Distance Protection for Half Wavelength Transmission Lines

Renzo G. Fabián E., M. C. Tavares

Abstract—**This work presents a distance protection algorithm to be used mainly in half-wavelength power transmission lines. The performance of distance protection available commercially was tested to half-wavelength lines (HWL). The study was conducted in RTDS and two basic problems were identified. First, the fault type selector cannot correctly identify the phases in fault in the entire line. Furthermore, the calculated apparent impedances do not have linear behavior with direct correspondence with the fault distance in order to define protection zones. The distance protection algorithm presented in this paper includes a phase selector and the appropriated computation of apparent impedances for HWLs. This new distance protection can also be applied to conventional shunt compensated long lines, above 600 km length.**

Keywords—**AC link, Half-wavelength lines (HWL), Protection relay, Phase selector, Apparent impedances, Distance Protection.**

I. INTRODUCTION

THE study of transmission of large blocks of power over long distances is very important in countries with continental dimensions. Brazil has great energy potential in the north region in the Amazon rainforest, which also encompasses neighboring countries, while large consumer centers are in the southeastern region of Brazil.

Nowadays, these huge bulk power systems are made by high-voltage direct current transmission lines (HVDC), but an alternating current (AC link) option with some particular characteristics might be the most economical one, having much less dependence on the Power Electronics technology. In the 1960s [1]-[2], the first studies were done showing that the AC line has an interesting behavior in terms of voltage, current and stability of the system when it has electrical length equal to a little higher than a half the length of the electromagnetic wave, 2600 km for 60 Hz. These lines are called half-wavelength power transmission lines, so for convenience, the term half-wavelength line (HWL) will be used. Nowadays new researches have been studying this alternative, as [3], [4], [5] and [6].

There are no HWLs in the world yet and there are many challenges ahead for constructing these links, such as relay protection studies, since the conventional philosophy of TLs protection, i.e. the distance traditional function, is not adequate to protect the HWLs. Some studies were conducted to adjust commercial relays to protect HWLs, but several protection functions acting together were required to properly protect the whole line without load and there was still a central region without protection when three-phase faults were analyzed [7], [8].

In the phase selector and the apparent impedances computation, two main components of traditional distance protection, critical problems were observed. The phase selector does not identify correctly the involved phases in faults after 600 km and the apparent impedances have non-linear behavior for faults along the line, so it is not possible to use distance protection zones (MHO or quadrilateral).

This paper proposes solutions for these problems: a new distance protection called distance protection for HWLs. This protection can also be used in very long transmission lines (i. e. 600 km) where the traditional distance protection have the same problems.

The analysis of the protection algorithms were conducted using a steady state method where it is possible to represent a transmission system and all shunt faults occurrence in order to obtain phasors of voltage and currents for each phase in the terminals.

II. PERFORMANCE OF TRADITIONAL DISTANCE PROTECTION FOR HWLS

In this section, the performance of traditional distance protection for faults in HWLs will be analyzed. Algorithms implemented in existent protection relays, phase selector and apparent impedance computation, will be studied using a steady state method.

A. Phase selector

The phase selector stage is very important in distance protection because when a short circuit occurs the correct fault loop must be selected to measure the fault distance (that is proportional to the apparent impedance). If the correct fault loop is not identified, the protection zones do not work properly.

All short-circuit types and their corresponding fault loops, based on [9], are presented in Table I.

Many traditional relays have a selector phase algorithm based on the difference of angles of the symmetrical components of currents, [10], [11], [12].

The method detailed in [10] shows a Fault Identification Selection (FIDS) logic that uses measured negative (IA2)

This work was financially supported by CNPq, CAPES and FAPESP in Brazil.

R. G. Fabián E. is with School of Electrical and Computing Engineering, University of Campinas, Av. Albert Einstein 400, Campinas-SP, Brazil, zip code 13083-852 (e-mail: elrrenzo@dsce.fee.unicamp.br).

M. C. Tavares is with the University of Campinas, Brazil (e-mail: cristina@dsce.fee.unicamp.br).

Paper submitted to the International Conference on Power Systems Transients (IPST2015) in Cavtat, Croatia June 15-18, 2015.

