Behavior of the Single-Phase Auto-Reclosing in Half-Wavelength Transmission Line

O. Dias, M. C. Tavares

***Abstract*— In this paper the main results of single-phase auto-reclosing (SPAR) switching in half-wavelength transmission lines are presented. Naturally very high secondary arc magnitude prevents the use of such maneuver in this very long AC line. However, with the mitigation technique proposed in the present document, this issue is eventually solved.**

Petersen coils can reduce secondary arc current to very low levels, allowing SPAR application to half-wavelength lines. The studies were implemented in a real time digital simulator.

***Keywords*: Half-wavelength transmission line, protection system, secondary arc, single-phase auto-reclosing.**

I. Introduction

IN countries with continental extensions, such as Brazil, China and Russia, there is a great need to transmit large blocks of energy through distances ranging from 2000 to 3000 km [1]. This happens due to the long distance between major generation substations and load centers. Recently also global interconnection is considered to take full profit of available power supply in different regions of the world. The solution often used to bulk transmission in such distances is the High Voltage Direct Current (HVDC), since conventional alternated current (AC) lines would require a large amount of series and shunt compensation to maintain the voltage level and the stability acceptable, besides several intermediate substations.

An alternative to transmit such energy would be through AC half-wavelength transmission lines (HWL), what for a 60 Hz fundamental frequency corresponds to a line of approximately 2500 km. Such lines show a behavior similar to that of a short line in stability view point. As in short lines, it is not necessary to use shunt reactors to compensate for the Ferranti effect, eliminating the need for intermediate substation. As a result, HWL transmission is an AC point-to-point transmission system [1-6].

Although this new type of transmission system does not exist in the world, it has been extensively studied in the last decades. There are several documents related to traditional switching's, such as: line energization [6-8], HWL in high-frequency [9], conventional protection tests [10-11], solution for: distance protection [12], faulted phase selector [13], fault location [14-15], and single-phase auto-reclosing (SPAR) [16, 17 and 18], among others.

In the specific case of SPAR, the HWL shows a very different behavior when compared to conventional lines. Some studies [16, 17 and 18] show that the secondary arc current (SAC) for HWL has extremely high value, demanding new mitigation methods to promote arc extinction and, thereafter, a successful reclosing.

In this work, we first present the SAC behavior and the main quantities related to SPAR in HWL. Then, we introduce a novel mitigation technique that properly reduces SAC, allowing safe SPAR implementation for such lines. The proposed method to minimize SAC inserts a Petersen Coil in each transformer neutral at transmission line terminals. The SAC declines to values below 80 A, which would provoke fault extinction within traditional dead-time. The simulations were implemented in RTDS.

II. Basic Concepts of Single-Phase Reclosing

Most faults in electrical power systems occurs in transmission lines, and the line-to-ground (LG) fault is the most frequent among them. In Brazil, almost 80% of faults on 500 kV transmission lines are LG and transient [19], caused mostly by lightning. In this case, the protection system should act and quickly remove the fault to maintain system stability, isolating the faulty section from the rest of the system, and restoring the power supply as quickly as possible.

The use of single-phase switching is the most suitable in these cases, since during the procedure the remaining phases continue to transmit energy, allowing a flow of around 54% of the total power for single circuit line, and up to 75% for double circuit lines [20]. It is also possible to improve the stability and reliability of the system and reduce torsional impacts on turbo-generator rotors with this maneuver [21], since the system is still interconnected during the fault, in spite of operating in an unbalanced condition.

The single-phase opening and reclosing switching is made by opening only the faulty phase. To complete the maneuver, after the dead time, it is performed the reclosing of the phase that was disconnected.

When a LG fault occurs, the short-circuit current is called primary arc current. This current exists since the arc formation until the moment the faulty phase circuit-breaker (CB) poles open. The primary arc current has a high value, in order of dozens of kA.

After circuit-breaker opening at both ends, the arc continues existing for a certain period, and it is named secondary arc. This arc is maintained through the capacitive and inductive coupling

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of other healthy phases, and the current value, now called secondary arc current (SAC), is reduced to dozens of amperes in conventional lines.

