SINGLE PHASE RECLOSING IN UHV LONG LINES FOR AMAZON TRANSMISSION SYSTEM

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ABSTRACT

This paper presents a description of the studies performed, and an interpretation of the results obtained on the single phase reclosing of a 2400 km UHV transmission line. Secondary arc currents, induced voltages, and resonances are analysed and solutions are proposed taking into consideration this system characteristics. A synthesis of arc extinction criteria obtained from EHV transmission lines experiences, applied to UHV are also here presented.

Key Words

Single phase reclosing, secondary arc, neutral reactor and grounding switches.

1. Introduction

The aim of this paper is to evaluate the viability of the single phase reclosing in an 2400 km UHV transmission line that has been studied for energy transmission from the Amazon to the southeastern region of Brazil.

The study focused on: a) the analysis of viable equipment technologies used to favour the secondary arc extinction in UHV systems, emphasising neutral reactors use and fast grounding switches ; b) transmission lines modelling; c) Resonance during 1 or 2 phases opening and between parallel circuits; d) secondary arc extinction models and establishment of preliminary criteria to analyse its extinction, aiming at checking on the single phase reclosing viability in this system.

The performed studies with the ATP program were subdivided into three phases: in the first one, the obtained values correspond to linear and to steady state conditions, that is, with no representation of reactors and transformers saturation and other non-linearities.

An analysis for checking the influences of the non linear elements and the harmonic currents paths was done. In the last stage the transient single phase was simulated from the primary arc to its extinction. In this case the non-linear elements were represented.

The AC studied system (figure 1) is composed by a transmission line of 1000 kV with five sections of 480 km, being the first stage part of one of the alternatives which are being studied for energy transmission from the Amazon to the south-eastern region.

The system studies performed by Eletrobras led to a hypothesis with 70 % series compensation and 90% reactive compensation without using transformation or voltage control equipment at the intermediary substations. This system is able to transmit to the SE about 4000 MW, considering the single phase reclosing criteria and supporting the load rejections with some restrictions concerning the short-circuit level of the receiving terminal.

The need of adequate equipment for future stages of the system were considered, taking into account the resonance conditions in the configuration with two circuits .

The main data of this system can be seen on table 1.

Transmission Line	Positive Sequence	Zero Sequence
r (Ω/km)	0.0063	0.1840
x (Ω/km)	0.2710	1.408
y (μMhos/km)	6.136	3.390
SERIES CAPACITORS (Ω)	85.00	
REACTORS (MVAr/1000kV)	1370	

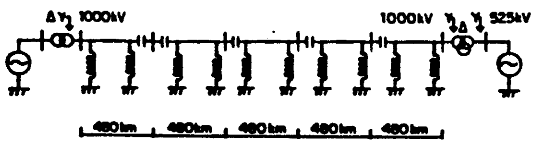

Figure 1 - Studied System

Usually the transmission systems present natural paths to the ground for the unbalanced currents. In this 2400 km line without earth paths, some aspects such as: the voltage control during failures to ground or unbalanced situations and harmonic currents paths deserve a special attention.

Another aspect of this system is related to the high level of the reactive compensation. By allocating the compensation on the line terminals, the resonance conditions during one or two phases opening are closer to the nominal condition, so that this aspect should be criteriously analysed noting that for frequencies or electrical parameters deviations can lead to unwanted syntonizing

The same happens by the resonance analyses between parallel circuits.

2. Induced Voltages and Arc Currents

2.1. Performed Studies

The behaviour of the system during single phase opening was mainly studied for the central line section, being also exploited the behaviour of the sections nearby the terminals (first and last).

The values of the secondary arc steady state and the induced voltages after the extinction were evaluated considering:

a) various relations X_0/X_1 at the neutral reactors.

b) influence of the faulted section and switched phase.

c) configuration with one or two circuits.

d) short-circuit power of the receptor system of 7.5 GVA and 20 GVA.

e) loading of the UHV line.

2.2. Measures for the Secondary Arc Extinction in UHV Transmission Lines

After a preliminary investigation on the possible measures, the efforts were concentrated on the neutral reactors and on the use of fast grounding switches.

These measures aim at lowering the electrostatic coupling effect (the neutral reactor acts reducing the coupling between the phases and the switches divide the secondary arc current); however for this configuration, the use of earthing switches have enlarged the electromagnetic coupling effect making the extinction of the secondary arc difficult. The eletromagnetic effect depends on the intensity and on the unbalance of sound phases currents (figure 2).

Disregarding the capacitive couplings, the electromagnetic effect would be null, for the mesh currents i_1 and i_2 are equal.