TABLE I
SHORT-CIRCUIT TYPES AND FAULT LOOPS FOR THE DISTANCE MEASUREMENT

Fault type	Phases involved	Fault loops for the distance measurement
Two-phase without earth	A-B B-C C-A	A-B B-C C-A
Three-phase without earth	A-B-C	A-B or B-C or C-A
Single-phase	A-G B-G C-G	A-G B-G C-G
Two-phase with earth	A-B-G B-C-G C-A-G	A-G or B-G or A-B B-G or C-G or B-C C-G or A-G or C-A
Three-phase with earth	A-B-C-G	A-B or B-C or C-A A-G or B-G or C-G

TABLE II
FIDS LOGIC IN MODERN DESIGN

Angle Between IA2 and IA0	Fault type Permission
IA2 is $\pm$ 30 degrees of IA0	AG or BC
IA2 lags IA0 by 90 to 150 degrees	BG or CA
IA2 leads IA0 by 90 to 150 degrees	CG or AB

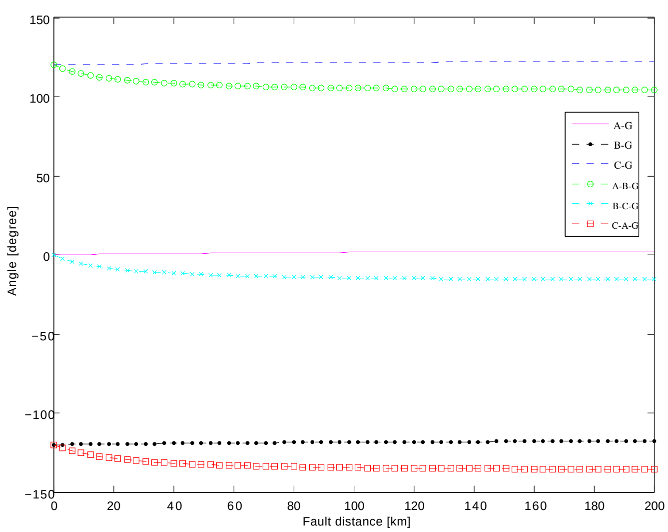

Fig. 1. Angles difference between IA2 and IA0 for a 200 km line for different faults.

and zero-sequence (IA0) currents to determine the fault loop according to Table II.

The angles difference between IA2 and IA0 for faults along the line a 200 km line are shown in Figure 1.

It is possible to observe that FIDS logic summarized in Table II properly classifies the faults. Therefore, this method identifies the correct fault loop for this transmission line.

Figure 2 presents the angles difference between IA2 and IA0 for faults along the a line of 2600 km long using the same electrical parameters.

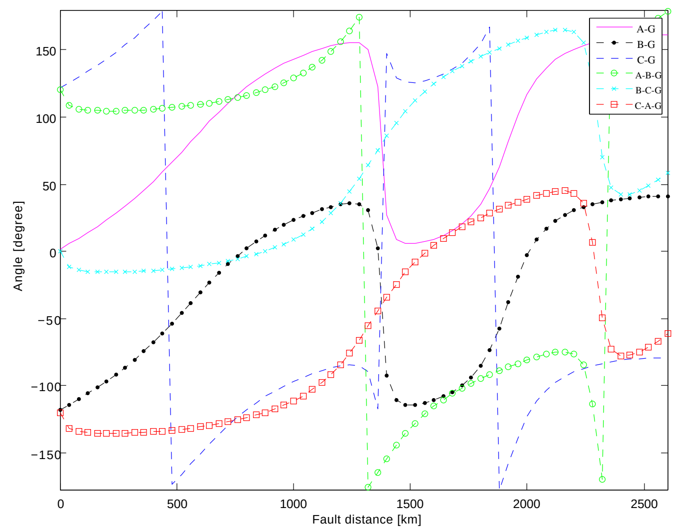

Fig. 2. Angles difference between IA2 and IA0 for a 2600 km HWL for different faults.

