Single-Phase Auto-Reclosure Studies: Influence of Transversal Parameters of a Transmission System on the Secondary Arc Current Reduction

M. E. Zevallos and M. C. Tavares

Abstract – **The present paper analyzes the influence of transmission line transversal parameters together with reactive shunt compensation parameters in the reduction of secondary arc current. A simple approach at preliminary design stage of transmission system is proposed to enhance SPAR success probability. Some electromagnetic transient simulations were performed with optimized neutral reactors in order to observe the secondary arc current minimization.**

Key-words – **Neutral Reactor, Secondary Arc, Single-pole Reclosing, Transmission Lines, Transversal Admittance Parameters.**

I. Introduction

STATISTICAL studies [1] related to the defects occurred at EHV lines show that more than 90 % of total line outages are due to single-phase to ground fault type. Beside that, the majority of the faults are non-permanent. A single-phase fault can be eliminated through three-phase opening or through tripping just the faulty phase. The most evident advantage of the single-phase opening is that this procedure ensures power transmission continuity through the other two healthy phases [2].

Before the faulty phase tripping the electrical arc current amplitude can reach 10^1 kA and the arc is named primary arc. After the faulty-phase is openned at both sides, the electrical arc is sustained due to coupling with the healthy phases. This arc current can reach 10^1 to 10^2 A for long lines (around 10^2 km long) and the electrical arc is called secondary arc. The secondary arc can self extinguish in a rather short time (less than 500 ms) or can be maintained for longer time by the healthy phases. If the phase is reclosed before the secondary arc extinguishes the procedure will fail and the three-phase tripping will be implemented [3].

Single-phase opening/reclosure procedure (SPAR) was imposed for every new line in Brazilian electrical system since 2000. In order to reduce SPAR failure rate it is important to minimize the secondary arc current (Iarc) amplitude. This optimization can be performed in a preliminar stage of transmission system design, reducing mitigation procedures costs.

EHV and UHV transmission lines with some hundreds of kilometers lengths generally use reactive shunt compensation to compensate line capacitive reactance to reduce voltage rise in remote terminal during line energization or during light load operation. A simple method to reduce secondary arc current is to properly specify a neutral reactor [4] installed at the common point of the shunt compensation reactors.

Steady state analysis of transversal transmission system parameters (line + shunt compensation) can enhance the sizing of neutral reactor. By doing so, it is possible to assure minimization of secondary arc current in first stage, increasing SPAR success probability [5]. If the secondary arc values are not reduced and remains severe, other possibilities for reducing secondary arc must be used, such as installing HSGS (high speed ground switches) or including a particular arc model based on time or interaction procedures arc-network. Such scenarios are not used in this paper.

In this work an extensive transmission system transversal parameter analysis is presented, varying shunt compensation level and neutral reactor values. Some transient results in the first stage of SPAR in steady-state are also presented for different line lengths, optimizing the neutral reactors and utilizing regular used Brazilian neutral reactor values.

II. Transversal Parameters of a Transmission System

The secondary current is mantained through capacitive and inductive coupling between the healthy phases and the faulty one. In the proposed method the secondary coupling will be minimized at a preliminary design stage and for so an analysis of the transmission system behavior during the energization maneuver is adequate. A supplementary enhancement can be performed for different load levels. For the energization analysis the capacitive coupling is much more proiminent and therefore it is important to optimize the transversal parameters of the transmission system composed of transmission lines and

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shunt compensation system.

In this section both transmission line transversal parameters and shunt compensation reactors will be described through their admitance matrices.

A. Transversal Parameters of Long Transmission Line

The present approach means to reduce the secondary arc current amplitude. As the arc is maintained through the energized phases coupling in steady state, the secondary current is basically a 60 Hz signal. It is an acceptable assumption to take the line as ideally transposed at fundamental frequency.

The transposed line can be represented by its symmetrical components as presented in Figure 1.

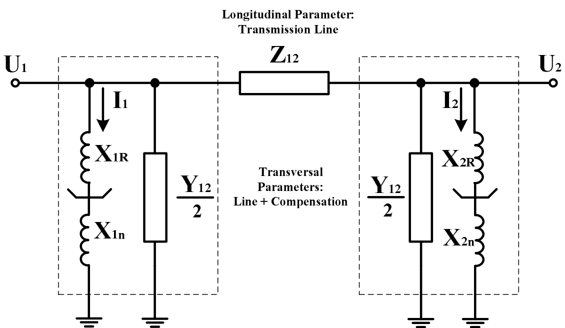

Fig. 1. Transmission system representation - transmission line together with compensation reactors.

