Transmission System Parameters Optimization – Analyzing Secondary Arc Current and Recovery Voltage

Maria Cristina Tavares[1] and Carlos Medeiros Portela[2]

(1) School of Electrical and Computer Engineering, State University of Campinas, PO Box 6106, 13083-970, Campinas, SP, Brazil (e-mail:cristina@dsce.fee.unicamp.br), (2) COPPE – Federal University of Rio de Janeiro, Rua Eng. Cesar Grillo, 249, Rio de Janeiro, RJ, 22640-150, BRAZIL (e-mail : portelac@ism.com.br)

Abstract **– This paper shows the importance of optimizing transmission system parameters from its conception, considering altogether the relevant options and possibilities, in order to have better cost-performance result. The presented results were obtained in the study of a real transmission system expansion, based on a 865 km long line. The Single-Phase Auto-Reclosing (SPAR) procedure was one of the aspects carefully studied, in order to assure adequate transmission reliability. The secondary arc current was mitigated through the traditional solution of using the neutral reactor on the existing shunt reactor banks. The way of obtaining the optimized value for the neutral reactor and its implications on the system performance are important aspects discussed in this paper.**

Keywords – Transient Analysis, Optimization, Transmission System, Secondary Arc Current, Recovery Voltage, Single-Phase Auto-Reclosing, EMTP.

I. Introduction

When planning a new transmission system, or a system expansion, it is important to think carefully in all the aspects, which can imply in a better performance and also in lower cost. In order to obtain the best cost-performance result, it is important to consider altogether the relevant options and possibilities in the first stages of study, when the basic system conception is defined. In fact, some interesting solutions imply in joint measures and coordinated choices, and can hardly be detected if different aspects are dealt with separately or sequentially, as it is done in many system studies. The joint evaluation of different aspects is critical when non-conventional solutions are considered, as it is the case of long distance transmission systems, for which extrapolation of common practice would lead to solutions quite far from optimum. As an example, we present some aspects of a real transmission system-expansion study [1].

A conventional solution for this transmission trunk would have very important drawbacks. So, an "open" solution was searched, including non-conventional bundles, towers, and reactive compensation, switching of the 865-km line in a single step, optimization of voltage operation ranges along the line, special switching and protection criteria, and special additional procedures. In order to obtain an optimized solution, considering investment cost, losses, reliability and flexibility to different load increase rates, it was necessary to consider simultaneously all relevant options and parameters, identifying ranges in which basic constraints are met and optimum solution must be searched. It is out of the scope of this paper to present all relevant aspects and how it was possible to identify such ranges and to optimize the solution.

One important aspect was the need to assure high reliability of supply with a single line trunk. It was necessary to choose together a large number of parameters, in order to obtain a convenient solution. We do not discuss here procedures used in the systematic search to identify adequate ranges of all relevant parameters, and concentrate in the basic definition of specific system parameters within such ranges, to assure successful single-phase auto-reclosing (SPAR) for non persistent single-phase short-circuits.

The presented methodology 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 in the next sections.

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:

- 420 kV "non-conventional" transmission line conception, with structure external to the three phases and phase bundles not equal for all three-phases. The structure being external to the three phases allows the reduction of the distance between the phases and more adequate line characteristics for the analyzed transmission. The cable arrangement in the lateral phases (rectangular bundle disposal of 0.5 m horizontal length and 1.5 m vertical length) and in central phase (square bundle of 0,5 m length) are different, and both do not have traditional geometry of line bundles.

- 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 in derivation, 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 mentioning that it is possible to have just one point of compensation along the line (besides the compensation at both line ends). The shunt reactors located at Terminal 1 and at the series capacitor terminals are **always** in service, while the reactor at Terminal 2 is connected **only** at low load or when Terminal 2 bus circuit breaker is opened (any pole of it).
- The initial load at Terminal 2 is 400 MW, with a medium term increase till 600 MW. It may increase in future till 800 MW.

The line was modeled considering ground with frequency dependent parameters, being the conductivity at low frequencies around 0.5 mS/m [2], [3].