It is possible to observe that FIDS logic cannot be applied. The angle differences are not in a characteristic region. Therefore, this method does not identify the correct fault loop for HWLs.

B. Computation of Apparent Impedances

Traditional computation of apparent impedances uses the following formulation in order to obtain the phase-ground impedances: Z_A, Z_B and Z_C; and the phase-phase impedances: Z_{AB}, Z_{BC} and Z_{CA} [9].

$$Z_{Ph-Ph} = \frac{V_{Ph-Ph}}{I_{Ph-Ph}} = \frac{V_{Ph1-G} - V_{Ph2-G}}{I_{Ph1} - I_{Ph2}} \tag{1}$$

$$Z_{Ph-G} = \frac{V_{Ph-G}}{I_{Ph} - k_E I_E} \tag{2}$$

In order to compute properly the phase-ground impedances is necessary to know the residual compensation factor k_E , which can be found by means of Eq. (3).

$$k_E = \frac{Z_{L0} - Z_{L1}}{3Z_{L1}} \tag{3}$$

where Z_{L0} is zero sequence line impedance per unit length and Z_{L1} is positive sequence line impedance per unit length. I_E is the ground-current, defined by means of Eq. (4).

$$I_E = -(I_A + I_B + I_C) \tag{4}$$

Figure 3 presents the apparent impedances computed for A-B faults along a transmission line of 200 km of length. It is possible to see that the impedances Z_{AB} have a linear behavior, allowing the use of protection zones (MHO or quadrilateral) to cover this fault type.

Figure 4 presents the apparent impedances for a 2600 km line with the same electrical parameters. It can be seen that it

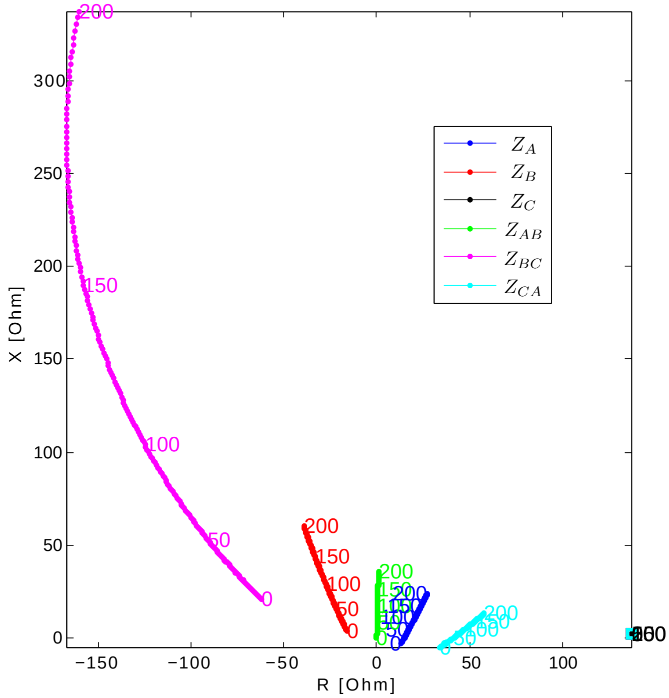

Fig. 3. Apparent Impedances for A-B fault for a 200 km transmission line.

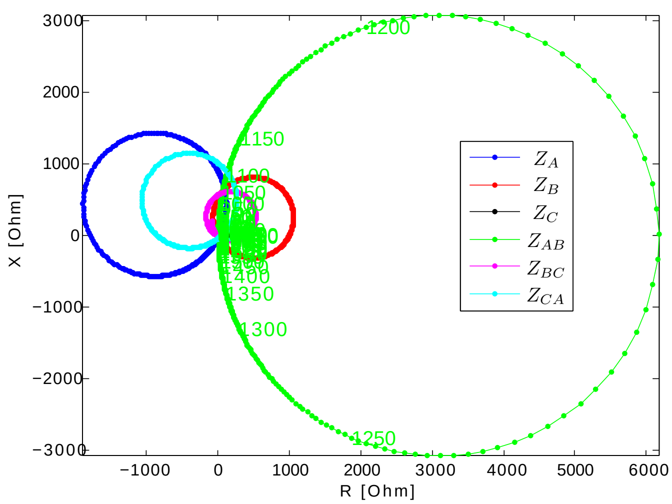

Fig. 4. Apparent Impedances for A-B fault for a 2600 km HWL.

is not possible to use protection zones (MHO or quadrilateral) because the impedances Z_{AB} do not have a linear behavior.

