# Proposing a New Methodology to Optimize the Transient Study of a Transmission System

C. M. Portela
portelac@ism.com.br
COPPE – Universidade Federal do Rio de Janeiro
Rua Eng. Cesar Grillo, 249
Rio de Janeiro, RJ, 22640-150

M. C. Tavares
cristina@sel.eesc.sc.usp.br
Universidade de São Paulo
PO Box 359
São Carlos, SP 13560-970

BRAZIL

*Abstract* – **In the presented paper it is shown how the use of a systematic three-phase load flow analysis and three-phase frequency scan can become a helpful tool in an electromagnetic transient study. The present methodology was applied to a study of a real transmission system expansion, and it allowed the identification of some rather severe cases which would be very hard to find out through the ordinary transient study procedure.**

**Keywords:** Transient Analysis, Analysis Methodology, Transmission System, EMTP.

## I. INTRODUCTION

During a transient study of a transmission system, it is rather frequent that the number of possible situations of switching and faults which can be dangerous for the system is quite huge. They can imply, in the majority of the cases, in :

- Necessity of processing a large amount of cases, considering the different types of faults which can occur, the fault location, the network previous conditions, and the influence of switching sequences (among different circuit breakers and poles of each circuit breaker, including eventual failures or stuck poles, and reclosing and alternatives associated to reclosing).
- Non identification of cases which can be extremely severe.
- Misinterpretation when analyzing the influence of the circuit breakers' closing and opening times.

In the present paper it is shown how the use of systematic three-phase load flow analysis and three-phase frequency scanning can become a helpful tool in an electromagnetic transient study.

The idea is to identify the critical conditions, which can be detected through a fundamental frequency analysis (three-phase load flow) and three-phase frequency scanning, and later reprocess these conditions with a transient simulation program. Also, in some conditions, an hybrid frequency-time procedure can be useful, reducing still more the number of simulations in time domain, and allowing to do these simulations with detailed representation of network elements.

The present methodology was applied in the study of a real transmission system expansion, and it allowed the identification of some rather severe cases which would be very hard to find out through the ordinary transient study procedure.

Some results of the aforementioned study are shown.

## II. TRANSMISSION SYSTEM ANALYZED

The analyzed transmission system is based on a 420 kV line, 865 km long, 50 Hz, with "non-conventional" concept, connecting Terminal 1 to Terminal 2, being its most important characteristics shown below :

- 420 kV "non-conventional" transmission line conception. The structure is external to the three phases, what allows to reduce the distance between the phases and to obtain more adequate line characteristics for the transmission analyzed.
- Ground with frequency dependent parameters, being the conductivity at low frequencies around 0.5 mS/m [1-2].
- Series compensation corresponds to 0.5 times the direct longitudinal line reactance.
- Shunt compensation (for direct and inverse components) corresponds to 0.8 times the direct line transversal admittance.
- The compensation system, both in series and shunt, as shown in Fig. 1, with a compensation installation in the middle of the line, as well as shunt compensation at both line terminals. It is worth mention that it is possible to have just one point of compensation along the line (besides the compensation at both line ends).
- Maximum eventual 800 MW load at Terminal 2.

In Fig. 1 it is shown the basic transmission scheme, including the series and shunt compensation equipment.

In Table 1 it is shown a summary of the line basic parameters and of the compensation equipment, in series and derivation, at fundamental frequency. The parameters related to the neutral reactor of the shunt compensation systems, which appears in this table, were determined in the next section, as explained there.

In Fig. 2 it is shown, schematically, the line considered.

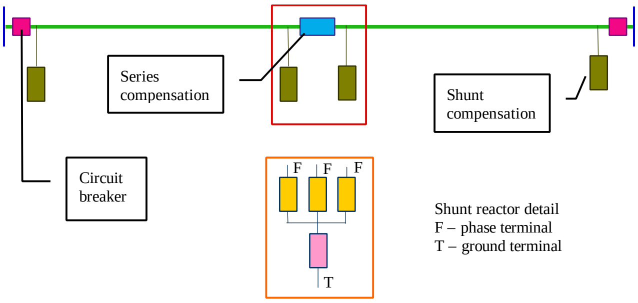

Fig. 1 – Line basic scheme, including series and shunt compensation system.

Table 1 – Basic parameters, at fundamental frequency (50 Hz)

| Variable | Value |
|---|---|
| Per unit longitudinal impedance, for non-homopolar components | 0.0350 + i 0.2267 Ω/km |
| Per unit longitudinal admittance, for non-homopolar components | i 5.162 µS/km |
| Per unit longitudinal impedance, for homopolar components | 0.2955 + i 1.2282 Ω/km |
| Per unit longitudinal admittance, for homopolar components | i 3.003 µS/km |

[1] With phase conductor at 60 $^0$C, without compensation effects, and considering mean values for a transposed line.