The success of this switching depends mainly on the secondary arc extinction. The probability of the arc extinction is directly related with the arc current magnitude, among other factors. The smaller the SAC the more quickly the arc will self-extinguish, reestablishing faster the normal conditions of the TL operation and the reliability of the electric system.

III. Single-Pole Reclosing in Half-Wavelength Lines

To analyze SAC and transient recovery voltage (TRV) at fault location an electrical system was defined to perform the SPAR tests in a half-wavelength line. The electrical system consists of a 15 kV generator, a step-up transformer 15/800 kV Δ/Y, a transmission line with a length of 2600 km, and an equivalent remote system. The TRV is the sustained voltage at fault location after fault removal. Fig. 1 shows the test system single-line diagram.

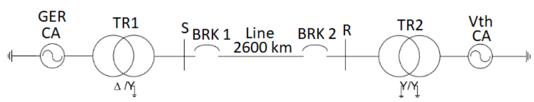

Fig. 1. Single-line diagram of the system studied.

Table I shows the main parameters of the generator. Table II, on the other hand, shows the data of the transformers, Table III shows the transmission line parameters, and Table IV shows the data of the system's equivalent source.

With Table III data, surge impedance (Z_c), nominal current (I_c), and the surge impedance loading (SIL) were calculated with the equations (1), (2), and (3).

$$Z_c = \sqrt{\frac{Z_{l1}}{Y_{l1}}} = 160.0\ \Omega \tag{1}$$

$$I_c = \frac{P_c}{V_n\sqrt{3}} = 2886.75\ \text{A} \tag{2}$$

$$\text{SIL} = \frac{V_n^2}{Z_c} = 4000\ \text{MW} \tag{3}$$

This HWL line has high transmission capacity and competitive right of way. The tower design is optimized to achieve a high SIL by modifying the bundle geometry compared with traditional lines [22].

The values of the equivalent source (Table IV) were defined using equation (4).

$$X_{1vth} = \frac{V_l}{\sqrt{3}I_{3\phi}} \tag{4}$$

Where:

X_{1vth} - Positive sequence reactance of the equivalent source;
V_l - Line voltage of the equivalent source;
$I_{3\phi}$ - Current of maximum and minimum three-phase short-circuit of the equivalent source.

The remaining values of Table 4 were found using the following relations:

$$\frac{X_{1vth}}{R_{1vth}} = 6; \quad \frac{X_{1vth}}{X_{0vth}} = 0.2; \quad \frac{X_{0vth}}{R_{0vth}} = 5.$$

We used as Strong source at 500 kV system, $I_{3\phi}$ = 40 kA, and Weak source, $I_{3\phi}$ = 10 kA. Those are actual Brazilian data.

TABLE I
GENERATOR PARAMETERS, 2600 KM.

Equipment	Power (MVA)	Voltage (kV)	Sub-transient reactance (Ω)	Resistance (Ω)
Generator 1 SIL	4252.5	16.75∠ 177.82°	0.014389	0.00041
Generator 0.1 SIL		14.07∠ 154.76°		

TABLE II
TRANSFORMERS DATA, 2600 KM.

Equipment	Power (MVA)	Voltage (kV)	Leakage reactance (p.u.)	Quality Factor
Transformer TR1 (Δ/Y)	4252.5	15/800	0.071	40
Transformer TR2 (Y/Y)		800/500		

TABLE III
LINE PARAMETERS, 2600 KM.

Sequence	R (Ω/km)	X (Ω/km)	Y (μS/km)
Positive/negative	0.00695	0.20711	7.87732
Zero	0.38281	1.42784	3.45458

TABLE IV
DATA OF EQUIVALENT SOURCE, 2600 KM.