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

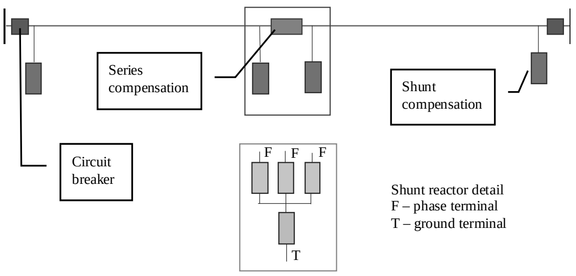

Fig. 1 – Line basic scheme, including series and shunt compensation system.

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

Variable	Value
Z, for non-homopolar components	0.0350 + i 0.2267 Ω/km
Y, for non-homopolar components	i 5.162 µS/km
Z, for homopolar components	0.2955 + i 1.2282 Ω/km
Y, 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.
[2] Z : per unit longitudinal impedance; Y : per unit longitudinal admittance.

Shunt reactors basic parameters, at fundamental frequency:
Admittance of each phase reactor, at 50 Hz : **2.3 - i 909.7 µS (-0 , +10 %)**
Admittance of each neutral reactor, at 50 Hz : **7.3 - i 2873 µS (-0 , +10 %)**
Maximum voltage in normal operation, 50 Hz, rms value, between phases : $\mathbf{U_{norm} = 420\ kV}$

Series capacitor basic parameters, at fundamental frequency :
Impedance, per phase, at 50 Hz : **0.095 - i 94.54 Ω (-0 , +10 %)**

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

III. Secondary Arc Current Analysis

Except in anomalous situations, the great majority of faults at a transmission system is due to single phase faults [4] - [7] originated by lightning activities (at least in regions of high or medium lightning intensity). 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 tripping and high speed reclosure, in the faulted phase, without quite affecting the load supply continuity. For a specific set of assumptions, in [8], it is presented a chart showing the power reduction for the numbers of conductors energized for a single circuit line, being 54 % of its initial value when a line has one phase tripped with the other two healthy phases operating normally. For the majority of loads, this type of disturbance, during, e. g., 0.5 or 1 s, can be accepted without harmful effects.

After the fast phenomenon extinction, and until the faulted phase is tripped, at both line terminals, short-circuit current flows through this arc, essentially at fundamental frequency. After tripping the affected phase, at the line terminals, the arc current suffers an eventual 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.

In this paper, it is used a rather simpler procedure than the arc-network interaction model, and which consists, essentially, in determining the secondary arc current and the corresponding recovery voltage at fundamental frequency [9] - [17]. Typically, for moderate values of these two parameters, there is a high probability of the secondary arc natural extinction, with a "reasonable" dead time between tripping (at both extremities) and reclosing the faulted phase. Naturally, with this procedure there is no meaning in a pseudo-rigorous definition of the relation between the two parameters involved and the opening duration, which assures high probability of secondary arc current extinction. For the results obtained in this specific network, it is not necessary a supplementary analysis, apart eventual confirmation purposes. Methods and procedures presented in [9] - [12], [17] - [21], can be used for such purposes, or in conditions of less favorable results than the presented network, which could justify a more detailed evaluation of secondary arc interruption constraints or a moderate change of network parameters. For other types of networks, it may be justified to evaluate the hypothesis of different solutions to obtain secondary arc extinction [5], [6], [22] - [27].

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 [4], [6] ,[8], [28]. With the adoption of groups of reactors formed by three phase reactors and a neutral reactor, this ratio can be obtained defining the neutral reactor impedance, which shall be coherent with the desired ratio r_h , with enough flexibility, and moderate effect in the shunt compensation system cost.

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

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

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).

IV. Neutral Reactor Definition

In order to define the value range in which the neutral reactor has the highest influence on transmission system stresses, reducing them to the lowest values, a systematic generalized three-phase simulation program (SGTPS) was used. With the aid of this program it was possible to make an extensive sensitivity analysis of the effect of fault location and neutral reactor value in the secondary arc current and recovery voltage.

The case used to identify the best ratio r_h range was the energization under fault (single-phase to ground) of the line, when the receiving end was opened and the shunt reactor at that extremity was in service. After choosing the neutral reactor value some simulations were made looking at the system performance when the line was in normal operation and a single phase to ground fault occurred, as shown in the next section. It is expected also that the correct neutral reactor will minimize the stresses level for other line faults.

The electric system, including the existing system and the transmission line, was modeled through two-port elements (ABCD constants) in the SGTPS program. This program enabled a high flexibility in analyzing the system, as described:

- The line was divided in various small sections, of 20 km each.
- Between two line sections, a single-phase to ground fault two-port representation was inserted.