The use of reactors at substations increases the mesh impedance, however there are no more currents equality, what causes an increase of the secondary arc current. For relatively short lines and in systems with adequate voltage control, the grounding switches are of interest because they do not increase the electromagnetic effect, taking into consideration that they tend to re-establish the equality of i_1 and i_2 mesh currents apart from the faulty point.

The same does not happen in long systems with high rated voltage because in this case the capacitive effect presents a considerable influence, affecting the mesh currents unbalance. This way, the use of grounding switches haven't proved to be adequate in this system considering the simulations done for the central section due to the increase of the electromagnetic effect caused by this grounding. This fact was a consequence of the unbalances of the sound phases currents, that are different along the section and dependent on the high unbalance voltage during the monopolar opening being aggravated by the reduction of the mesh impedances with switches.

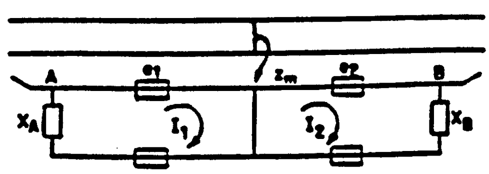

Figure 2 - Electromagnetic Effect

The use of neutral reactors is adequate in this system considering its effect on the capacitive coupling between phases during the single phase opening and as a mean to avoid resonant situations. Besides, the neutral reactor can also be adjusted to increase the mesh impedances contributing to reduce the electromagnetic effect.

With 90% compensation level the arc currents are reduced by the use of neutral reactors, but, some resonance uncertainties may be expected, so, in a later stage of the studies the compensation level can be optimized and, more comfortable situation can be reached transferring part of the reactors to the bar. However, an increase of X_0/X_1 relation may increase neutral insulating level.

The rated value of the neutral reactor must be optimized in this system considering its effect in the electrostatic and electromagnetic couplings and the value X_0/X_1 = 1.8 for the 90 % compensated line is , an adequate value. However, this is not very far (10%) from the zero sequence resonance between parallel circuits. This could be improved by changing the relation X_0/X_1 for this configuration.

2.3. System Aspects

The transmission planning phase needs a closer interaction between the electromagnetic transients studies of single phase reclosing and other system studies like stability, energization and load rejection.

The high overvoltage level on the sound part of the system during the monopolar openning depends on the grounding level that influences the impedance between the receptor system and the collector system during the monopolar openning and therefore on the system stability. This aspect could be improved by voltage control at the intermediate substations, what makes the transmission costly but convenient considering the power to be transferred by UHV system.

The system reactor location and the need of increasing the auto-transformers knee point at the receiving end, are influent aspects for the studies of resonances and secondary arc extinction. However that can only be decided based on overvoltage studies caused by load rejection and system energization, whose duties also depend on the short-circuit level of the sending and receiving systems.

Although it is important to analyse the best type of transposition for the lines, aiming at minimising the unbalances, this aspect has not influenced the studies results.

The lines were represented with the transpositions (1/6, 1/3, 1/3, 1/6), and with distributed parameters.
The saturation curve and the knee point of the UHV/EHV auto-transformers influence on the secondary arc current, were also investigated.

The reserving system short-circuit level is a relevant factor for the overvoltages and unbalances found at the monopolar openning. This short circuit power level was studied at 7.5 and 20 GVA, depending on planning stages.

2.4. Linear Stead State

A theoretic analysis was performed on the resonance points for the conditions of one and two open phases and with parallel circuits. This previous analysis considered a no load network, concentrated parameters and voltage profile of 1 p.u. at the line terminals. [1] [8].

Secondary arc current values and steady state recovery voltages were obtained in this simplified model as in table 2.

This table presents the theoretic resonance points, arc current variation ranges and induced voltages, considering a reactive compensation variation about 10% of the rated value (2700 MVAr), this range was used to express a pessimistic composition of the electric parameters and system frequency.

Table 2 - Resonance Points, Secondary Arc Currents and Voltages

	RESONANCE POINT (MVAR) OPENING		INDUCED VOLTAGE RANGE (kV)	CURRENT RANGE (A)
X_0/X_1	1 PHASE	2 PHASES		
1.00	2590,00	2136,00	+2125 ~ -620	-262,00
1.5	2913,00	2745,00	303 ~ -829	-115 ~ -56
1.8	3001,00	2943,00	136 ~ -205	-63 ~ +9
2.2	3165,00	3356,00	29 ~ 462	-16 ~ 68

These results present a qualitative analysis which gives more insight into the problem and all systems parameters uncertainties were grouped to the size of the reactors, varied in about 10% from the nominal values.

Table 3 presents the results for the detailed system. The voltage profile is presented for some studied conditions of short-circuit level (SCL) and of neutral reactors, varying X_0/X_1 relation.