It can be concluded that the traditional computation of apparent impedances does not have proportional correspondence with the fault distance in HWLs.

III. Distance Protection Algorithm Proposed for HWLs

In this section, the solutions for the traditional phase selector and computation of apparent impedances are presented in order to be used in distance protection for HWLs.

A. Phase selector

A method based in incremental quantities was studied in [13]. It requires the pre-fault and post-fault voltages and

TABLE III
Relation between ΔT parameters

Fault type	ΔT_{AB}	ΔT_{BC}	ΔT_{CA}
A-G	ΔT_{AB}	0	ΔT_{AB}
B-G	ΔT_{AB}	ΔT_{AB}	0
C-G	0	ΔT_{AB}	ΔT_{AB}
A-B or A-B-G	ΔT_{AB}	0.25 ΔT_{AB}	0.25 ΔT_{AB}
B-C or B-C-G	0.25 ΔT_{AB}	ΔT_{AB}	0.25 ΔT_{AB}
C-A or C-A-G	0.25 ΔT_{AB}	0.25 ΔT_{AB}	ΔT_{AB}
A-B-C	ΔT_{AB}	ΔT_{AB}	ΔT_{AB}

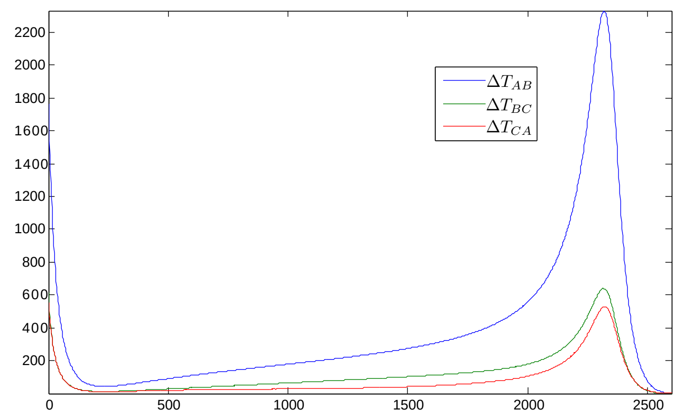

Fig. 5. Parameters ΔT for A-B-G faults along the HWL.

currents, and it uses the following formulation in order to calculate the parameters ΔT_{AB}, ΔT_{BC} and ΔT_{CA}.

$$\Delta T_{AB} = Re\{\Delta V_{AB}\}Re\{-\Delta I_{AB}\} + Im\{\Delta V_{AB}\}Im\{-\Delta I_{AB}\} \tag{5}$$

$$\Delta T_{BC} = Re\{\Delta V_{BC}\}Re\{-\Delta I_{BC}\} + Im\{\Delta V_{BC}\}Im\{-\Delta I_{BC}\} \tag{6}$$

$$\Delta T_{CA} = Re\{\Delta V_{CA}\}Re\{-\Delta I_{CA}\} + Im\{\Delta V_{CA}\}Im\{-\Delta I_{CA}\} \tag{7}$$

Where:

$$\Delta V_{\phi\phi} = V_{\phi\phi}^{fault} - V_{\phi\phi}^{pre-fault}$$

and

$$\Delta I_{\phi\phi} = I_{\phi\phi}^{fault} - I_{\phi\phi}^{pre-fault}$$

Using the criterion described in Table III it is possible to identify the fault type in the long transmission line. This method was proposed for traditional distance protection for conventional transmission lines, but not for HWLs. However, this criterion can be used in HWLs, as shown in Fig. 5, where A-B-G faults were applied along the 2600 km line. It is possible to see that the parameters have a defined characteristic according to Table III for faults in the entire line length.