This allowed the simulation of the fault along the line, observing the line at discrete points, which resulted in almost continuous “curves” of secondary arc current and recovery voltage for a constant ratio r_h. It was also possible to promptly analyze the influence of the ratio r_h for a pre-defined fault location.

The basic case simulated consisted of line energization with single-phase fault (At) applied. The phase involved in the fault was tripped and the secondary arc was established. The basic case characteristics were: reactor at receiving end in service (all others reactors are always in service); healthy phases in service; faulted-phase tripped at both extremities; series capacitor in service; fault maintained during throughout simulation.

In Fig. 2 the secondary arc current, at the arc terminals, (rms values at fundamental frequency), of sustained secondary arc current, in function of the ratio r_h , is shown, being the fault location: near Terminal 1 bus (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 bus (20 km far from Terminal 2).

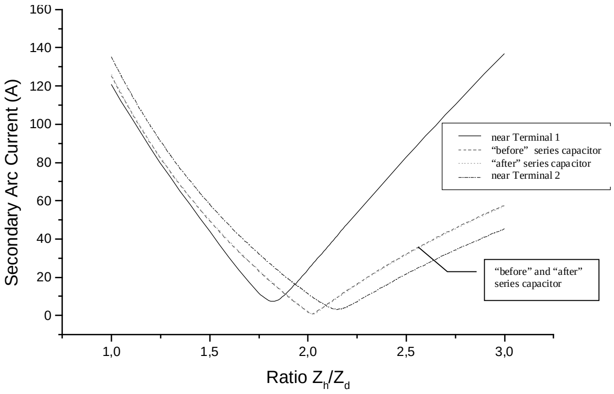

Fig. 2 - Secondary arc current (rms values at fundamental frequency), in function of the ratio r_h , for single-phase fault (At) applied in four different line locations, when the line was energized, and the phase A circuit-breakers poles at both line extremities tripped.

It can be observed that, for the same ratio r_h , the fault location influences the secondary arc current amplitude. The secondary arc current sensitivity for the fault location increased as the ratio r_h increased, which means that for low ratio r_h the secondary arc current did not vary so much regarding the fault location, as it did for higher ratio r_h values. The minimum stress, or better, the lowest secondary arc current, has a defined ratio r_h range for each fault location.

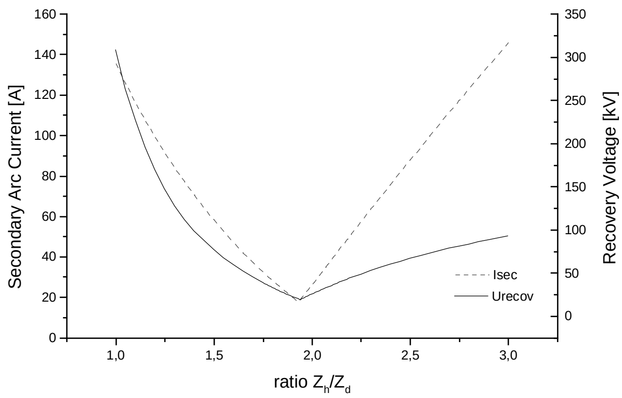

Fig. 3 - Maximum secondary arc current and recovery voltage at the arc terminals (rms value at fundamental frequency), in function of the ratio r_h , for single-phase fault (At) applied along the line, when the line was energized, and the phase A circuit-breakers poles at both line extremities tripped.

In Fig. 3 the secondary arc current and the recovery voltage at the arc terminals (rms values at fundamental frequency), in function of the ratio r_h , are shown, for single phase faults applied along the line, at each 20 km of the line, when the line was energized (Terminal 2 bus switch opened and Terminal 2 shunt reactor connected). For each ratio r_h the highest secondary arc current and the highest recovery voltage values for all these fault locations are plotted.

The extinction of secondary arc current requires the adequate choice of ratio r_h to define the neutral reactor. There is a well-defined r_h range associated to minimum stresses. The r_h values, which lead to the smallest secondary arc current and smallest recovery voltage, are in the range 1.93-1.95. The adopted value for the r_h was 1.95, which corresponds to a neutral reactor of 348.1 Ω.

