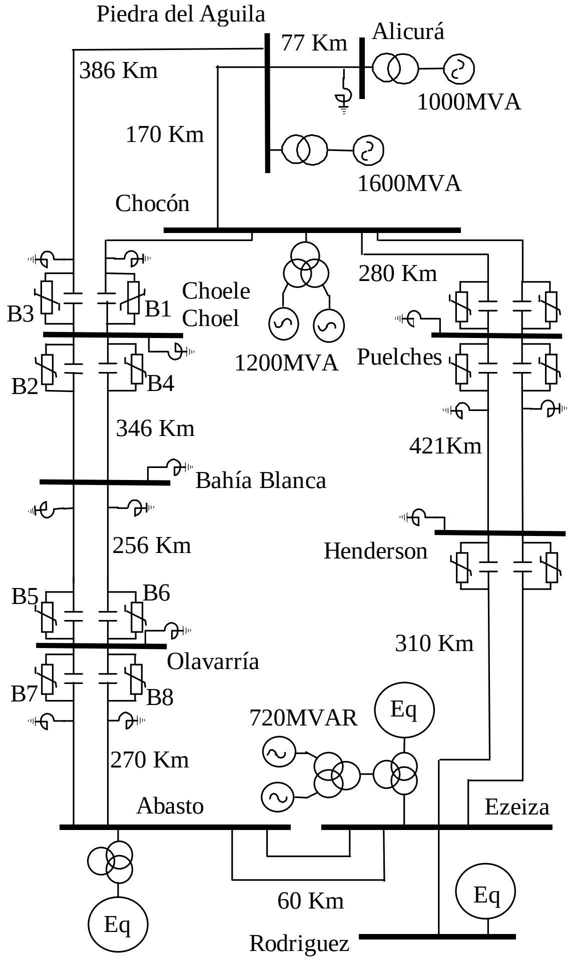

Fig. 3: 500kV System extensively studied in a TNA

In fig.3, capacitors of Choele Choel and Olavarria buses are in line side, they are operated together with the line. The overcurrent module of the protection is used to obtain selectivity respect to the fault position. The criterion of this protection is that for external faults to the line the capacitor must not be bypassed. The gap and the switch must not be triggered in order to avoid the loss of an unfaulty line. Thus, the instantaneous overcurrent relay must settled to a current level superior to the maximum current of external faults that can be observed in the system. Due to the non-lineal behavior of the varistor, many simulations have to be carried out to obtain external fault currents. Additionally, the action of a bypass in case of internal faults (which is permitted to protect the varistors), sensibly modifies the currents in the others varistors. In order to get the settings several simulations are carried out. In a first stage no bypass action is permitted, in a second simulation bypasses are settled to 1.2 times the external fault currents of the first simulation. The new external currents are used again for bypass action and the process is repeated untill a proper operation is achieved. Table 1 shows the changes of external fault currents, important changes can be seen in currents.

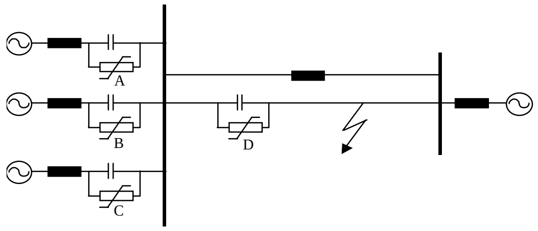

Fig. 4: Circuit Equivalent of the system of fig.3.

In order to detect the maximum level of dissipate energy in varistors, there are three different faults locations along the line that are very important to analyze [7]. Faults very close to the capacitor, usually in resonant points produce high current peaks. Although the gap can bypass the bank in few milliseconds, this time is enough to accumulate an important amount of energy in the varistor. A second criterion to dimension the varistor is based on external faults to the line that is compensated by the varistor. It has to support all the dissipated energy without the bypass operation. Only the faulted line has to be disconnected by reclosing action or triggered permanently by the protections.