Power	Vth	Voltage (kV)	R_{1th} (Ω)	X_{1th} (Ω)	R_{0th} (Ω)	X_{0th} (Ω)
1 SIL	Weak	600∠ 70°	7.70	46.19	46.19	230.94
0.1 SIL		500∠ 205°				
1 SIL	Strong	570∠ 100°	1.92	11.54	11.54	57.73
0.1 SIL		500∠ 205°				

The simulations were conducted for two extreme system conditions: full loading (transmitting SIL) and the light loading (10% of SIL), to verify the difference between the values of secondary arc current and TRV. Faults were applied in the following points: 1% 5%, 25%, 50%, 75%, and 98%. The fault inception angle was 90° (of voltage waveform), resulting in no DC current, and the fault resistance was 1 Ω. The simulation consisted in fault application in the indicated points, followed by faulted phase tripping at both terminals.

The loading condition was adjusted varying the equivalent source as shown in Table IV. Overall, four tests were performed: loading of 1.0 and 0.1 SIL with weak equivalent source, loading of 1.0 and 0.1 SIL with strong equivalent source.

Most values were measured during secondary arc fault, and TRV was measured after fault extinction with the phase A still open. The measured quantities are the following: secondary arc current (SAC), transient recovery voltage (TRV), transformer neutral current in the S bar (InS), transformer neutral voltage in the S bar (VnS), transformer neutral current in the R bar (InR) and transformer neutral voltage in the R bar (VnR). Fig. 2 shows measuring points for all cases examined.

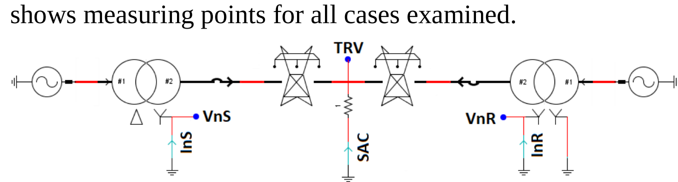

Fig. 2. Measuring points.

A. Half-wavelength line (2600 km) performance during SPAR

Fig. 3 shows SAC values, transformers´ neutral current, TRV for the defined points.

According to the presented results, it is clear that SAC in HWL shows a very peculiar behavior compared with conventional line. SAC values for faults in the middle of the line are close to that of the primary arc current and change with load profile. This change is associated with the electrostatic feeding as there is a huge voltage variation with line loading at HWL center region. Sound phase voltages reduce for light loading, while stay near 1.0 pu for 1.0 SIL. On the other hand, the line current does not change with loading level, indicating a strong electromagnetic feeding for the arc in this region (roughly the base 500 A in central region can be identified as electromagnetically provided). The last is not present in the central of conventional long lines, but appears along these extremely long AC lines.

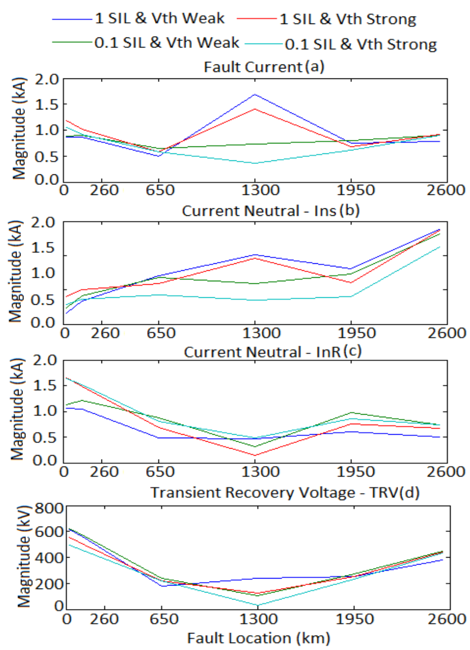

Fig. 3. Values of secondary arc current, currents at transformers neutrals and TRV at both terminals S and R.

The electromagnetic feeding is not present outside the HWL central region. Near terminals the mains source is due to capacitive effect, as sound phases voltages are almost constant at HWL terminals whilst phase currents change drastically.