B. Computation of Apparent Impedances

A correction method for apparent impedances computation for 600 km transmission line was studied in [14]. Based on some formulations studied in this paper and using some artifices it is possible to obtain apparent impedances proportional to the fault distance.

1) Deducing apparent impedances for low frequency system: The equations (8) and (9) describe the voltage and current phase-phase A-B of the transmission system where 1 is the sending terminal and 2 is the receiving terminal, where all formulation only depends on the positive sequence parameters.

$$V_{AB}^{S} = V_{AB}^{R} cosh(\gamma l) + Z_c I_{AB}^{R} sinh(\gamma l) \tag{8}$$

$$I_{AB}^{S} = I_{AB}^{R} cosh(\gamma l) + \frac{V_{AB}^{R}}{Z_c} sinh(\gamma l) \tag{9}$$

If an A-B fault occurs in receiving terminal R, $VR_{AB} = 0$. Then:

$$Z_{AB}^{S} = \frac{V_{AB}^{S}}{I_{AB}^{S}} = Z_c tanh(\gamma l) \tag{10}$$

From Eq. (10), it is possible to isolate l, that in this paper will be called *apparent distance*.

$$l_{calc} = atanh\left(\frac{Z_{AB}^{S}}{Z_c}\right)/\gamma \tag{11}$$

Apparent impedances calculated with traditional formulation have non-linear behavior due to $tanh(\gamma l)$. The argument γl of $tanh$ function produces the non-linearity in HWLs because the magnitudes l and γ were calculated for 60 Hz. If the electrical frequency were low, the apparent impedances would present linear behavior, because the wavelength would be higher than the 60 Hz case. With this criterion it is possible to use the pre-calculated propagation constant for a low frequency system, i.e. 4 Hz, γ^{4Hz} and together with the *apparent distance* obtained with Eq. (11) it is possible to deduce the apparent impedance for 4 Hz using the following formula.

$$Z_{AB}^{4Hz} = Z_c^{4Hz} tanh(\gamma^{4Hz} l_{calc}) \tag{12}$$

This method can be extended for faults B-C and C-A, and with a more rigorous analysis, to A-G, B-G and C-G.

This formulation allows to obtain apparent impedances for faults along the HWL proportional to the fault distance, which is necessary to use the principle of distance protection.

Figure 6 presents the low frequency apparent impedances obtained from impedances of Fig. 4. It is possible to see that Z_{AB}^{4Hz} impedances have a linear behavior, since the fault was $A-B$.

2) Correcting apparent impedances discontinuity: There is still a problem: the Z_{AB}^{4Hz} impedances of Fig. 6 have a discontinuity for faults near the middle of the line. The impedances start in the origin, then they increase up to their maximum value, they drop to their minimum value (negative impedance) instead of continuing to increase up maintaining their proportionality with the fault distance. Finally, they

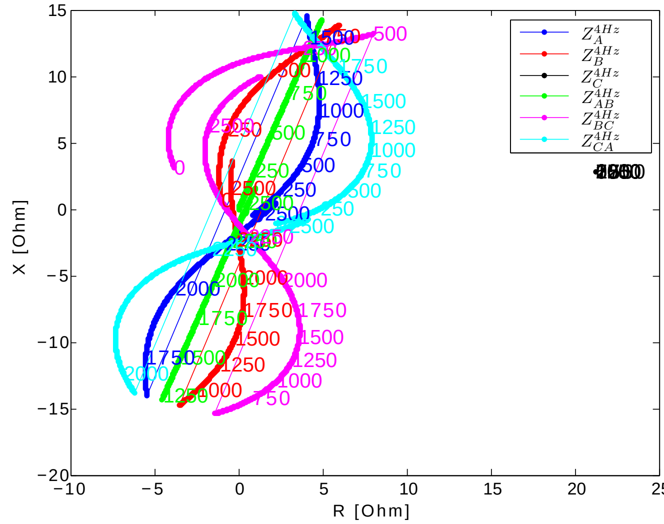

Fig. 6. Linearized Apparent Impedances for A-B fault.