Finally, there are cases of faults far away from the varistor, on the extreme of the line, which do not include high current levels but dissipate important energy in the varistor. Frequently, single-phase reclosings create this problem. The current level is not enough to trigger the protection of the varistor by overcurrent, but the line protection start the reclosing cycle. If successful, the cycle will produce the cleaning of the fault. The varistor has to support the accumulation of energy in the first stage of the fault and after the reclosing, including the high current originated in the connection transient.

Table 1: Maximum currents for external faults in the system of fig.3, Choele Choel and Olavarria buses.

Bank	**Without Bypass**		**With Bypass**		**Variat. %**
	Iext [kA]	**Fault**	**Iext [kA]**	**Fault**	
B1	6.06	B3, 3ϕ	6.36	B3, 3ϕ	5
B2	1.99	B4, 3ϕ	3.33	B1, 1ϕ	40
B3	4.78	B4, 3ϕ	4.78	B1, 3ϕ	0
B4	1.99	B2, 3ϕ	3.33	B1, 1ϕ	40
B5	3.90	Bus, 3ϕ	5.10	B7, 3ϕ	23
B6	5.36	Bus, 3ϕ	5.75	B8, 3ϕ	7
B7	3.90	Bus, 3ϕ	5.10	B5, 3ϕ	23
B8	5.36	Bus, 3ϕ	5.75	B6, 3ϕ	7

IV. INTERACTION BETWEEN CAPACITORS PROTECTIONS AND LINE PROTECTIONS

The zinc oxide varistors, commonly used to protect series capacitors, start to bypass them almost immediately, when voltage overcomes the protection level. Since the action of the varistor produce a very important modification of the circuit, its action affects the line protection operation.

However, since current is in advance by 90 degrees respect the voltage at capacitor terminals, there is a delay in the operation of the varistor. The capacitor voltage reaches the maximum a quarter cycle of the nominal frequency after the fault arrives to the capacitor. If the protection can send the trip signal in this time (approximately 5 msec.), the varistor has no influence over the operation of the protection; otherwise the action of the relay depends on the varistor influence over the network. Fig. 5a and 5b show a three-phase fault simulation in the line Puelches-Henderson of fig.3. Currents at Puelches capacitor are recorded. The delay in the varistor current can be seen. The bypass is closed at 65 msec., and currents from Puelches and Henderson start to decrease. For high series degree of compensation the fault can evolve to very low currents and it creates problems in the line protections.

V. TESTING TRAVELING WAVES RELAYS

Traveling wave protections were used in lines of the system shown in fig. 3. The particular relays used were analogical. Many filters and modules process the voltage and current measurements in order to obtain waves generated by the fault. The fault location is detected by comparisons between the signs of current and voltage waves. It can be shown that for faults inside the protected lines, signs of current and voltage traveling waves are different, meanwhile for external faults they are in equal.

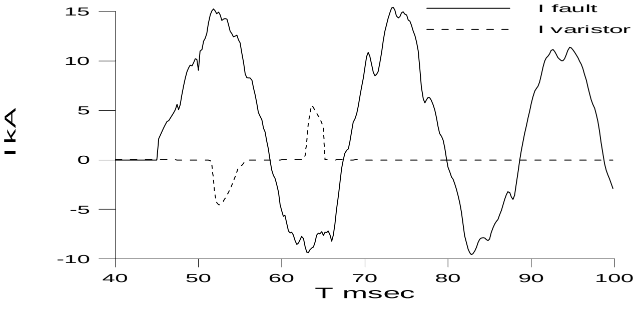

Fig. 5a: Fault and varistor current. ATP simulation of a fault in a line of fig.3.

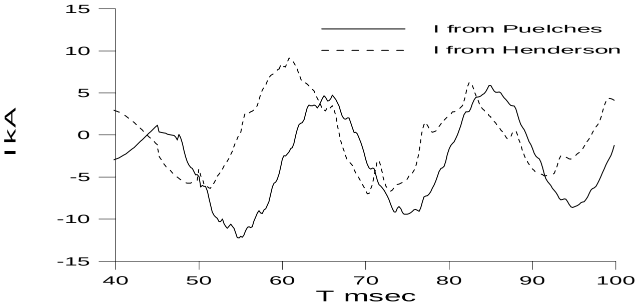

Fig. 5b: Currents by the protections. ATP simulation of a fault in a line of fig.3.