Due to large SAC value, it is clear that HWL needs some specific mitigation technique to enable SPAR. HWL does not have any shunt compensation bank, so it is not possible to use traditional neutral reactor to minimize SAC. Besides this could be effective to reduce SAC near terminals, but not in the central region.

Grounding switches could also be considered as a solution, but a large number of switches would be necessary, compromising the point-to-point nature of HWL. In this case several devices would be installed along the line, what is not an adequate solution.

Thus, another way of minimizing the arc current shall be postulated for applications in HWL.

B. Solution for SPAR in half-wavelength line

A technique widely used in distribution and subtransmission network [23-27] to minimize the fault current is the insertion of a reactor, known as Petersen coil (PC) [28], with the objective of compensating the phase-to-ground system capacitance. The connection of this reactor is usually done at the low side neutral of the power transformer.

Fig. 4 shows the Petersen coil neutral connection of the step-up transformer Δ/Y. The calculation of the reactor's value can be done through the equation (5) [29].

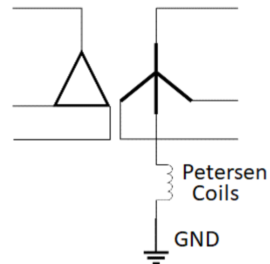

Fig. 4. Connection of the Petersen coil at the transformer neutral.

$$X_{GFN} = \frac{\frac{E}{\sqrt{3}}}{I_N} \quad (5)$$

Where: X_{GFN} = Neutral reactance;

E = line voltage magnitude, 800 kV;

I_N = Neutral current in kA.

To minimize SAC in HWL the Petersen coil will be used in the neutral of the transformers [18]. It is specified to obtain a neutral current around 80 A. The reactance is X_{GFN} = 5773.5 Ω. As the value is very high, we proposed to use a transformer to reduce it. A single-phase transformer of 345/69 kV was used. In the secondary side a 230.94 Ω reactor was inserted, with a quality factor of 40.

A neutral circuit-breaker (NB) and the Petersen coil was installed in both transformers' neutrals (S and R buses), as shown in Figure 5.

The coil only will be inserted in the transformer's neutral after faulty phase opens, which is made through the following steps:

(1) Pre-fault system: the NBs are in closed position and the transformers are solidly grounded.

(2) Primary fault system: the NBs remain closed, the protection operates by opening the phase A circuit-breakers' poles.

(3) Secondary fault system: three cycles (50 ms) after opening the faulty phase, NBs open, changing the transformers grounding to grounded by Petersen coil.

(4) Dead time exceeded: the reclosing of the open phase is performed. Six cycles (100 ms) after of the reclosing, NBs close. The neutral return to solidly grounded.

In the simulated case, Petersen coils are installed in both S and R bars, but only in the high voltage side (800 kV). The low side neutral (500 kV) is grounded.

The NB tripping is activated by the same line protection relay. The difference is in the operation time (3 cycles or 50 ms) which has the purpose of preventing a NB tripping during the transient of the secondary fault. This operation time is not a strict value and should be dimensioned with pre-operational studies.

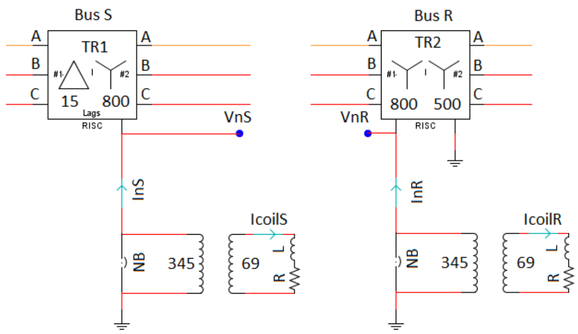

Fig. 5. Petersen coil in the low-voltage transformer side.

Figs. 6 and 7 show SAC, current neutral, TRV, and voltage neutral for the defined points, respectively.

In this case, we observe that the neutral current of transformers S and R (InS and InR, Figure 6) reduced as desired. The decay of these two currents led to the low SAC value, below 80 A as designed.