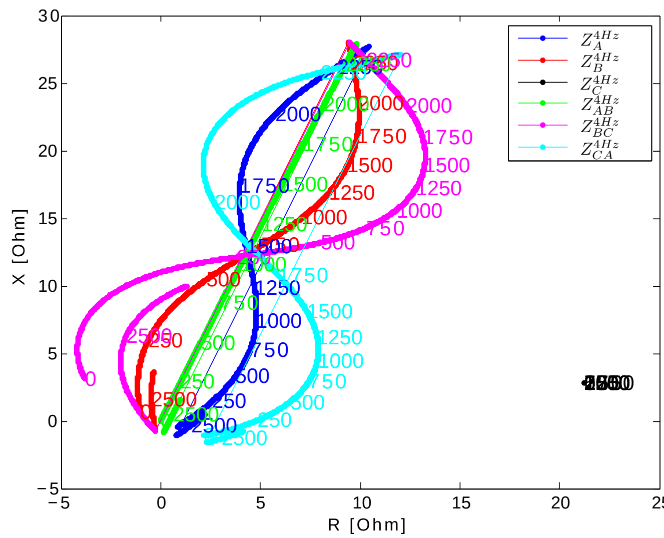

Fig. 7. Discontinuity corrected for apparent impedances for A-B fault.

continue to increase. To understand this discontinuity, the analysis of $atanh(z)$ complex function is necessary, as analyzed in (13)-(15).

$$atanh(z) = log[(1+z)/(1-z)]/2 \tag{13}$$

$$log(z) = Log|z| + iArg(z) + i2\pi k \tag{14}$$

$$k = ... -2, -1, 0, 1, 2, ... \tag{15}$$

Many computer programs use the convention $Arg(z) \in (-\pi;\pi]$, but this generates the discontinuity. If $Arg(z) \in (0;2\pi]$ is used this problem is solved. Additionally, it is possible to choose the appropriate value of k in order to obtain always positive values of *apparent distances*. Figure 7 shows the apparent impedances ready to be used in distance protection.

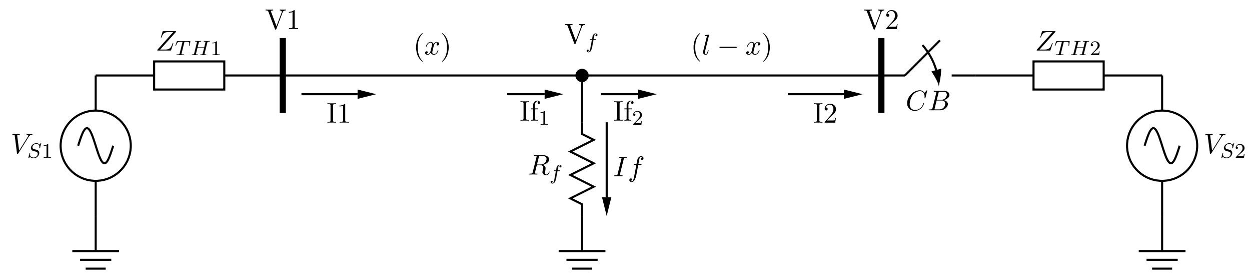

Fig. 8. Transmission system for tests.

IV. Tests and Results

Several tests were conducted using the proposed phase selector and apparent impedance calculation for the 2600 km line with success.

To test the proposed algorithms, an EHV transmission system of 800 kV and 2600 km of length according to Figure 8 was used with the following electrical parameters.

Equivalent impedances:

$$
\begin{aligned}
Z_{Th1}^{+-} &= 0.714 + j26.6457\ \Omega \\
Z_{Th1}^{0} &= Z_{Th1}^{+} \\
Z_{Th2}^{+-} &= Z_{Th1}^{+} \\
Z_{Th2}^{0} &= Z_{Th2}^{0}
\end{aligned}
$$

Distributed parameters of the transmission line:

$$
\begin{aligned}
R^0 &= 0.42123\ \Omega/km \\
X^0 &= 1.1976\ \Omega/km \\
B^0 &= 0.4078 \times 10^{-5}\ S/km \\
R^{+-} &= 0.0048493\ \Omega/km \\
X^{+-} &= 0.17359\ \Omega/km \\
B^{+-} &= 0.9481 \times 10^{-5}\ S/km
\end{aligned}
$$

Phase-ground, phase-phase and phase-phase-ground faults were tested with fault impedance R_f from 0.001 to 20 Ω with the system transmitting the characteristic power and without transmitted power. In this section, two cases will be analyzed with the relay at Bus 1.