Transversal admittance of a long single-phase transmission line (Y_{12}) (or of a line sequence component) is obtained through (1). In equation (2) admittance matrix [Y] of a three-phase line is presented in mode components, specifically homopolar mode (y_h) and non-homopolar modes (y_d), which are numerically equal to positive and negative sequence component. Propagation constant (γ_c) of a component is seen in (3). z_c and y_c terms correspond to series impedance and transversal admittance per unit length for a specific line component.

$$\frac{Y_{12}}{2} = \frac{y_c . l}{2} \cdot \left[\frac{\tanh(\gamma_c . l / 2)}{\left(\gamma_c . l / 2\right)} \right] \tag{1}$$

$$[Y] = \begin{bmatrix} y_h & 0 & 0 \\ 0 & y_d & 0 \\ 0 & 0 & y_d \end{bmatrix} \tag{2}$$

$$\gamma_c = \sqrt{z_c . y_c} \tag{3}$$

For a better understanding, the line admittance matrice will be presented in phase components, so the self (y_p) and mutual (y_m) admittance elements will be derived from the sequence components, as presented in (4) and (5).

$$y_p = \frac{y_h + 2\, y_d}{3} \tag{4}$$

$$y_m = \frac{y_h - y_d}{3} \tag{5}$$

Transversal admittance matrix per unit length in phase components is shown in (6), relating the line transversal voltages and currents that circulate in the equivalent phases.

$$[Y_{12}] = \begin{bmatrix} y_p & y_m & y_m \\ y_m & y_p & y_m \\ y_m & y_m & y_p \end{bmatrix} \tag{6}$$

B. Transversal Parameters of Reactive Shunt Compensation Scheme

The arrangement utilized at the four-legged reactor is shown at Figure 2. With this arrangement, it is guaranteed a normal system operation under steady-state conditions for long lines lengths. During contingency occurrence at the network, such as opening/reclosing procedures, rejection, energization or faults, reactive arrangement is converted into a security element for stability problems or other kinds of problems that may arise from these maneuvers.

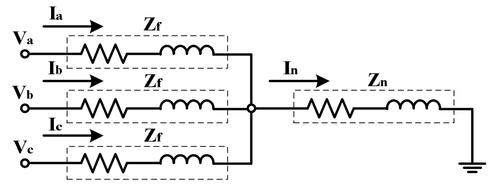

Fig. 2. Four-legged reactor arrangement scheme (with neutral reactor).

From Figure 2, it is obtained boundary conditions equations (7) for the analysis of the reactive compensation scheme.

$$\begin{aligned} V_a &= Z_f \cdot I_a + Z_n \left(I_a + I_b + I_c\right) \\ V_b &= Z_f \cdot I_b + Z_n \left(I_a + I_b + I_c\right) \\ V_c &= Z_f \cdot I_c + Z_n \left(I_a + I_b + I_c\right) \end{aligned} \tag{7}$$

Through (7), the impedance matrix (9) of shunt reactive compensation arrangement is obtained.

$$[V_{abc}] = [Z_R][I_{abc}] \tag{8}$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} Z_f + Z_n & Z_n & Z_n \\ Z_n & Z_f + Z_n & Z_n \\ Z_n & Z_n & Z_f + Z_n \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{9}$$

Following in equations (10) to (13), self and mutual elements of admittance matrix in shunt reactive compensation are obtained in the phase domain.

$$Y_{Rp} = \frac{\left(1 / \left(Z_f + 3Z_n\right)\right) + 2\left(\frac{1}{Z_f}\right)}{3} \tag{10}$$

$$Y_{Rm} = \frac{\left(1 / \left(Z_f + 3Z_n\right)\right) - \left(\frac{1}{Z_f}\right)}{3} \tag{11}$$

$$Y_{Rp} = \frac{Z_f + 2Z_n}{Z_f \left(Z_f + 3Z_n\right)} \tag{12}$$

$$Y_{Rm} = \frac{-Z_n}{Z_f \left(Z_f + 3Z_n\right)} \tag{13}$$

In (14), it is shown admittance matrix of the shunt reactive compensation.