Main features of the protections are:
- Ultra-high speed of fault detection, approximately 3msec, and directional detection scheme.
- Selective and independent operation channel for high-level faults, which are near to the protection.
- A conventional impedance relay is added as a backup protection. Additionally, after a first fault is detected, the impedance relay acts as main protection, in order to detect evolving faults. The traveling wave protection is block to avoid misoperation due to reflected waves.
- Passive and active filters are added to cut nominal frequency and its harmonics. It permits avoid protection misoperation due to saturation of power transformers, reactors, CT, CV, etc.

After some misoperations were detected over part of the system, and also due to expansion of the other part (under construction at that time) TNA simulations were carried out. The studies shown some problems in filter operation. Small changes in components of active filters, mostly due to temperature changes, create problems in the performance of the relay. But not only the hardware created problems. Due to series capacitors locations, resonance conditions were frequently achieved. For those faults, the traveling wave spectrums included many frequencies close to nominal frequency and its harmonics. Since filters were designed to cut those frequencies, poor detection was obtained and in several cases the backup modules acted, introducing delays in the line tripping. Fig.6 shows current in Chocón protection for a fault in Puelches (in the second zone). With small changes in the fault time, the protection detects the fault in first zone. Fig.7 shows the frequency spectrum of both currents, the normal operation has major amplitude than over-operation. This permits the blocking action of the detector module. Besides, some frequencies can be seen around harmonics of 50 Hz, which are removed by filters, decreasing the quality of the detection.

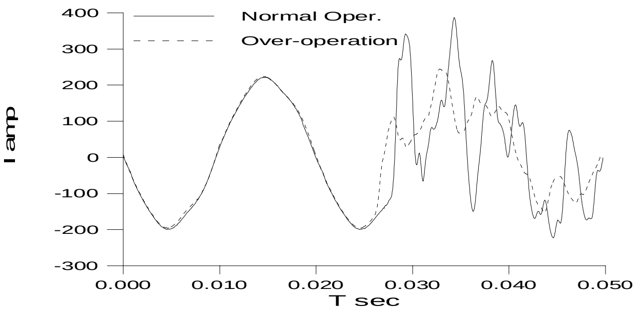

Fig. 6: Currents in Chocón protection, line Chocón-Alicura for a fault in Puelches bus.

Other problems were detected in relation with reflected waves. A fault over the line Rodriguez-Ezeiza (fig.3), trips the protections of the line Alicura – Chocón. The Alicura power plant was not in operation and the line remained connected to feed the auxiliary of the station. The fault was reproduced in the simulation and the protection showed similar behavior to the system. It was found that the incoming wave from the fault to the Chocón bus had not enough level to block the protection. The traveling wave was reflected in Alicura extreme and arrived again to Chocón bus where the protection tripped by weak end feed mode. Modifications of the blocking levels produced the right operation of the protection.

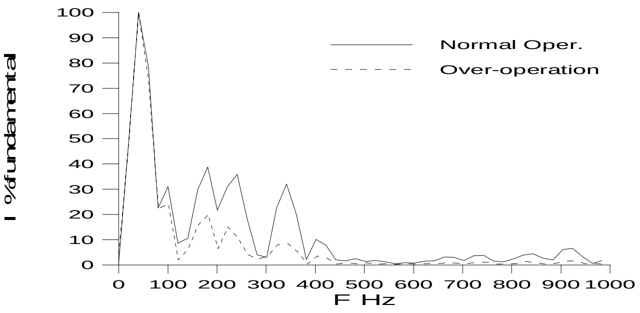

Fig. 7: Frequency spectrum of two fault currents of fig.6

VI. SYSTEMS WITH HIGH SERIES COMPENSATION DEGREE

High compensation degree in capacitors, located at one end of the line, creates difficulties in line protection operations. Many particular effects, linked to very low or very high fault currents can be observed in systems of similar characteristics [8]. Fig. 8 shows a 345 kV system in the north of Chile and Argentina with a line length of 412 km and a series compensation degree of 70 %. This system has two extreme operation conditions; under maximum power transference the capacitors are in operation, otherwhile, under minimum power transference they are bypassed.