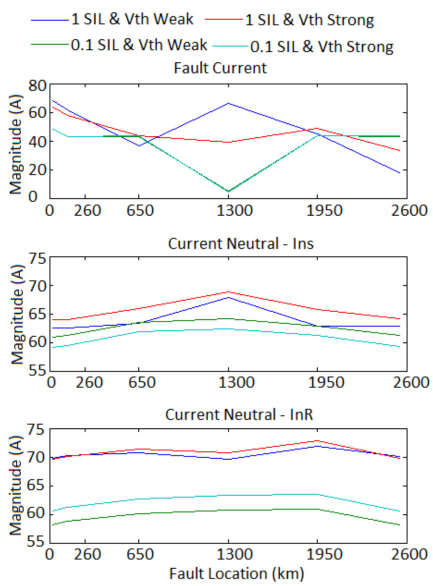

Fig. 6. Values of current of secondary arc and of neutral in transformers of the S and R bars – HWL case with the solution proposed.

The use of the Petersen coils at both TL ends allows secondary arc extinction. The magnetically coupled current was canceled in central region, and capacitive coupling was controlled as desired.

High neutral voltage values (VnS and VnR, Figure 7) appear with the insertion of the reactors. The transformers neutral voltages reached 250 kV (sustained value). The voltage in the Petersen Coil is the same as that of the neutral voltage, considering the transformation ratio. As a result, there will be a need to isolate the neutral of the transformers for these overvoltages. As the transformers will not be solidly grounded only during SPAR (for a period lower than dead time), we did not anticipate any impact associated with temporary overvoltage during unbalanced operations.

To conclude this study, a test is presented with all SPAR stages: primary fault, secondary fault, post-fault and single-phase reclosing. In this test the fault was applied at 1300 km which is the fault point that generates the highest value of the secondary arc current, as presented in Fig. 6. The case is for 1 SIL and Vth Weak. The fault duration is 500 ms and the single-phase reclosing is performed after a dead time of 700 ms. We adopted 700 ms because this value is normally used in conventional lines (in the range of 500 ms to 1 s) in Brazil.

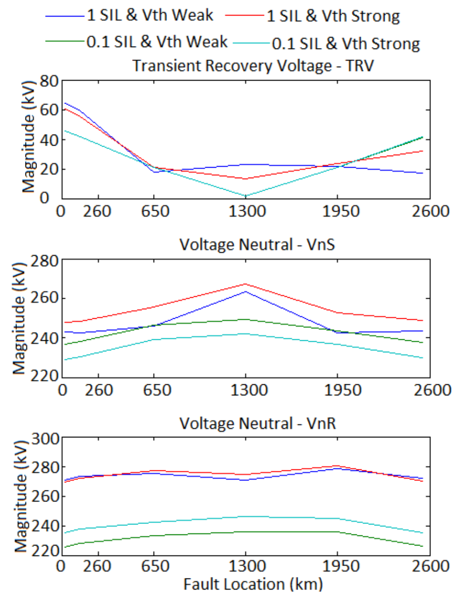

Fig. 7. Values of voltage of secondary arc and of neutral in transformers of the S and R bars – HWL case with the solution proposed.

In Fig. 8 the fault current, currents neutral and the currents in PCs are shown, and the transient recovery voltage, voltages neutral and the voltages in the PCs are shown in Fig. 9.

The fault analysis can be divided in three stages, as shown at Fig 8a: Primary Fault (1), Secondary (2) and Post-Fault (3). The former (1) is the primary fault, with primary arc current in the range of kA. Protection identifies the fault and trips the faulted phase after 100 ms.

The secondary arc waveform is presented in Fig 8b, and with Petersen Coil, the SAC reduction is obtained as specified, 80 A. Stage 3 consisted in fault extinction, which occurred after 400 ms of opening of phase A, Fig. 8b.

While transformers' neutrals are solidly grounded, the neutral currents present values similar to SAC (Fig. 8c). With the insertion of PC in both transformers, SAC values decrease as desired (Fig. 8d). After arc extinction, current due to unbalanced operation will flow through PCs. When faulty phase is reclosed, current through PC will smoothly decay.