The influence of the future line loads, 400 MW, 600 MW and 800 MW, for the selected neutral reactor was verified and showed no displacement in the optimum neutral reactor selection region. This means that the neutral reactor selected was adequate and would result in a similar performance even when the transmitted load increases in the future.

The optimum value of ratio r_h is obtained, practically, when transversal coupling between different line phases, considering together the line and the shunt reactors, is minimized. For the considered line and non-homopolar parameters of line reactors, such minimum occurs for $r_h \cong 1.95$. Longitudinal coupling between phases, load conditions, series compensation and parameters of terminals networks have a small effect in optimum r_h value, at least for the considered transmission system.

In Fig. 4 the secondary arc current and the recovery voltage at the arc terminals (rms values at fundamental frequency), in function of the single-phase (At) fault location along the line when energizing the line are shown for the selected neutral reactor. The faults were applied at the line terminals, being more serious if the fault occurs near Terminal 1.

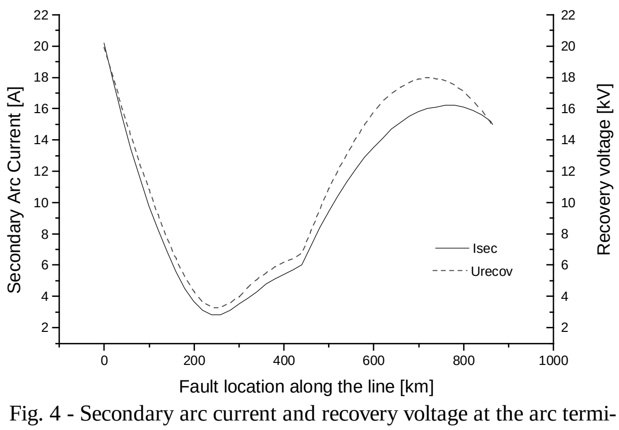

Fig. 4 - Secondary arc current and recovery voltage at the arc terminals (rms values at fundamental frequency), in function of the single-phase fault (At) location along the line, when the line was energized, and the phase A circuit-breakers poles at both line extremities tripped. The defined neutral reactor (ratio $r_h = Z_h/Z_d = 1.95$) was used.

With the definition of the neutral reactor value, some tests were realized to investigate the transmission line performance when the line was operating in normal conditions and a single-phase to ground fault (At) occurred. The cases were simulated with the SGTPS program, considering that the fault had occurred and only the faulted phase (A) poles of the two circuit-breaker at line extremities tripped to clear the fault, while the sound phases were operating normally, in order to observe the secondary arc current and the recovery voltage. The fault location was varied, being the fault applied at each 20 km of the line. Some alternatives were considered, in order to observe the influence of having or not the Terminal 2 shunt reactor connected, and also the secondary arc current sensitivity to the line load.

In Fig. 5 two conditions were considered:

- The Terminal 2 shunt reactor was switched on when the faulted phase was tripped;
- The Terminal 2 shunt reactor was not connected when Terminal 2 circuit-breaker pole of the faulted phase was tripped (phase A).

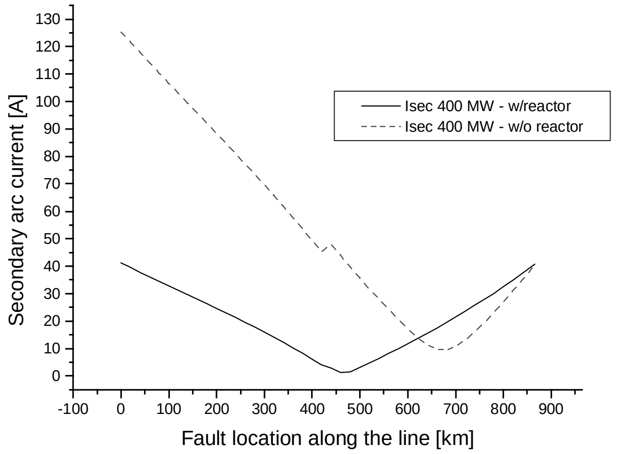

Fig. 5 - Secondary arc current (rms value at fundamental frequency), in function of the single-phase fault (At) location along the line, with the transmission system in operation, and the phase A circuit-breakers poles at both line extremities tripped.