When a fault close to Atacama bus appear, with the capacitors in service, most of the fault current is feed from Atacama side. This creates difficulties to the Salta line protections to detect the fault. The protections of the faulted extreme detect the fault very close, so they open the line switches; but the protection distant from the fault can take different actions. Fig. 9 shows currents detected by Salta protections in a TNA simulation of a two-phase with earth contact fault, close to Atacama side. Phase B shows a fault current lower than the load current. It can be seen the wave changes due to Atacama opening, also the protection delays its decision after that operation.

In another way, if capacitors are not working, faults far away from Atacama bus are fed mostly from Salta power station. Fig. 10 shows again a two-phase earthed fault but close to Salta extreme. Currents oscilogramas correspond to Atacama protections. Due to the low fault current level in one of the phases, the protection starts a single-phase reclosure. It could be a dangerous operation of reclosing over fault with the Atacama extreme open. Overvoltages in unfaulty phases could reach important levels.

In both cases currents mislead the protection. Using more sensitive levels of detection produces over operations in other type of faults. The best solution was to implement a transfer trip that triggers both sides when one of the protections detects the two-phase fault. Since the current level does not reach very high values, the delay of the communications system does no affect the operation.

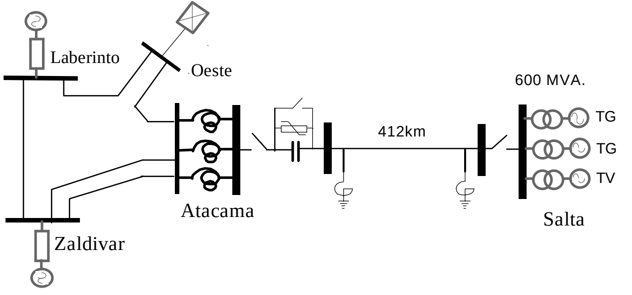

Fig. 8: 345 kV system, with series compensation in the north of Chile and Argentina

VII. CONCLUSION

In this work major aspects of setting complex protections systems are remarked:

- Protections should be settled together in an iterative process, where changes in settings of one protection affect the operation of other relays. The process must be view as the setting of a system and not as setting individual protections.
- The optimum settings are reached after many simulations, considering statistically computed times for fault variations. The fault angle insertion should be carefully analyzed.
-A very flexible acquisition system is necessary to record many analogical and digital responses of the protection.

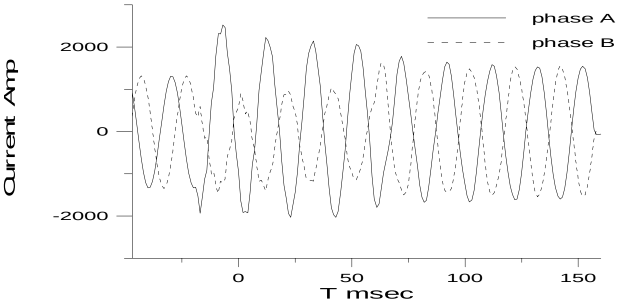

Fig. 9: Current in Salta extreme for a two- phase earthed fault, close to Atacama. Capacitors are in service.

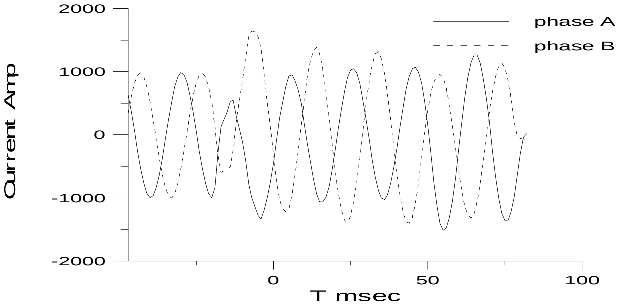

Fig. 10: Currents detected by Atacama protection in a two-phase earth fault close to Salta.