A. Case 1: Phase-phase fault over the system transmitting characteristic power

In this case, $R_f = 20\Omega$ was used, the fault imposed was A-B and $S2$, power at Bus 2, was scaled in order to transmit the characteristic power of 4.7 GW.

For this test, the phase selector operated according to Table III and chose the fault loop A-B to operate.

The six apparent impedances are presented in Figure 9 and it is possible to observe that there is a non-linear region due to the fault impedance, but the behavior conserves proportionality with fault distance.

B. Case 2: Phase-phase-ground over the system no-load condition

In this case, $R_f = 10\ \Omega$ was used, the fault imposed was A-B-G and as there is no power transmitted, $S2 = 0$.

For this case, the phase selector operated according Table III and chose the fault loop A-B to operate.

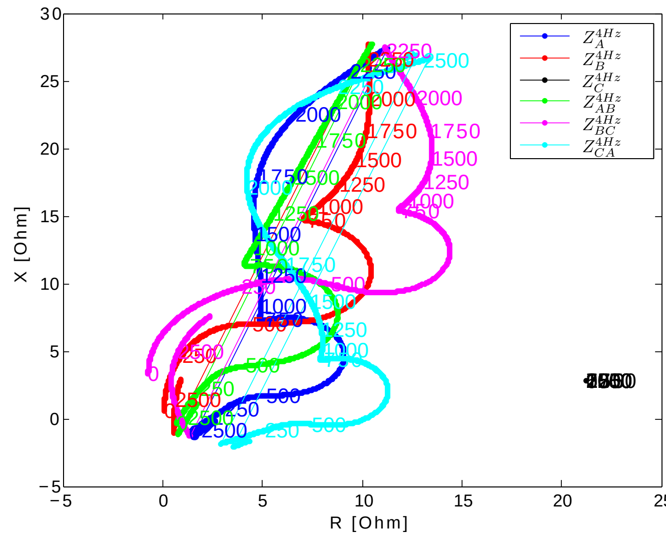

Fig. 9. Apparent impedances for A-B fault in a HWL. $R_f = 20\ \Omega$.

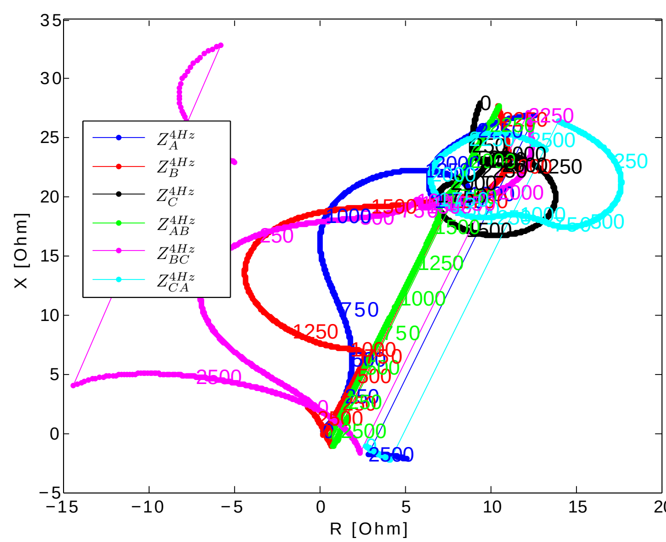

Fig. 10. Apparent impedances for A-B-G fault for a HWL. $R_f = 10\ \Omega$.

The six apparent impedances are presented in Figure 10 and it is possible to observe that the impedances are linear for faults in the entire line, thus the behavior conserves proportionality with fault distance.