Table 3 - Open Phase Voltages

X_0/X_1	SCL	CO	SE	RE	Vr
1,00	7.5	1.01	1.61	1.63	6.31
1,8	7.5	1.12	1.91	1.58	0.11
1,8	20.00	1.12	1.45	1.23	0.12

Vr - open phase voltage
CO, RE - sending ("coletora") and receiving system voltages
SE - substation voltage in the 3º section

Considering the short-circuit level of the receiving system in 7.5 GVA, the high degree of unbalance observed provokes a severe stress not only at the intermediate substation equipments but also at the neutral reactors.

With the short-circuit level increase there is a voltage level decrease in other points of the line (network) and in the transformer, which might improve the single phase reclosing conditions.
Table 3 shows that with the short-circuit power increase from 7.5 to 20 GVA, there is a voltage reduction of 1.91 p. u. to 1.45 p. u. in the sound system.

Tables 2 and 3 highlight the need of neutral reactors, lowering the open phase (Vr), but on the other hand worsening the grounding of the system and increasing the overvoltages on the sound system. Thus, similar results to the ones in Table 3 should be obtained for the opened section (Vr) for X_0/X_1 = 1.8 and for the rest of the system with X_0/X_1 = 1.

The problem of high overvoltages on the sound open phase voltage of the system is more serious for the terminal section, mainly for the first one. To solve this problem by pass neutral reactors with breakers were proposed , which are included in the neutral with the phase openning (tripping) at the same bar.
Table 4 shows values obtained at the first section (SE_1) and the benefit of the use of the breakers, by passing the neutral reactors.

Table 4

X_0/X_1	SCP	SECTION	NEUTRAL REACTOR BY-PASS	CO	SE_1	RE	Vr
1.8	20.0	1º	NO	1.12	2.13	1.32	0.21
1.8	20.0	1º	YES	1.06	1.63	1.26	0.18

2.5 . Non linear elements representation

A reference value from the literature for the extinction of the secondary arc current is between 40 Arms and 50 Arms.

Figure 3 presents the wave form of the current and the distortion is caused mainly by the saturation of the receptor auto-transformer with 1.2 p.u. knee point and with a preponderance of 3rd harmonic interference. The transformer is very little saturated in this case.

The maximum current peak value is 80 A and the rms value is 40.9 A.

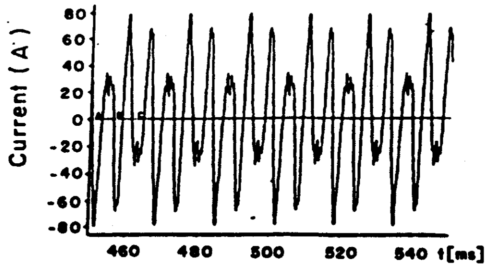

Figure 3 - Steady State Arc Current

Figure 4 presents the complete fault application followed by the line opening, with 100 Ohms arc resistance.

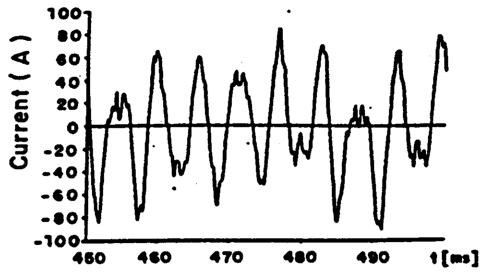

Figure 4 - Transient Arc Current

These cases show that the current is under an almost steady state condition, in a period of 500 ms, although the electric arc dynamics has not been considered in these simulations.

The neutral reactor is efficient in the 60 Hz component reduction of the arc current.

By increasing the transformers knee point, the harmonic effects are attenuated.

The derivatives of the secondary arc current and of the recovery voltage, close to zero, are important parameters to analyse the possibility of succe... arc current extinction (see item 4). The relatio... 1.8 was used in this analysis and the dynamic ... of the electric arc was not taken into considera... representation of the arc model may reduce ... current, what would imply in inferior increasing ... favouring extinction.

In saturated conditions, the rate of rise of the recovery voltage at various points of possible current extinction have values around 50 kV/ms (figure 5).

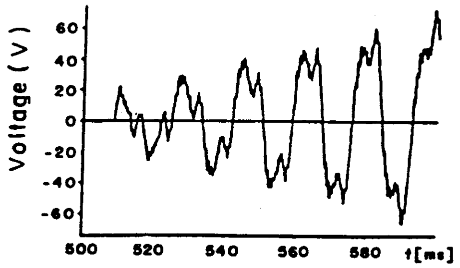

Figure 5 - Induced Voltage Increase

Considering that the rate of rise of the current is an important parameter for the analysis of the electric arc extinction, the results in figure 3 present some concerning values. However, when the transient curve is analysed (figure 4), more favourable points of the arc extinction can be observed at relatively low rates.