$$[Y_{Rabc}] = \begin{bmatrix} Y_{Rp} & Y_{Rm} & Y_{Rm} \\ Y_{Rm} & Y_{Rp} & Y_{Rm} \\ Y_{Rm} & Y_{Rm} & Y_{Rp} \end{bmatrix} \quad (14)$$

Analyzing together the line transversal admittance (6) and the shunt reactive compensation (14) it is obtained an Y_{TOTAL} matrix of the transmission system composed of line + compensation scheme (16).

$$[Y_{TOTAL}] = [Y_{12}] + [Y_{Rabc}] \quad (15)$$

$$[Y_{TOTAL}] = \begin{bmatrix} y_p + Y_{Rp} & y_m + Y_{Rm} & y_m + Y_{Rm} \\ y_m + Y_{Rm} & y_p + Y_{Rp} & y_m + Y_{Rm} \\ y_m + Y_{Rm} & y_m + Y_{Rm} & y_p + Y_{Rp} \end{bmatrix} \quad (16)$$

Equation (16) allows the analysis of the influence of shunt compensation level in the mutual and self elements, with the objective of reducing capacitive coupling that feeds the secondary arc during SPAR. To promote the secondary arc current reduction it is necessary to minimize the mutual admittance term of Y_{TOTAL} matrix.

Formerly, it is described in (17) to (19) the mutual admittance of transmission system (Y_M) in function of the system reactive compensation level (ξ).

$$Y_M = y_m - \frac{Y_f}{3 + \frac{Y_n}{Y_f}} \quad (17)$$

$$Y_f = \xi \, y_d \quad (18)$$

$$Y_M = y_m - \frac{\xi \, y_d}{3 + \left(\frac{Y_n}{\xi \, y_d}\right)} \quad (19)$$

Where Y_f is the phase reactor admittance and Y_n is the neutral reactor admittance of the shunt compensation.

From (19) it is possible to notice that, increasing reactive compensation degree, total mutual admittance (Y_M) of transmission system diminishes, that is, coupling among phases is reduced.

III. Analyzed Transmission System

In Table II, electrical parameters of conventional 500 kV line (Tucuruí - Marabá) are shown. The line SIL is 1199 MW. For the study, the line length was varied, being utilized: 450 km, 600 km and 900 km.

Figure 3 shows the upper silhouette of the tower used in the analysis, where the distances between conductors and between phases and their respective heights at the tower are depicted.

The line has a reactive compensation scheme based into "four-legged" setting, which is shown at Figure 2. The reactors are located at line extremities. For each line length in analysis, phase and neutral reactors values are varied.

A. Neutral Reactor Optimization

As stated before, the present approach is based in minimizing the secondary arc current in a preliminary stage of transmission system design in order to increase the success probability of SPAR maneuver. At this stage no arc model is used.

In (20) the factor r_h is presented. A sensitivity analysis of r_h will allow the minimization of Iarc [3].

$$r_h = \frac{Y_d}{Y_h} = \frac{Y_1}{Y_0} = \frac{1/Y_f + 3/Y_n}{1/Y_f} \quad (20)$$

Being Y_d, Y_h, respectively, the non-homopolar and homopolar admittance of the shunt compensation reactor, at 60 Hz.

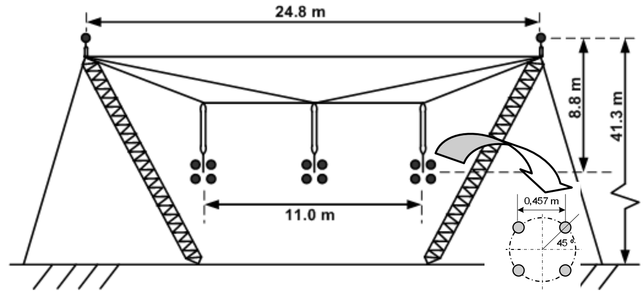

Fig. 3. Tower upper silhouette of the conventional 500 kV line in study.