**Derivative reactors basic parameters, at fundamental frequency:**

Admittance of each phase reactor, at 50 Hz : **2.3 - i 909.7** mS **(-0 , +10 %)**

Admittance of each neutral reactor : **7.3 - i 2873** mS **(-0 , +10 %)**

Maximum voltage in normal operation, 50 Hz, rms value, between phases : **$U_{norm}$= 420 kV**

**Series capacitor basic parameters, at fundamental frequency :**

Impedance, per phase, at 50 Hz : **0.095 - i 94.54** W **(-0 , +10 %)**

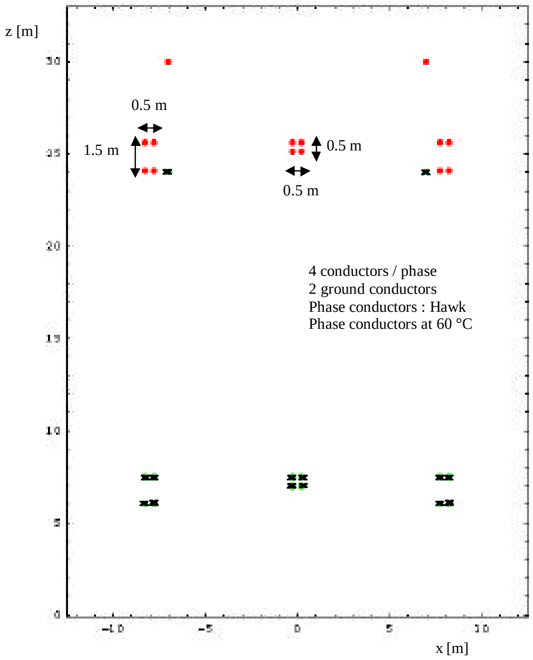

Fig. 2- Transmission line schematic representation. The symbol ✖ represents the conductors position at the middle span. The dots (●) the conductors near the tower. The figure refers to a 380 m span, with phase conductors at 60 $^0$C .

## III. SECONDARY ARC CURRENT ANALYSIS

Except in anomalous situations, the great majority of faults at a transmission system are due to single phase faults originated by lightning. In the transmission of large blocks of energy through a transmission trunk, the load supply reliability is greatly increased if the majority of the short-circuits is eliminated with single phase opening and reclosing, in the phase where the fault occurs, without quite affecting the load supply continuity [3].

In a well projected and executed line, the majority of lightning discharges which results in short-circuit originates a disruption between phase and ground (including grounded systems, such as towers and ground conductors), which is an electric arc. After the fast phenomenon extinction, and until the fault phase is opened, at the line terminals, a current flows through this arc. It is a short-circuit current, which is essentially at fundamental frequency.

After opening the phase where the short-circuit occurs, at the line ends, the arc current suffers a potentially reduction, for conditions usually designated as “secondary arc”. These conditions are associated to electromagnetic coupling between the interrupted phase and the other phases, and to the coupling resulting from the shunt compensation systems, which are kept galvanically connected to the interrupted phase.

The natural extinction of the secondary arc current, if it happens, allows the following reclosing of the phase where the fault occurred, without originating a new short-circuit.

The basic form, constructively simple and of moderate cost, of limiting the arc current and the recovery voltage, is to dimension properly the ratio, $r_h$, between the homopolar impedance and the non-homopolar impedance of the shunt compensation system reactor banks. With the adoption of reactors groups formed by three phase reactors and a neutral reactor, this ratio can be obtained defining the neutral reactor impedance. This definition is in accordance with the intended value of the ratio $r_h$, with enough flexibility and has moderate effect in the shunt compensation system cost.

The parameter chosen, to the basic characteristics selection of the neutral reactor, is the ratio $r_h$, being :

$$r_h = \frac{Z_h}{Z_d} = \frac{Z_f + 3Z_n}{Z_f} = \frac{1/Y_f + 3/Y_n}{1/Y_f}$$

and being $Y_f$ , $Y_n$ , respectively, the reactors phase and neutral admittance, at 50 Hz, and $Z_f$ , $Z_n$ the corresponding impedance, at 50 Hz (in complex notation), and the impedance $Z_d$ , $Z_h$, respectively, the non-homopolar and homopolar impedance of the shunt compensation reactor, at 50 Hz (in complex notation).

In Fig. 3 the secondary arc current and recovery voltage, at the arc terminals, (rms values at fundamental frequency), in function of the ratio $r_h$, are shown. Single phase faults were applied along the line, being the fault locality : near Terminal 1 busbar (20 km far from Terminal 1), just “before” the series capacitor compensation (in sense of Terminal 1 to Terminal 2), just “after” the series capacitor and near Terminal 2 busbar (20 km far from Terminal 2). The highest secondary arc current and recovery voltage values for these cases were plotted. In these cases the line was being energized, the switch breaker poles at Terminal 2 were opened (there was no load in Terminal 2). Only pole A of Terminal 1 circuit breaker was opened, simulating the single phase opening. The existing electric system was modeled.