It can be observed that, when the Terminal 2 shunt reactor is switched on, the secondary arc current is lower than when the reactor is not in service. In the latter case the secondary arc current goes to a level which can prevent successful SPAR. This fact imposes additional relaying constraint of switching Terminal 2 neutral reactor whenever any Terminal 2 switch-breaker pole receives an order to trip. When the control is properly performed, the secondary arc current is maintained within a level which should, in normal conditions, allow SPAR [28]. The highest current occurs when the fault is near the line terminals, being as low as 40 A (rms value at fundamental frequency).

V. Electromagnetic Transient Simulations

The simulations with general-purpose time domain simulation programs confirmed the solutions chosen and presented in this paper. In our case the ATP was used to represent the system. The transmission line analyzed was modeled with Quasi-Modes model, which represents properly the longitudinal frequency dependent parameters [15]. The line energization was performed with controlled closing time of Terminal 1 circuit-breaker. The first pole to close was in phase A, when its voltage was near zero. The following pole to close was in Phase C, after **T**/6 seconds of the phase A, and finally the pole in B, after 2***T**/6 seconds of the phase A, being **T** the time period at the fundamental frequency. With the controlled closure it was possible to close the whole line at a single shot, even though it has 865 km long, when the line had no fault. Some cases of phase-to-ground fault followed by tripping the faulted phase were simulated, observing the secondary arc current. The cases are described below:

- Case 1: Fig. 6 – A single-phase to ground fault was supposed existing (t_{fault} = - 1 s) when Terminal 1 bus was closed. The fault was applied at Terminal 1, as we had observed that there would be the critical fault location. The line was opened at Terminal 2, with the shunt reactor at Terminal 2 connected. The case description is: a) line energized through controlled switches at Terminal 1, being the closing time (t_A = 23.7 ms, t_B = 27 ms, t_C = 30.3 ms), with Terminal 2 opened and with phase A to ground short-circuit at Terminal 1; b) circuit breaker pole of Terminal 1, phase A receives order to trip at t = 78.7 ms; c) arc is assumed with negligible impedance and without extinction capability; d) Terminal 2 reactor is connected during all simulation time. The rms value of current after extinction of transient parcels, if arc would not extinguish, is about 20 A

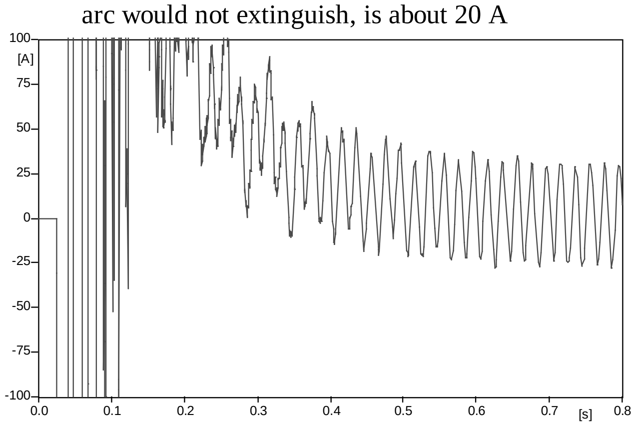

Fig. 6 – Arc current (short-circuit current), i , instantaneous value in function of time, t – Case 1.

- Case 2: Fig. 7 – the line was in normal operation when a phase-to-ground fault (At) at Terminal 1 occurred. In this case the shunt reactor at Terminal 2 was not connected while the line was in normal condition. After the fault occurred, the faulted phase (A) circuit-breakers poles at both line extremities received order to trip. The shunt reactor circuit breaker control was interlocked with the Terminal 2 circuit breaker. An order was sent to connect the shunt reactor before Terminal 2 circuit breaker tripped. The reactor should stay connected until the system is back to normal operation, when all poles of Terminal 2 breaker were closed. The case description is: a) line was operating normally, for t < 45 ms , with 400 MW load at Terminal 2, and with reactor at Terminal 2 disconnected; b) at t = 45 ms it occurs a short circuit at phase A to ground at Terminal 1; c) at t = 90 ms phase A circuit breakers poles at both line terminals receive order to trip and circuit breaker of reactor at Terminal 2 closes; d) arc is assumed with negligible impedance and without extinction capability. The rms value of current after extinction of transient parcels, if arc would not extinguish, is about 40 A.