Table II
Electrical Parameters of 500 kV line at 60 Hz

Zero Sequence	**R_0 (Ω/km)**	0.3235
	X_0 (Ω/km)	1.5504
	Y_0 (μS/km)	2.7290
Positive/negative Sequence	**R_1 (Ω/km)**	0.0154
	X_1 (Ω/km)	0.2670
	Y_1 (μS/km)	6.1800

In Table III, the ratios r_h that resulted in optimal X_n to reduce Iarc amplitude for the analyzed line are presented. The compensation levels were varied to keep a voltage gain in the range: 0.95~1.05.

Table III
Optimal Ratio R_H to minimize Iarc during SPAR

U_1 500 kV	Length 450 km			Length 600 km			Length 900 km		
ξ (%)	r_h (X_0/X_1)	X_n (Ω)	X_f (Ω)	r_h (X_0/X_1)	X_n (Ω)	X_f (Ω)	r_h (X_0/X_1)	X_n (Ω)	X_f (Ω)
72(*)	3.75	889.9	970.9	-	-	-	-	-	-
80	2.9	553.4	873.8	2.8	384.3	640.5	-	-	-
84(**)	-	-	-	2.6	325.3	610.1	-	-	-
90	2.4	362.5	776.7	2.3	246.7	569.3	1.9	106.2	354.1
92(***)	-	-	-	-	-	-	1.9	103.8	346.3
95	-	-	-	-	-	-	1.8	89.4	335.4
100	2.1	256.3	699.1	2.0	170.8	512.4	1.8	84.9	318.6

(*) minimum degree of reactive compensation for the length: 450 km.
(**) minimum degree of reactive compensation for the length: 600 km.
(***) minimum degree of reactive compensation for the length: 900 km

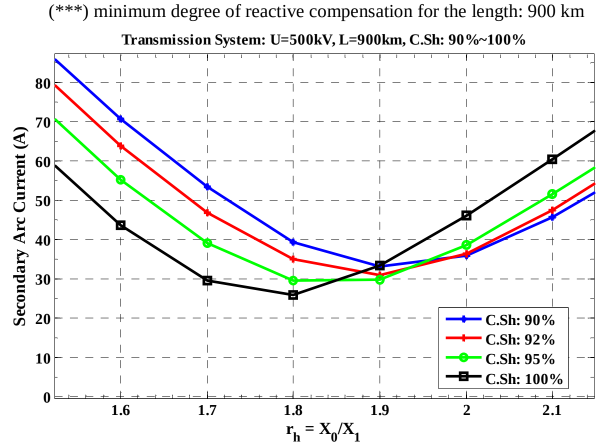

Fig. 4. Maximum Iarc for single-phase faults along the line, when varying the neutral reactor values. Line length: 900 km.

For each r_h ratio a sliding fault was represented and the highest Iarc was obtained. Taking for example the 900 km line with 92 % of shunt compensation (figure 4), the worst fault condition along the line was obtained for r_h range between 1 and 6. The lower arc current (Iarc = 30 A) is obtained with a factor r_h = 1.9 and represents a neutral reactor X_n = 103.8 Ω.

IV. Admittance Parameters Analysis

A preliminary analysis of transmission system admittance parameter was implemented in order to identify the optimized neutral reactors to reduce Iarc. In Figure 5 it is shown the absolute values of the ratio between mutual admittance and the self admittance (abs[Y_m/Y_{12s}]) for the 450 km line varying the neutral reactor value and the compensation level. The minimal values of this ratio is coincident with the optimal values of neutral reactors as presented at Table III. It can be observed that for high compensation level the optimum neutral reactor value diminishes. Also, for a neutral reactor value there is an optimal compensation level that will result in a minimum Iarc. The regularly used neutral reactor in Brazilian 500 kV lines (800-Ω) is not indicated for highly compensated lines, when optimizing SPAR maneuver.