The TRV presented a value below of 30 kV, Fig. 9a. Considering the neutral voltages (Fig. 9b), while transformers neutrals are solidly grounded, both voltages are zero. When the transformer neutral becomes grounded by PC, neutral voltage will rise to 254 kV sustained value. During transient the maximum voltage is 600 kV-peak. Transformer neutral should be insulated for these voltage levels. The voltages in PCs are the same as neutrals' voltages, respecting the transformation ratio, Fig. 9c. These voltages are originated by unbalanced sound phases and will disappear when open phase is reclosed.

Figure 10 shows the voltages at both line terminals. It can be verified that in the beginning of the secondary fault, without PC, the healthy phases present overvoltages in both

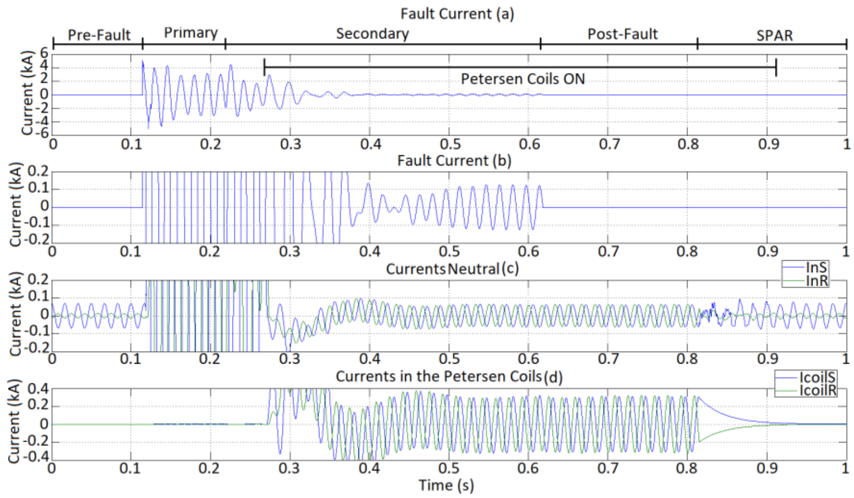

Fig. 8. Fault current, currents neutral and currents in the Petersen Coils for the fault at the phase A in 1300 km of HWL.

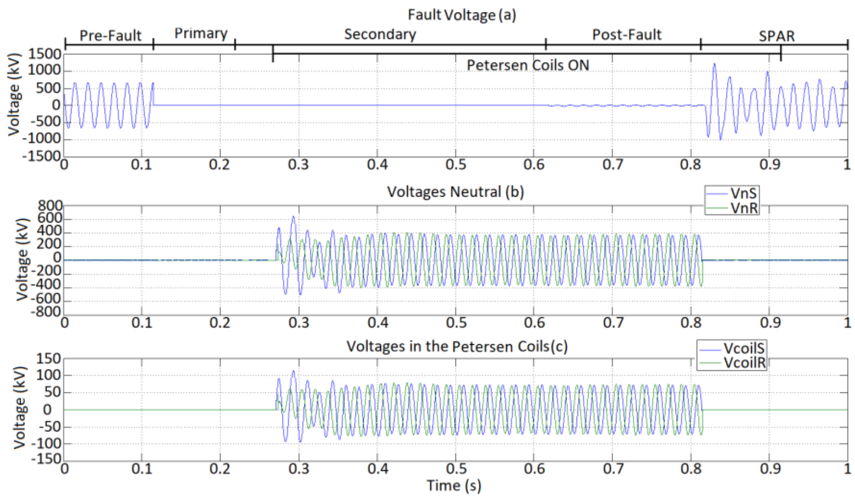

Fig. 9. Fault voltage, voltages neutral and voltages in the Petersen Coils for the fault at the phase A in 1300 km of HWL