For the almost linear network the knee point of the receiving auto-transformer in 1.35 p.u. a rate of rise of the recovery voltage and of the current are 1 kV/ms and 3 A/ms, respectively, being then the case favourable for extinction.

3. Electric Arc Extinction Analysis

It is clear that in this first approach the need of consistent theoretic basis followed by tests research efforts with experiments in 1000 kV lines that should give sequence to these preliminary investigations.

There are some results taken from experiments with the extinction of the electric arc in the air obtained at the laboratory and in the field [2 to 7] for EHV lines. The results were submitted to an analysis that separated each one according to the limiting effect (dielectric or thermal). The rate rise of the current and voltage were calculated per unit length of insulator strings making the experiments of 50 Hz comparable to the ones of 60 Hz. Another important effect is the arc elongation with the time and it was assumed as moderate after an analysis and of the discussion among the specialists of the various papers.

Taking an insulator string of 7 meters for 1000 kV transmission line and considering also the arc elongation the limiting curves of the recovery voltage rate of rise (kV/ms) can be obtained according to the current rate of rise (A/ms) after from primary arc. In the following figure the conservative curve is presented for the thermal phenomena, for the time Te 400 ms duration of the secondary arc (adequate to the reclosing, after 500 ms). This curve was obtained from a regression analysis of the experimental results by length of insulator (kV/ms)/m and in figure 6 they are referred to a 7 m string.

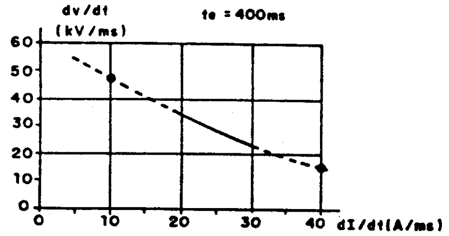

Figure 6 - Thermal Extinction Curve for a 7 m Insulator String - Te 400 ms

Figure 7 fits a curve, in a conservative way, to the data of the rate of rise recovery voltage of the dielectric insulation, according to the time of Te after the primary arc interruption for a 7 m insulator string.

It is relevant to mention that this rate is already corrected (discounted effect) of the arc elongation that corresponds to the increase of the strength due to the air temperature drop around the arc and to the consequent deionization. For 400 ms the conservative limit is of 27 kV/ms.

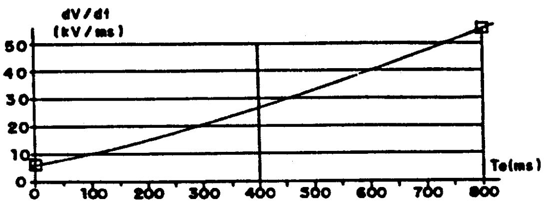

Figure 7 - Dielectric Extinction Curve for a 7m Insulator String Te 400 ms

4. Numerical Aspects

In the analysis of this 1000 kV system the interest is on the secondary arc current with few Amperes, and its distortion caused by saturations.

The comparisons obtained with the results with less sophisticated models (concentrated parameters in transmission lines and linear network); and with more sophisticated models performed during all tests showed the need of working with these more detailed models so that the whole phenomena can be accurately represented.

These comparisons contributed to a better checking against the used models, as well as to obtain more sensibility on the systems particularities.
The detail of the simulation lead to a work involving a great number of elements, many of them non linear type.

The system reactors were represented by type 98 elements and the transformers also considered the saturation.

The non-linear reactors were connected to the neutral reactors considered linear in a total of 30 non-linear elements.

In the arc analysis and voltage at the neutral reactors some numerical errors were observed , difficult to control with parallel resistances , and in some cases contributing to instabilities in arc currents.

5. Conclusions

The grounding switches are not a solution for the secondary arc current reduction, considering long lines with low voltage control.

The results showed that the neutral reactor is efficient to control the secondary arc current fundamental component and the neutral reactor insertion, only at the faulty section, showed an interesting option to this system characteristics.

The transformers saturation caused a harmonic distortion in the current, increasing the rate of rise of currents and voltages.

A solution for this problem would be the increase of the transformer kneepoint, however, it can not be concluded this way yet due to the various favourable points for a well succeeded extinction that occur in the transient period. The definition of the auto-transformers or the use of other equipments which have been studied premilinarly such as filters, and switches at the neutral reactors or the subdivision of the reactive power will be evaluated in coming studies.

This paper proposed a synthesis of the experimental results of the electric arc extinction with an analysis of the current and voltage rate of rise (dv/dt and di/dt) obtained from EHV line tests considering both, the dielectric and the thermal aspects. These curves are the first analysis reference that should be confirmed through specific tests in the future.

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