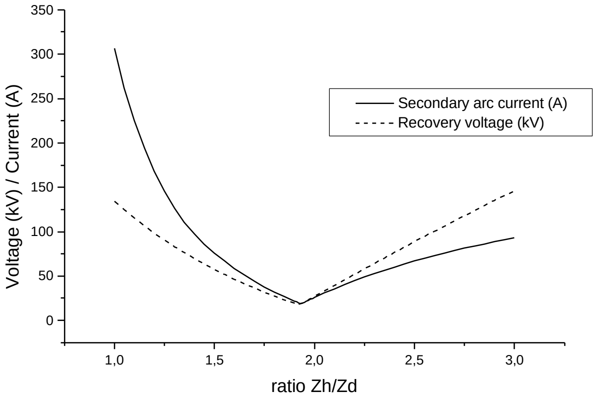

Fig. 3 - Maximum secondary arc current and recovery voltage for fault applied along the line.

It was observed that the lowest stress varies according to the fault place, and that for some places the secondary arc current and the recovery voltage were very severe. The ratio $r_h$ value which corresponds to the smallest perturbation is in the region 1.93-1.95. For the secondary arc the best ration $r_h$ value is 1.93 and for the recovery voltage the best value is 1.94, and the adopted value for the $r_h$ was 1.95, which corresponds to a neutral reactor of 348.1 Ω.

Essentially, it can be said :

- Being the line opened in Terminal 2, or with a reduced load, and with the selected ratio $r_h$, low values of both secondary arc current and recovery voltage at the arc terminals were obtained. This results in a quite fast arc extinction, during the fault phase opening, allowing the following phase reclosure, without defect, and, for the majority of the usual loads, practically without perturbation or load interruption.

## IV. FREQUENCY SCAN ANALYSIS

It is important to make an analysis of the basic aspects related with the transient phenomena and their consequences, in order to :

- Register the basic relevant parameters for analysis and studies of transient phenomena in a transmission system.
- Characterize the basic aspect of the transmission system behavior which has relevant influence in its performance at the line and the equipment solicitations, and in identifying potentially critical conditions or states.
- Verify the correctness of the options chosen, relative to the transmission system concept, and detect eventual potentially unfavorable consequences.
- Present recommendations relative to equipment parameters and characteristics of the transmission system.

It should be mentioned that several aspects treated in this article are, very often, ignored, or treated superficially. However, if they are not properly analyzed, there is the risk of not detecting critical conditions and of having incorrect or non-optimized conceptions, with consequences which, unfortunately and in some real cases, are very serious.

In the case of this transmission system, which has non-conventional characteristics, under several aspects, starting from the line length, and which price optimization depends on an “integrated” conception, if the ordinary procedure was applied, the risk of not detecting critical conditions would be very high.

In Figs. 4 and 5 the per unit length line parameters, in frequency domain, for the range 10 Hz to 10 kHz, are shown. The graphics analysis characterizes, direct and immediately, the basic line parameter, which does not show any anomalous condition. There are some differences when compared with the results frequently presented in the literature, namely because the soil model considered includes dielectric permittivity and the electric soil parameters are frequency dependent [1-2]. It should be emphasized that the transmission line parameters variation with frequency is very important for the transient behavior of the line. It should not be used transient phenomena study methodologies which does not take this variation into account, in a proper way [3].

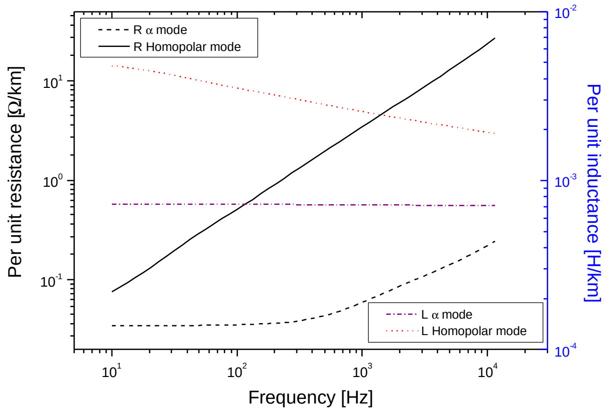

Fig. 4 – Per unit length resistance of transmission line.

Another aspect which was analyzed were the non-homopolar and homopolar line impedances, in a terminal, with the other terminal opened, considering or not the series and shunt compensation. Some results are presented in Figs. 5 to 6.

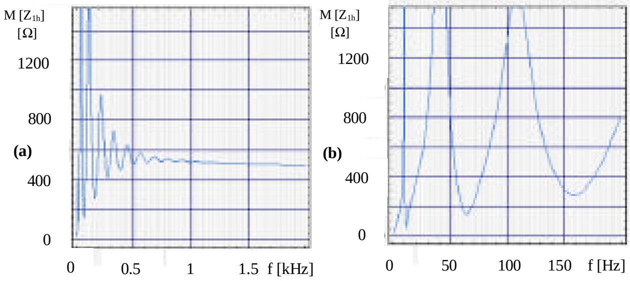

Fig. 5 – Modulus of homopolar line impedance at one terminal, being the other opened, with series and shunt compensation. Frequency range [1 Hz to 2000 Hz] (a) and [1 Hz to 200 Hz] (b).