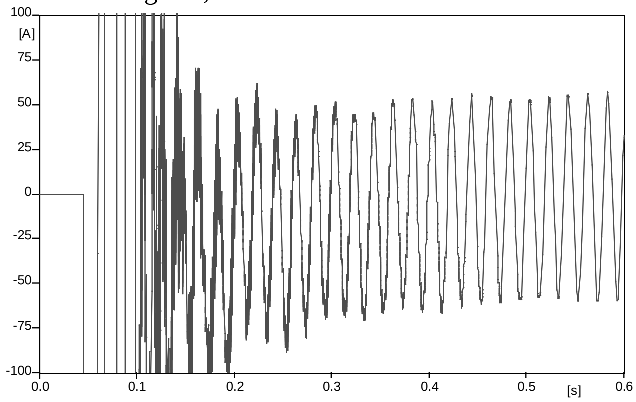

Fig. 7 – Arc current (short circuit current), i , instantaneous value in function of time, t – Case 2.

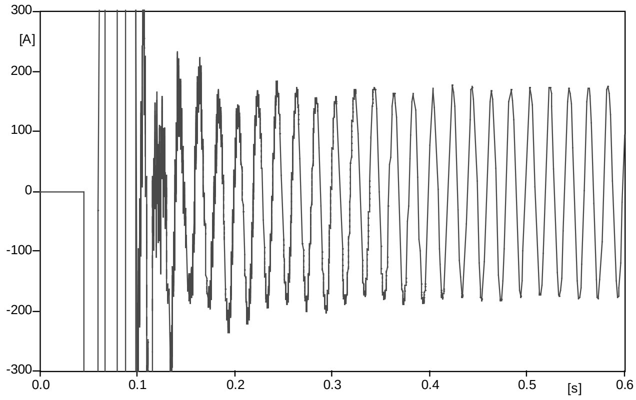

Fig. 8 – Arc current (short circuit current), i , instantaneous value in function of time, t – Case 3.

- *Case 3*: Fig. 8 – the line was in normal operation when a phase-to-ground fault (At) at Terminal 1 occurred. In this case the shunt reactor at Terminal 2 was not connected while the line was in normal condition. Then the faulted phase (A) poles of the circuit breakers at both line terminals received order to trip. The shunt reactor circuit breaker control was blocked, so the shunt reactor was never connected. The case description is: a) line was operating normally, for t < 45 ms , with 400 MW load at Terminal 2, and with reactor at Terminal 2 disconnected; b) at t = 45 ms it occurs a short circuit at phase A to ground at Terminal 1; c) at t = 90 ms phase A poles of circuit breakers at both line terminals receive order to open; d) and circuit breaker of reactor at Terminal 2 is opened during all simulation time; e) arc is assumed with negligible impedance and without extinction capability. The rms value of current after extinction of transient parcels, if arc would not extinguish, is about 125 A.

It can be verified that the secondary arc current values are near the predicted values with the previous analysis. It is also important to observe that the Terminal 2 shunt reactor cannot stay disconnected when any Terminal 2 circuit-breaker pole is opened, as that can jeopardize the system and prevent successful SPAR.

VI. CONCLUSIONS

In the present paper it is described a more optimized transmission system solution. In our case several system elements were adjusted to improve the system performance, and in this paper it was shown how a system element could be important to improve the whole system performance.

One important aspect was the need to assure high reliability of supply with a single line trunk. It was necessary to choose together a large number of parameters, in order to obtain a convenient solution. We do not discuss here procedures used in the systematic search to identify adequate ranges of all relevant parameters, and concentrate in the basic definition of specific system parameters within such ranges, to assure successful single-phase autoreclosing (SPAR) for non-persistent single-phase shortcircuits. Through the correct definition of the neutral reactor of the shunt reactors compensation banks, it was possible to reduce the secondary arc current (and the recovery voltage) to values low enough to allow SPAR with no need of other additional mitigation equipment.

To perform such analysis we developed a systematic analysis program to simulate the system at fundamental frequency with very high flexibility, which allowed us make a sensitivity analysis of the secondary arc current and recovery voltage in function of the neutral reactor and the fault location along the line. We were then capable of identifying the neutral reactor range, which reduced to the minimum values the secondary arc stresses.

After the fundamental frequency analysis some time domain simulations were performed with ATP, only for some most significant cases.

ACKNOWLEDGMENTS

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