V. Conclusions

The main conclusions of this work are as follows:

- Phase selector and computation of apparent impedances are fundamental processes in distance protection. An incorrect operation of phase selector could cause a false trip in the relay and it is necessary to obtain apparent impedances proportional to the fault distance in order to use protection zones (MHO or quadrilateral).
- The phase selector and computation of apparent impedances algorithms of commercial distance relays do not operate properly for HWLs.
- A phase selector based on incremental quantities was proposed and the faulted phases for HWL were properly identified.
- A new algorithm for computing apparent impedances to be used in the distance protection for HWL was proposed and tested. The impedances behavior is proportional to the fault distances, allowing the use of protection zones.
- Based on two previous items, a new distance protection for HWLs was successfully implemented and tested for a 800 kV HWL under different load levels, including no-load.
- The distance protection for HWLs have not been proposed before and ongoing research is testing the algorithm in RTDS simulator.

VI. References

[1] F. J. Hubert and M. R. Gent, "Half-Wavelength Power Transmission Lines," *IEEE Transactions on Power Apparatus and Systems*, vol. 84, no. 10, pp. 965–974, Oct. 1965.

[2] F. Prabhakara, K. Parthasarathy, and H. Ramachandra Rao, "Performance of Tuned Half-Wave-Length Power Transmission Lines," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-88, no. 12, pp. 1795–1802, Dec. 1969.

[3] G. Samorodov, T. Krasilnikova, V. Dikoy, S. Zilberman, and R. Iatsenko, "Nonconventional reliable ac transmission systems for power delivery at long and very long distance," in *Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. IEEE/PES*, vol. 2, Oct 2002, pp. 982–987 vol.2.

[4] M. C. Tavares and C. M. Portela, "Half-Wave Length Line Energization Case Test ¿ Proposition of a Real Test," in *2008 International Conference on High Voltage Engineering and Application*. IEEE, Nov. 2008, pp. 261–264.

[5] X. X. X. Xiang, L. Q. L. Qi, and X. C. X. Cui, "Electromagnetic transient characteristic of 1000kV half-wavelength AC transmission lines," pp. 4–7, 2010.

[6] L.-t. Wang and X. Cui, "A method for suppressing steady-state operating overvoltages of the half wave-length UHV AC power transmission line," in *2011 7th Asia-Pacific International Conference on Lightning*. IEEE, Nov. 2011, pp. 551–554.

[7] E. Gomes and M. C. Tavares, "Protection scheme for single-phase fault along a half wavelength transmission trunk using conventional relay," in *International Conference on Power System Transients, IPST 2013*, Jul. 2013.

[8] R. Fabian and M. C. Tavares, "Using of conventional relays for protecting half-wavelength transmission line from three-phase faults," in *International Conference on Power System Transients, IPST 2013*, Jul. 2013.

[9] G. Ziegler, *Numerical Distance Protection: Principles and Applications*. John Wiley & Sons, 2008.

[10] D. Costello and K. Zimmerman, "Determining the faulted phase," in *2010 63rd Annual Conference for Protective Relay Engineers*. IEEE, Mar. 2010, pp. 1–20.

[11] T. Adu, "An accurate fault classification technique for power system monitoring devices," *IEEE Transactions on Power Delivery*, vol. 17, no. 3, pp. 684–690, Jul. 2002.

[12] B. Kasztenny, B. Campbell, and J. Mazereeuw, "Phase Selection for Single-Pole Tripping: Weak Infeed Conditions and Cross-Country Faults."

[13] G. Benmouyal and J. Mahseredjian, "A combined directional and faulted phase selector element based on incremental quantities," *IEEE Transactions on Power Delivery*, vol. 16, no. 4, pp. 478–484, 2001.

[14] Z. Xu, S. Huang, L. Ran, J. Liu, Y. Qin, Q. Yang, and J. He, "A Distance Protection Relay for a 1000-kV UHV Transmission Line," *IEEE Transactions on Power Delivery*, vol. 23, no. 4, pp. 1795–1804, Oct. 2008.