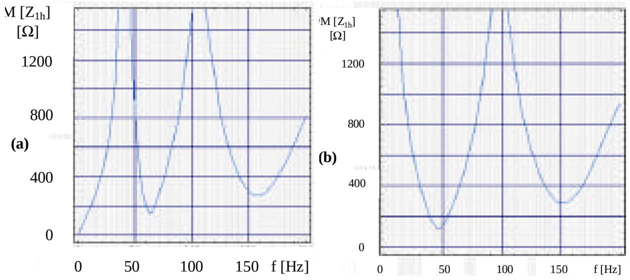

Fig. 6 – Modulus of homopolar line impedance at one terminal, being the other opened, without series compensation and : with shunt compensation (a) , without shunt compensation (b). Frequency range [1 Hz to 200 Hz].

Concerning the non-homopolar behavior, in terms of the line with compensation impedance, at one of the terminals, being the other opened :

- The series and shunt compensation change drastically the compensated line behavior, for low frequencies (in modulus), up to around 100 Hz. As the frequency increases, the effect of compensation, for the compensated line behavior, decreases rapidly, being this effect noted up to 300 Hz, but very small for higher frequencies.
- For frequencies up to 4 kHz, the non-homopolar mode attenuation, at the compensated line, is moderate. So, there is important influence, at one terminal, of the other terminal conditions.

Concerning the homopolar behavior, in terms of the line impedance, at one of the terminals, being the other opened, and with compensation :

- The series and shunt compensation change drastically the compensated line behavior, for low frequencies (in modulus), up to around 100 Hz. As the frequency increases, the effect of compensation, for the compensated line behavior, decreases rapidly, being this effect noted up to 300 Hz, but very small for higher frequencies.
- For frequencies up to 100 Hz, the homopolar mode attenuation, at the compensated line, is moderate, occurring important influence, at one terminal, of the other terminal conditions.

In summary, this procedure characterized the basic aspects of the transmission system behavior, what has relevant influence on its behavior, in the line and equipment stresses, and allowed to identify potentially critical conditions or states.

## V. SYSTEM BEHAVIOR AT FUNDAMENTAL FREQUENCY

To detect and characterize potentially unfavorable situations, in what is related to overvoltages, it was performed a rather systematic analysis of the occurrences. This study was performed only at fundamental frequency, what allows to identify resonance situations and to define solutions to these cases. It would not be possible to perform such a detailed analysis in an electromagnetic transient study, varying systematically a large number of parameters values, as it was done at fundamental frequency.

To realize this systematic analysis a three-phase load flow was used, and all the existing electric systems and the new transmission system were represented.

The line was divided in 50 km long sections, in order to allow the observation in all points of phase-to-ground voltage, phase-to-phase voltage, current in each phase, fault current and current through the series capacitor. Some extra points were included to allow observation at the line terminals, and at both terminals of the series capacitor.

The types of faults simulated were : single phase fault, two phase fault (including or not the ground) and three phase fault (including or not the ground). The faults were applied along the line, from Terminal 1 to Terminal 2, at each 50 km.

An important variable for the systematic analysis is the circuit breaker pole position. All the stages of the circuit breaker opening were simulated, like photographs of the complete opening sequence since it received the order to open till it was completely opened, for all three phases. At the intermediate stages, e. g. when one pole is opened and the others are still closed, it can be understood either as an intermediate condition or a rather severe condition, where the circuit breaker pole got stuck. These cases, however, can identify resonant system configurations, which in a transient study would be very difficult to be detected.

Due to the great number of possible combinations, each circuit breaker status was varied supposing that the circuit breaker at the other terminal was either completely closed or opened. The cases where Terminal 2 circuit breaker was completely opened represent the line energization situation.