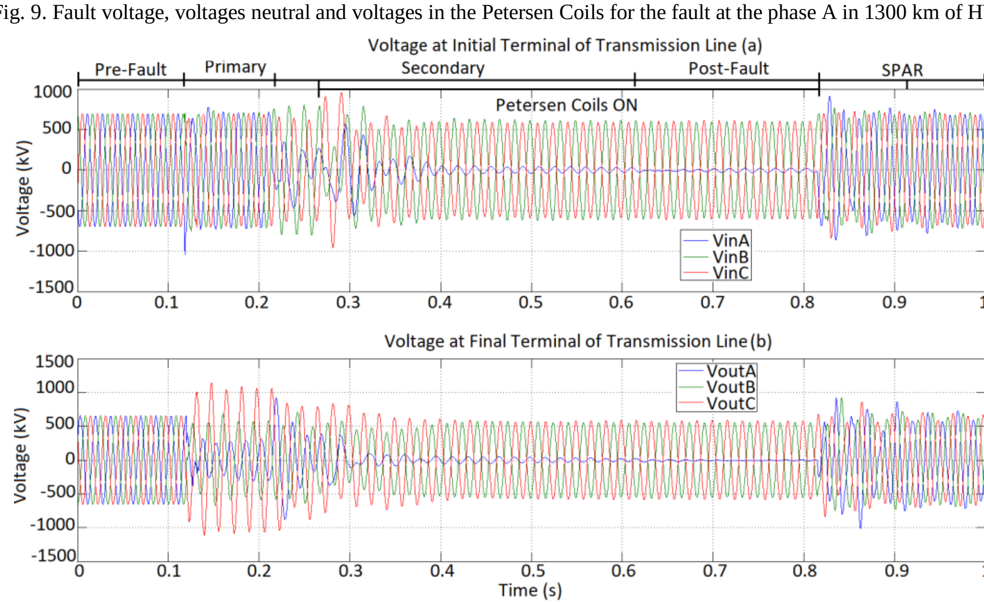

Fig. 10. Voltages (A, B and C) at both line terminals for the fault at the phase A in 1300 km of HWL.

line terminals. With the change for grounded by Petersen Coil, the overvoltages in the healthy phases are removed, improving the system response.

In this figure it is also possible to verify the successful SPAR implementation after the dead time of less than 1 s, and that system returns to normal operation smoothly.

As the transformer will be grounded by Petersen Coil for just some small period of time (less than 1 s), no important impact associated to temporary overvoltage during unbalanced operations is expected. However ongoing research with further results will be presented soon.

IV. Conclusions

The present document analyses single-phase auto-reclosing (SPAR) switching to eliminate line-to-ground fault in half-wavelength (HWL) transmission lines.

Due to the HWL large length, the coupling between healthy phases and the opened phase has an important electromagnetic parcel besides the regular electrostatic component. The former is important in the central region of the line, and combined with capacitive coupling results in extremely high secondary arc current (SAC), where current magnitude reaches a few kA. In terminal regions electrostatic coupling is dominant and independent of line loading level, as terminal voltage is almost constant whichever the power flow. Therefore lower SAC values are measured for faults near terminals regions, but still higher when compared with regular lines values.

No conventional solution could be applied, as no shunt compensation is used, and, therefore, no neutral reactor could be considered. Due to the large line length, the number of grounding switches that would diminish SAC would be too high and that would imply in having intermediate substations. This solution would compromise the point-to-point nature of HWL alternative.

To circumvent this problem, we used a reactor to ground the transformers at transmission line terminals. After the occurrence of LG fault and the opening of the faulty phase, the transformer grounding was modified to grounded via Petersen Coil. As a result, we verified the decay of secondary arc current to values below 80 A as desired in 250 ms after faulty phase opened.

When the transformer neutral becomes grounded by Petersen Coil, neutral voltage will rise to 254 kV sustained value, with maximum overvoltage of 600 kV. Transformers' neutrals should be insulated for these high overvoltage levels.

We can say that with the insertion of such coil, the values for both secondary arc current and transient recovery voltage indicate secondary arc self-extinction for half-wavelength lines in regular SPAR dead-time.

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