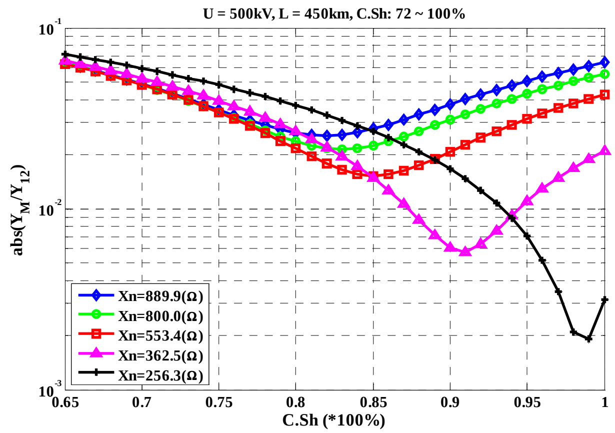

Fig. 5. Abs[Y_m/Y_{12s}] for different levels of reactive compensation: C.Sh (%), varying Xn. Line length: 450 km.

In figure 6 the neutral reactor value is the basic parameter for the 450 km line analysis when varying the compensation level. It can also be observed that when the compensation level increases the optimum neutral reactor value diminishes. The same response could be observed for longer lines (600 and 900 km)

In Figure 7 maximum secondary arc currents are presented, obtained for several reactive compensation levels for different neutral reactors (X_n). It is possible to observe that a neutral reactor has an optimum compensation level that will result in a minimum Iarc. Beside that, the lower the shunt compensation level the greater the value of optimal neutral reactor. The 800 Ω neutral reactor is indicated for ξ = 0.75, while for ξ = 0.9 the indicated reactor is 362.5 Ω. This results that when utilizing a neutral reactor of 800 Ω for a 500 kV line, 450 km long, strongly compensated (ξ = 1.0), Iarc will be much higher (Iarc = 50 A) than when utilizing a lower value neutral reactor, for example, of 256 Ω (Iarc < 1 A).

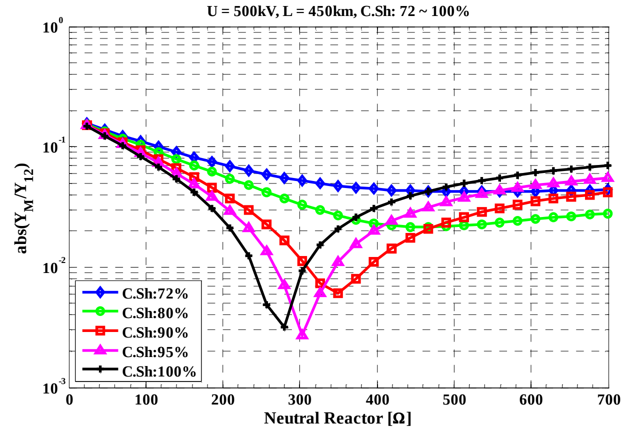

Fig. 6. Abs[Y_m/Y_{12s}] function of Xn for different levels of reactive compensation C.Sh (%). Line length: 450 km.

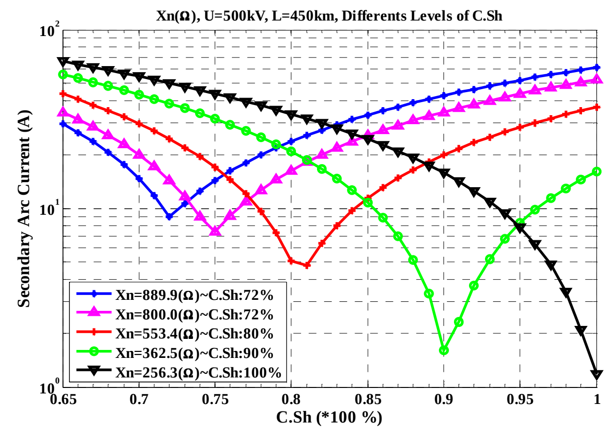

Fig. 7. Maximum Iarc for different Xn, varying reactive compensation levels. Line length: 450 km.

Table IV summarizes the obtained results of mutual admittance relation (Y_m/Y_{12s}) and the increase of shunt reactive compensation level (ξ). Secondary arc current reduction is also presented.