Table 2 – Series capacitor operating

| Terminal 2 reactor | Short-circuit type | Poles opened | | $\hat{U}_{ft}$ [kV] | $\hat{U}_{ff}$ [kV] | $\hat{I}_{c}$ [A] |
|---|---|---|---|---|---|---|
| | | At Terminal 1 | At Terminal 2 | | | |
| connected | Single phase (fault at phase A) | | | **339.6** | **381.9** | **2075.4** |
| | | | A B C | 405.8 | 411.9 | 1096.7 |
| | | A | A B C | 271.2 | 411.9 | 117.3 |
| | | B | A B C | 391.5 | 381.8 | 1283.6 |
| | | C | A B C | 406.4 | 389.6 | 1207.9 |
| | | A B | A B C | 272.4 | 273.6 | 116.5 |
| | | A C | A B C | 272.4 | 273.6 | 116.5 |
| | | B C | A B C | 211.7 | 133.3 | 1386.5 |
| | | | **A** | **335.6** | **381.9** | **2309.0** |
| | | A | A | 226.3 | 381.9 | 694.3 |
| disconnected | Single phase (fault at phase A) | | | **351.7** | **403.5** | **2013.2** |
| | | A | | 232.1 | 403.5 | 735.6 |
| | | **B** | | **322.2** | **482.6** | **2008.7** |
| | | C | | 425.8 | 480.3 | 1577.8 |
| | | A B | | 218.1 | 230.8 | 501.2 |
| | | A C | | 218.0 | 230.4 | 493.7 |
| | | B C | | 212.4 | 135.5 | 1367.9 |
| | | | **A** | **340.5** | **403.5** | **2240.2** |
| | | A | A | 238.8 | 403.5 | 765.9 |
| | | | **A B C** | **569.8** | **458.2** | **693.8** |
| | | B C | A B C | 212.0 | 105.3 | 1378.6 |
| connected | Two phases without ground (fault at phases A and B) | | | **792.4** | **1404.3** | **7623.4** |
| | | | **A B C** | **781.2** | **1404.3** | **7462.3** |
| | | | **A C** | **760.4** | **1404.5** | **7455.7** |
| | | | **B C** | **762.2** | **1404.1** | **7456.7** |
| | | | **A B** | **821.3** | **1404.3** | **7481.2** |
| | | | **A** | **807.9** | **1404.4** | **7601.4** |
| | | | **B** | **809.2** | **1404.2** | **7601.1** |
| | | | **C** | **741.8** | **1404.3** | **7439.8** |
| | | A C | A B C | 363.9 | 329.2 | 426.2 |
| | | B C | A B C | 363.9 | 329.3 | 426.0 |
| | | A B | A B C | 270.0 | 256.1 | 115.7 |
| | | A | A B C | 337.6 | 438.6 | 397.9 |
| | | B | A B C | 363.1 | 459.0 | 429.3 |
| | | **C** | **A B C** | **805.9** | **1404.3** | **7474.7** |
| disconnected | Two phases without ground (fault at phases A and B) | | | **802.7** | **1404.3** | **7709.0** |
| | | A C | | 212.6 | 101.2 | 548.1 |
| | | B C | | 215.2 | 99.1 | 556.4 |
| | | A B | | 213.8 | 154.4 | 487.7 |
| | | A | | 251.9 | 408.4 | 880.9 |
| | | B | | 261.1 | 418.2 | 989.5 |
| | | **C** | | **744.6** | **1404.3** | **7477.1** |
| | | A B C | | 5.2 | 8.9 | 14.7 |
| | | | **A B C** | **793.0** | **1404.3** | **7543.0** |
| | | **B C** | **A B C** | **712.2** | **527.2** | **1536.6** |
| connected | Three phases with ground | | | **809.8** | **1402.7** | **8568.0** |
| | | | **A B C** | **809.8** | **1402.6** | **8567.9** |
| | | B C | A B C | 212.4 | 125.9 | 1370.3 |
| | | **A** | **A B C** | **715.6** | **1402.6** | **7571.1** |
| | | | **B C** | **809.8** | **1402.7** | **8568.0** |
| | | | **C** | **809.8** | **1402.7** | **8568.1** |
| disconnected | Three phases with ground | | | **809.8** | **1402.7** | **8568.0** |
| | | B C | | 212.4 | 125.9 | 1370.3 |
| | | **C** | | **715.6** | **1402.7** | **7571.2** |
| | | | **A B C** | **809.8** | **1402.7** | **8567.9** |
| | | B C | A B C | 212.4 | 125.9 | 1370.3 |

Another parameter varied was the status of the shunt reactor at Terminal 2, if it was connected or not. The normal operation condition was without the reactor, when the circuit breaker at Terminal 2 was closed and the load at Terminal 2 was connected. The Terminal 2 shunt reactor must be connected whenever any Terminal 2 circuit breaker pole opens. In the systematic analysis it was also considered the hypothesis of not respecting this rule, in order to identify any severe condition if or when the recommended procedure was not followed.

The other shunt reactors, at Terminal 1 and at both series capacitor terminals, were always connected.

Some results are reproduced at Table 2. Only some types of faults are shown due to space constraint, namely single-phase, two-phases without ground and three-phases with ground. The values for Table 2 are the highest ones, considering the three phases, as the fault point is varied, being :

- $\hat{U}_{ft}$ : greatest phase-to-ground voltage value, rms value, along the line measured points.
- $\hat{U}_{ff}$ : greatest phase-to-phase voltage value, rms value, along the line measured points.
- $\hat{I}_{c}$: greatest current value which flows along the series capacitor, rms value.

In some cases the phase-to-ground voltage is extremely high, while in others the capacitor current is above the maximum operating current value, being these limits : $U_{ft}$ = 455,4 kV; $I_{capac}$ 500 s = 1710 A.