- The protection response should be analyzed in terms of statistical analysis, to get a minimal number of over-operations without sub-operations. Simulations with settings forcing misoperation should be carried out in order to define proper ranges for settings.
- Additional computations with transient programs should be

carried out to detect resonant locations of faults and the critical configurations to study.

-Traveling wave relay shows a very good principle of operation, but it could be improved, working on filter techniques and detection limits of the modules.Digital filters could improve notably the perfomance of the relay

- Operation states with bypassed capacitors should be analyzed.
- Special care should be taken with two phase faults.

VIII. ANNEX A: THE INFEED PROBLEM.

The infeed problem, very well known among protections experts, can be explained using fig.11a. It shows a simplified circuit of a fault in a line. Za and Zb include line extreme equivalents, series compensation and line series impedance. Rf represents fault resistance. Based on the compensation theorem, the voltage fall produced in Rf due to Ib can be replaced by an equivalent voltage source Va. Depending on impedances and angles of sources Vfb could act against Va to reduce Ia. As indicate in fig 11b, if Ib grow Ia decrease. Series compensation modify its impedance dynamically, i.e. varistor conduction, gap changes abruptly the impedance of the circuit.

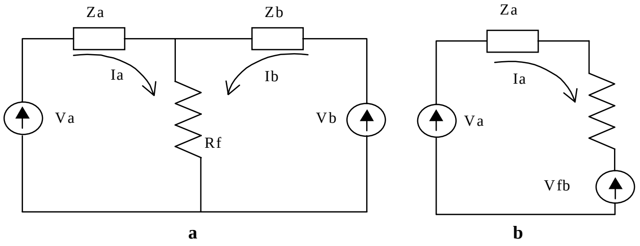

Fig. 11: The infeed problem.

IX. ANNEX B: TWO PHASE FAULTS.

The transient behavior of two-phase faults present particular problems when happens in long lines with bypassed series compensation.

Let’s consider the simplified phase diagram of fig.12, representing a two-phase fault (between phases b and c), without earth contact and close to the middle of the line. Subscript b and a identify magnitudes pre and post fault. Considering the fault arc, its voltage difference is V_{fbc} and the voltage respect earth in the middle of the arc is V_f. Since the arc is pure resistive, fault current I_{fbc} is in phase with V_{fbc}. Due to the long reactance of the line, fault current is small, of the same magnitude order that load currents I_{ba}, I_{bb} and I_{bc}. When added to current loads it produces different total currents for each phase. Current of phase c is enlarge meanwhile current in phase b has little change in magnitude. The protection can mislead the two-phase fault, detecting a single phase and start a reclosure cycle. The previous analysis discharge the dc component, considering the pre-fault and post-fault only. The dc component can help the protection to act (provide it does not create saturation problems in CT and CV transformers). The dc component increases the value of peaks. But since the fault reaches each phase with the voltages at different levels, the dc components are different for each phase. Fig.10 shows this situation, the dc component is lower in phase a.

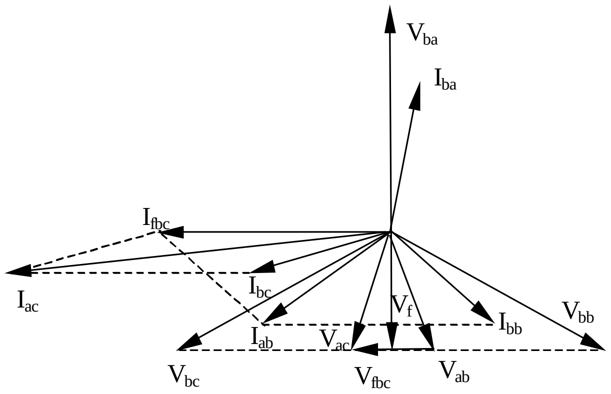

Fig. 12: Simplified phase diagram of voltages and currents in a long line for a two-phase fault, without earth contact

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