TABLE IV
RELATION ABS[Y_M/Y_{12S}], NEUTRAL REACTOR AND SECONDARY ARC CURRENT

U_1 500 kV	Length 450 km			Length 600 km			Length 900 km		
ξ (%)	$\lvert Y_M\rvert / \lvert Y_{12}\rvert$	X_n (Ω)	I_{arc} (A_{rms})	$\lvert Y_M\rvert / \lvert Y_{12}\rvert$	X_n (Ω)	I_{arc} (A_{rms})	$\lvert Y_M\rvert / \lvert Y_{12}\rvert$	X_n (Ω)	I_{arc} (A_{rms})
72(*)	0.0432	889.9	9.6	-	-	-	-	-	-
80	0.0216	553.4	5.0	0.0214	384.3	13.0	-	-	-
84(**)	0.0140	471.6	3.3	0.0151	305.1	10.0	-	-	-
90	0.0073	362.5	1.6	0.0083	246.7	5.0	0.0180	106.2	33.2
92(***)	0.0071	329.3	2.5	0.0082	222.8	5.6	0.0161	103.8	31.0
95	0.0070	294.3	2.4	0.0045	215.8	5.5	0.0165	89.4	30.0
100	0.0048	256.3	1.2	0.0070	170.8	5.0	0.0140	84.9	26.0

V. Time Domain Analysis

Based on the worst location suitable for single-phase fault in steady-state analysis, some simulations with the help of ATP were made to verify the current Iarc (rms).

Phase reactors were supposed to have a quality factor of 400 and the neutral reactor a quality factor of 40. The system was supposed to be, initially, at steady state and the line was energized with a fault at the location which was identified as generating the highest secondary arc current. For some cases the fault was applied in the remote line terminal. The fault was applied at t = 0.1 s. Faulty phase circuit breaker was opened at t = 0.2 s. Iarc was measured at the fault location. At this preliminary optimization stage only the secondary arc fundamental frequency response was analyzed, so the fault was modeled by a simple resistance with $R_f = 20\ \Omega$. Figures 8 to 12 do not have the same scale in the vertical and horizontal axes because the objective was to observe the reduction of the amplitude of the secondary arc current for the cases under study. This would not be possible if a single scale were used for all graphics.

A. Analyses of Line with Shunt Compensation, without Neutral Reactor.

Formerly the cases with phase reactors without neutral reactor are presented. It was observed that, at the three cases, Iarc was greater than 140 A_{rms}. At Table V, rms currents values are shown for the worst fault location, without neutral reactor installation.

TABLE V
I_{ARC} SECONDARY ARC CURRENT DURING SINGLE-PHASE FAULT WITHOUT INSTALLATION OF NEUTRAL REACTOR

U_1 500 kV	Length 450 km		Length 600 km		Length 900 km	
ξ (%)	X_d (Ω)	I_{arc} (A_{rms})	X_d (Ω)	I_{arc} (A_{rms})	X_d (Ω)	I_{arc} (A_{rms})
72(*)	970.87	144.29	-	-	-	-
80	873.79	138.47	640.51	-	-	-
84(**)	832.18	136.82	610.10	179.11	-	-
90	776.70	135.01	569.34	174.77	354.1	236.97
92(***)	759.81	134.62	556.97	173.18	346.3	233.78
95	735.82	133.54	539.38	171.49	335.4	227.91
100	699.03	132.61	512.41	168.81	318.6	220.70

At Figure 8 it is presented the result from single-pole opening after single-phase fault for the cases of compensated lines without neutral reactor (for the three line lengths).

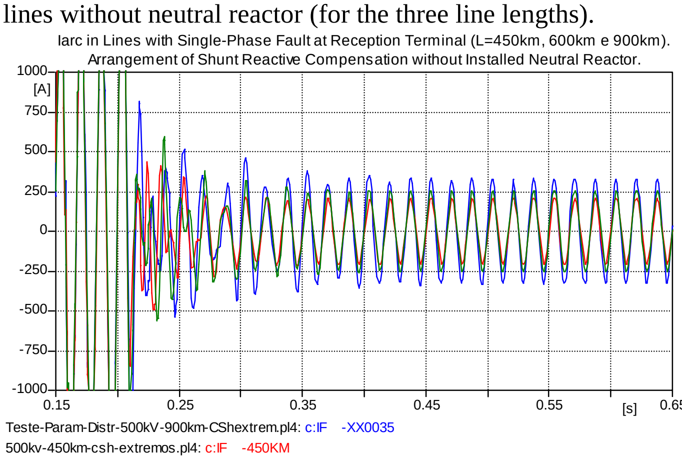

Fig. 8. Fault current for compensated lines of 450 km, 600 km and 900 km, without neutral reactor.