For the most severe cases resonance occurs, which happens for some types of fault or circuit breaker pole position, when the fault is located “after” the series capacitor at Terminal 2 side. It can be observed that, apart the high overvoltage level, the series capacitor current is extremely high. The main reason is associated to the fact that, with 50 % series compensation and without network impedance effects, a resonance condition would occur for faults “after” series compensation station in the middle of line, in sense of Terminal 2. Network at line terminals, fault type, location and pole condition of circuit breakers have also influence, and a situation similar to resonance may occur. To diminish this problem, some measures have been taken, e. g., choosing the homopolar impedance of transformers at line terminals. To get out quickly from this resonance it is necessary to remove the series capacitor from the circuit. The solution to eliminate the sustained overvoltage and to protect the capacitor was to short-circuit longitudinally the capacitor. This procedure was done per phase and only for the phase involved in the fault.

The new cases are presented at Table 3.

Table 3 – Series capacitors short-circuited at faulted phase.

| **Terminal 2 Reactor** | **Short-circuit type** | **Poles opened** | | $\hat{U}_{ft}$ **[kV]** | $\hat{U}_{ff}$ **[kV]** | $\hat{I}_{c}$ **[A]** |
|---|---|---|---|---|---|---|
| | | **At Terminal 1** | **At Terminal 2** | | | |
| connected | Single phase (fault at phase A) | | | 279.2 | 381.9 | 1113.2 |
| | | | A B C | 370.0 | 411.9 | 157.6 |
| | | A | A B C | 271.4 | 411.9 | 117.3 |
| | | B | A B C | 350.5 | 383.7 | 152.4 |
| | | C | A B C | 341.5 | 382.6 | 148.8 |
| | | A B | A B C | 272.5 | 274.7 | 116.5 |
| | | A C | A B C | 272.5 | 274.7 | 116.5 |
| | | B C | A B C | 213.0 | 149.8 | 20.2 |
| | | | A | 279.2 | 381.9 | 1013.6 |
| | | A | A | 223.8 | 381.9 | 682.0 |
| disconnected | Single phase (fault at phase A) | | | 289.2 | 403.5 | 1217.0 |
| | | A | | 231.9 | 403.5 | 735.2 |
| | | B | | 286.6 | 405.3 | 1221.5 |
| | | C | | 376.1 | 393.1 | 1195.7 |
| | | A B | | 217.2 | 234.1 | 499.8 |
| | | A C | | 217.2 | 232.7 | 492.3 |
| | | B C | | 213.5 | 86.0 | 48.1 |
| | | | A | 293.9 | 403.5 | 1144.0 |
| | | A | A | 233.9 | 403.5 | 752.0 |
| | | | **A B C** | **572.2** | **458.2** | **592.6** |
| | | B C | A B C | 213.2 | 121.8 | 27.6 |
| connected | Two phases without ground (fault at phases A and B) | | | 218.1 | 376.4 | 573.9 |
| | | | A B C | 237.1 | 379.6 | 103.9 |
| | | | A C | 305.9 | 375.7 | 129.9 |
| | | | B C | 300.5 | 375.8 | 128.0 |
| | | | A B | 262.3 | 371.5 | 346.6 |
| | | | A | 218.1 | 378.1 | 486.1 |
| | | | B | 218.2 | 377.9 | 478.6 |
| | | | C | 319.2 | 374.6 | 134.4 |
| | | **A C** | **A B C** | **443.2** | **414.5** | **10.3** |
| | | **B C** | **A B C** | **443.2** | **414.5** | **10.3** |
| | | A B | A B C | 270.0 | 256.2 | 115.7 |
| | | A | A B C | 413.2 | 489.2 | 125.3 |
| | | **B** | **A B C** | **443.5** | **536.9** | **92.7** |
| | | C | A B C | 206.5 | 347.8 | 3.9 |
| disconnected | Two phases without ground (fault at phases A and B) | | | 229.9 | 389.3 | 689.0 |
| | | A C | | 213.6 | 85.8 | 63.2 |
| | | B C | | 213.5 | 74.2 | 66.6 |
| | | A B | | 213.8 | 155.2 | 485.0 |
| | | A | | 260.6 | 394.9 | 873.3 |
| | | B | | 259.0 | 390.0 | 685.9 |
| | | C | | 205.2 | 347.8 | 34.7 |
| | | | A B C | 256.4 | 412.8 | 343.3 |
| | | **B C** | **A B C** | **1202.5** | **919.0** | **36.2** |
| connected | Three phases with ground | | | 200.8 | 347.8 | 0.0 |
| | | | A B C | 200.8 | 347.8 | 0.0 |
| | | B C | A B C | 213.5 | 83.1 | 0.0 |
| | | A | A B C | 205.3 | 347.8 | 0.0 |
| | | | B C | 200.8 | 347.8 | 0.0 |
| | | | C | 200.8 | 347.8 | 0.0 |
| disconnected | Three phases with ground | | | 200.8 | 347.8 | 0.0 |
| | | B C | | 213.5 | 83.1 | 0.0 |
| | | C | | 205.3 | 347.8 | 0.0 |
| | | | A B C | 200.8 | 347.8 | 0.0 |
| | | B C | A B C | 213.5 | 83.1 | 0.0 |

In the majority of the cases, the procedure of short-circuiting the series capacitor at the faulted phase has reduced the overvoltage, eliminating the resonance.