B. Analyses of Lines with Shunt Compensation and Neutral Reactor installed.

In Figure 9 it is presented the fault current for the 450 km line with neutral reactor installed. It was verified an important reduction of Iarc to 12.13 A_{rms} with $X_n = 889.96\ \Omega$ ($\xi = 0.72$). The single-phase fault was simulated at the line end terminal, which corresponds to the local resulting in the worst secondary arc current.

If a neutral reactor different from the proposed value presented at Table IV were used for the 450 km line, as for example $X_n = 106\ \Omega$, Iarc would increase to 101.82 A_{rms} (Figure 10).

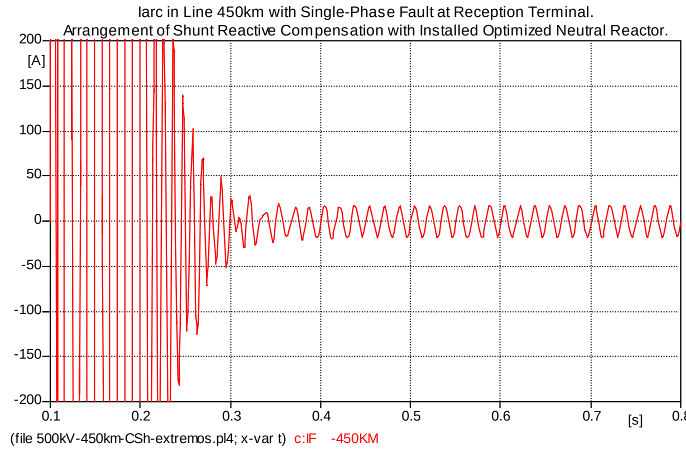

Fig. 9. Iarc for 450 km line with optimized Xn reactor.

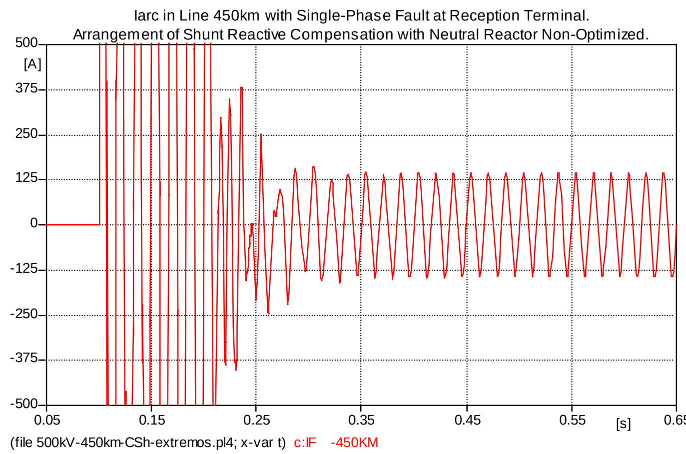

Fig. 10. Detail of Iarc for 450 km line with $X_n = 106\ \Omega$.

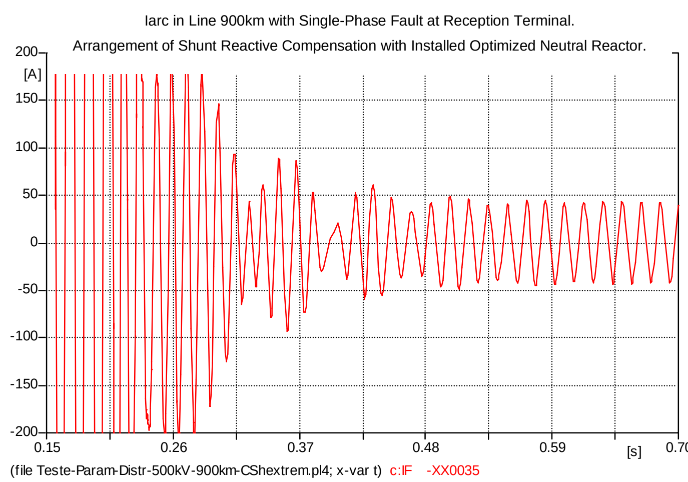

Fig. 11. Iarc for 900 km line with optimized neutral reactor X_n.

The same simulation is presented for the 900 km long line. In figure 11 the line energization maneuver under single-phase fault with open reception terminal is presented for neutral reactor $X_n = 103.8\ \Omega$ ($\xi = 0.92$). The secondary arc value was limited to 30.46 A_{rms}. If the neutral reactor value is altered to a higher value, for example, $X_n = 800\ \Omega$, Iarc will increase to 270.07 A_{rms}. In this case, there is a high probability that SPAR does not succeed without additional mitigation procedures [6]. Figure 12 shows Iarc for this case.

VI. CONCLUSIONS

In this work, transversal parameters influence of a transmission system formed by EHV transmission line and its shunt compensation was analyzed regarding SPAR. The main objective of the presented methodology was to reduce secondary arc current with simple and low cost specification at former stage of transmission system specification.

It is important to determine the relation between the mutual admittance of transmission system (line + compensation) for the desired compensation level. Through this relation, some parameters can be optimized to improve system performance.

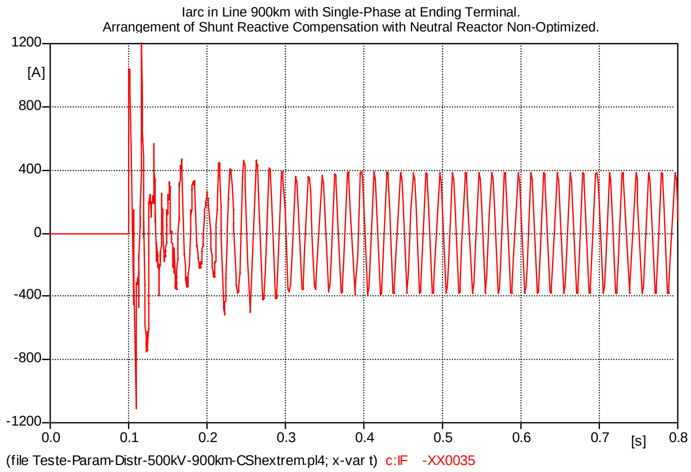

Fig. 12. Iarc for 900 km line with neutral reactor X_n = 800 Ω.

The correct sizing of the neutral reactor of shunt compensation banks has resulted into secondary arc current reduction. With the appropriate neutral reactor selection these low arc current values should result in successful SPAR, without the need of additional mitigation procedures.

A typical line in 500 kV of the Brazilian system was used for the studies. The main results can be summarized as following:

- The assessed line, when supposed to be without any kind of compensation will only have a high probability of performing single-pole reclosing maneuver with success for lengths smaller than 140 km.
- The assessed line, with 450 km long and with shunt reactive compensation installed at both line extremes, will have a high probability of succeeding at single-pole reclosing maneuver if a neutral reactor is installed, indicated for each level of compensation. For example, for a compensation of 72 %, the optimal neutral reactor is X_n = 889.9 Ω.
- The assessed line, with 600 km long and with shunt reactive compensation installed at both line extremes, will have a high probability of succeeding at single-pole reclosing maneuver if a neutral reactor is installed, indicated for each level of compensation. For example, for a compensation of 84 %, the optimal neutral reactor is X_n = 305.1 Ω.
- The assessed line, with 900 km long and with shunt reactive compensation installed at both line extremes, will have a high probability of succeeding at single-pole reclosing maneuver if a neutral reactor is installed, indicated for each level of compensation. For example, for a compensation of 92 %, the optimal neutral reactor is X_n = 103.8 Ω.

It is possible to observe that the lower the level of shunt compensation of the line, the higher the value of optimal neutral reactor, that is, the higher the value of neutral reactor which will result into the lower secondary arc current. When utilizing a neutral reactor of 800 Ω for a line of 500 kV, 450 km, strongly compensated (compensation level of 100 %), secondary arc current will be much larger than that of a lower neutral reactor, for example, of 256 Ω.

When identifying an optimal neutral reactor for a determined compensation level, the mutual admittance of transmission system admittance-matrix achieves its lowest value.

Each transmission system needs a specific study that checks the probability of a successful SPAR. The same X_n value can be inadequate for systems with the same voltage level or lines with same length.

Besides the secondary arc current, the voltage at the arc terminals and at the openned phase ends should also be analyzed.

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