In the cases where the voltage was high, but the capacitor current was small, the fact of removing the capacitor did not affect the result, and in other cases this procedure has even generated a worst case, with a higher phase-to-ground voltage. These particular conditions are dealt with additional measures, not discussed here.

## VI. ELECTROMAGNETIC TRANSIENT SIMULATIONS

Two different types of electromagnetic transient studies have been done, whose detailed results are not presented here. In the first type, we have used an hybrid time-frequency procedure, doing a frequency scanning, as presented above, and obtaining time domain results from them. Two main variants of hybrid methods were used:

- Direct Fourier transformation. This method is quite useful when non-linear conditions are quite simple, e. g. , closing of circuit-breaker poles or opening in defined instants. It allowed to identify aspects related to sensitivity of overvoltages, associated with frequency response and resonances at frequencies different from industrial frequency, to synchronous switching of circuit breakers, and to basic options to limit switching overvoltages.

- To use, in time-frequency conversion, an intermediate step, obtaining the Fourier transformation, e. g. for a step or similar time domain “excitation”, what allows the use of convolution procedures, quite adequate to consider a small number of eventually non-linear conditions, e. g. , surge-arresters, arcs in air and circuit-breaker arcs. This variant, for the transmission system presented example, was used for specific analysis, and not as a general purpose procedure. However, it appears quite promising.

The other type of electromagnetic transient studies were based in use of general purpose transient simulation programs, working in time domain [5]. This analysis was done for some specific conditions chosen with the procedures described above, with two main purposes:

- To consider details not taken into account in a systematic scanning (oriented to find eventual severe conditions, and not to perform a rather complete detailed analysis), and to obtain accurate results for some chosen conditions.

- To evaluate aspects for which the available general purpose time domain simulation procedures and programs are quite adequate.

The complete transmission system was represented in ATP and in Fig. 7 it is shown how the line was modeled.

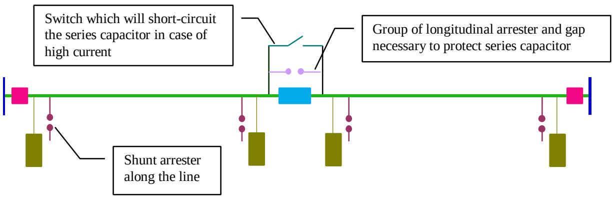

Fig. 7 – Detail of transmission line modeled in ATP.

In order to illustrate how the previous analysis are helpful, a transient case is shown. The condition modeled consisted of the transmission system operating in normal condition when a fault (involving phases A and B) occurred just “after” the series capacitor (in sense of Terminal 1 to

Terminal 2), at 20 ms. This case corresponds to the first case of Table 2 and 3, reactor at Terminal 2 disconnected, fault type two-phase without ground, all poles closed at Terminal 1 and 2. The series capacitor protection actuates and removes the series capacitor of the phases involved in the fault. A short-circuit switch removes both the series capacitor and its protection devices, only from the phases involved in the fault, after the current through the protection devices had reached a defined value. The line was opened (three-phase opening) in both ends, formerly in Terminal 1, at 80 ms, and afterwards in Terminal 2, at 120 ms. The circuit breaker of the reactor at Terminal 2 "sees" that a circuit-breaker pole of Terminal 2 bus is opened and connects the reactor. The overvoltage measured between the terminals of the series capacitor, in the phases involved in the fault, were extremely high, as identified with the three-phase load flow. This previous analysis enabled us to propose some mitigation procedures to protect the series capacitor. Namely, the series capacitor was protected longitudinally with an arrester and a gap, because the energy through the arrester would be extremely high. This protection was done per phase, e.g. only the series capacitor for the phase involved in the fault was short-circuited. It was also included a switch which would short-circuit both the series capacitor and its protection, per phase, in order to remove the arrester and the gap from the circuit. In Figs. 8 the voltage at Terminals 1 and 2 are presented and in Fig. 9 the voltage between the series capacitor terminal and its arrester energy are shown.

The simulations performed with general purpose time domain simulation programs confirmed the solutions chosen and presented in this paper.

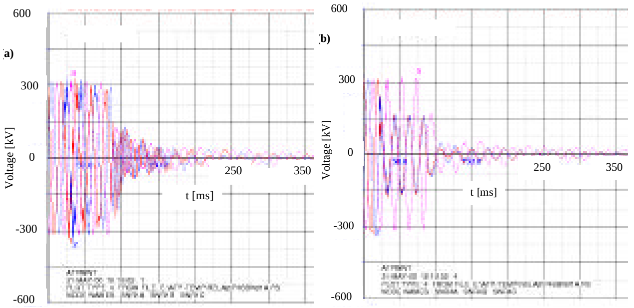

Fig. 8 – Voltage at Terminal 1 (a) and at Terminal 2 (b)

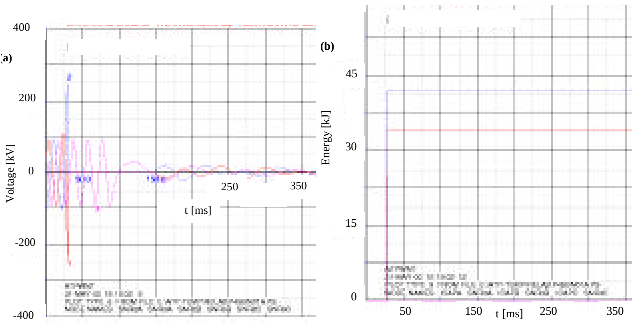

Fig. 9 – Voltage between the series capacitors terminals (a) and energy dissipated at the series capacitors arresters (b).

## VII. CONCLUSIONS

In the present paper it is shown how the use of a systematic three-phase load flow analysis and three-phase frequency scanning can become a helpful tool in an electromagnetic transient study.

With the three-phase load flow and frequency scanning, it is possible to do a systematic coverage of a large number of conditions, detecting eventual critical or severe cases, e. g. , considering:

- Combination of fault type, fault location along lines, point at which voltage is evaluated, situation of the circuit breakers poles at two line terminals, or in other points, longitudinal per phase series compensation short-circuit, single phase opening and reclosing, switching of reactors in case of faults or coordinated with line switching;

- Systematic variation of parameters of network elements, in order to obtain optimized solutions, e.g. line parameters, shunt and series compensation location and parameters, switching procedures;

- Systematic comparison of alternatives of project and operation options, and abnormal occurrences, e. g., incorrect operation of circuit breakers or protections.

The systematic coverage allows the elimination of the risk of not detecting critical or severe conditions.

For the small number of selected cases, a more detailed analysis can be done, using procedures adequate for such analysis, according to its specific aspects.

The present methodology was applied in the study of a real transmission system expansion, and it allowed the identification of some rather severe cases which would be very hard to find out through the ordinary transient study procedure.

This transmission system has some unfavorable constraints (e. g. 865 km ), compared with "most common" transmission systems, and in order to obtain an optimized solution, it was necessary to perform a systematic analysis covering a large number of options and parameters. With the study procedure used it was found a solution with a non-conventional line, in which it was possible to conciliate apparently contradictory requirements and solutions. These solutions allowed a relatively low cost transmission system with good operational performance.

Some interesting aspects of proposed transmission system are:

- There are reactive compensation only at line extremities and in an intermediate point.
- Switching of the 865 km transmission system directly from one extremity, without switching at intermediate points.
- Line arrangement optimized for the specific line length and transmitted power.
- Single-phase opening and reclosing, assuring high probability of secondary arc extinction, for single phase faults, in order to obtain high reliability of transmission.
- Joint optimization of project and operational criteria, allowing important cost reduction.

## VIII. ACKNOWLEDGEMENT

Part of the examples results included in this paper were obtained in a study for EDP – Electricidade de Portugal S. A. , of an eventual transmission system in Mozambique, in which the new methodology discussed in the paper was used. The authors thank EDP the permission to include such examples results in the paper. The authors also thank the support received from FAPESP - Fundação de Amparo à Pesquisa do Estado de São Paulo.

## IX. REFERENCES

[1] Portela C.M., Tavares M.C. and Pissolato J., "Quasi-Modes Frequency Dependent Three-Phase Transmission Line Model - Analyzing the Earth Conductivity Influence to Electromagnetic Transient Phenomena", *2000 IEEE Winter Meeting*, January 2000, Singapure.

[2] Portela, C. – Grounding Requirement to Assure People and Equipment Safety Against Lightning - Proceedings IEEE 2000 International Symposium on Electromagnetic Compatibility, pp. 969-974, August 2000, Washington DC, United States.

[3] Tuan, TQ; Hadj-Said, N.; Sabonnadiere, J.C.; Feuillet, R., "Reducing dead time for single-phase auto-reclosing on a series-capacitor compensated transmission line", *IEEE Transactions on Power Delivery*, Vol. 15, No 1, pp. 51-56, Jan. 2000.

[4] Tavares, M.C., Pissolato, J. and Portela, C., "Mode Domain Multiphase Transmission Line - Use in Transient Studies" - *IEEE Transactions on Power Delivery*, vol. 14, No. 4, pp 1533-1544, Oct. 1999.

[5] Dommel, H.W., "Electromagnetic Transients Program Reference Manual (EMTP Theory Book)", Portland, OR, Bonneville Power Administration, Aug. 1986.