Series Compensated Transmission Line Protection Using Distance Relays

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Abstract

Use of series capacitors on transmission lines has become popular due to a variety of factors such as rapid increase in electricity demand, delays in implementing new transmission facilities and interconnection of new generation facilities such as large scale wind-farms. Most of these transmission lines are protected using conventional phasor based distance relays that operate based on voltage and current signals, measured locally. The presence of series capacitors can create abnormal system conditions (voltage inversions, current inversions, sub-harmonics and DC offsets) that potentially lead to unintended operation of conventional distance relays. This paper describes how such factors can affect the performance of the conventional distance relays and outlines solutions to overcome these challenges.

Keywords: distance protection, transmission lines, series capacitors, sub-harmonics

1. Introduction

Electrical energy generated at remote locations is delivered using transmission lines. Any faults associated with the transmission lines must be detected and isolated promptly to maintain a reliable power system and to satisfy day-to-day customer needs. A majority of transmission systems are protected using impedance relays. Although impedance relays are used in almost all protection schemes, their performance is less satisfactory in series compensated transmission systems. Impedance relays are designed with the assumption that the transmission lines are inductive. Inclusion of capacitors in series with transmission lines makes parts of the transmission lines capacitive, depending on the location of the fault. This may lead to voltage inversion, current inversion, or both voltage and current inversions. Distance relays used to protect series compensated transmission lines may mis-operate under these conditions. During faults, non-liner operation of series capacitors and other associated components (such as MOV, air-gap, and others) may also lead to sub-harmonic or exponential dc offset conditions. These conditions may sometimes lead to under-reach or over-reach problems [1-3].

Several attempts have been reported in literature [2-4] to overcome these challenges. A majority of methods involve the use of a different compensation method for distance relays to compensate for the effect of the series capacitor. These tend to slow down the relay and result in longer operating times. Few algorithms involve the use of modern methods such as artificial intelligence, pattern recognition, etc. [5-10]. Although these methods provide adequate protection for series compensated lines, they cannot be generalized for distance relays. This research investigates the development of an enhanced distance protection scheme for a specific distance relay with minimal modifications to the existing algorithm that has been initially designed to operate without series capacitors. Performance of the existing algorithm was evaluated under various system conditions such as different SIR (Source to line Impedance Ratio) ratios, transmission lines with mutual coupling, high impedance faults, etc. simulated in an electromagnetic transient simulation program. An enhanced algorithm was developed to overcome the problems associated with the existing algorithm. In order to ensure the correct operation, performance of the modified algorithm was also investigated, and compared using the same test cases.

This paper summarizes the effort involved in developing a new algorithm for protecting transmission lines with series capacitors. The remainder of the paper describes (i) the challenges in protecting series compensated transmission lines using distance relays, (ii) the modified distance algorithm, (iii) the simulation models used in this study and (iv) a performance comparison between the conventional algorithm and the modified algorithm, under different test conditions and (v) conclusions.

2. Challenges in protecting series compensated transmission lines

2.1 Voltage inversion

Distance protection operates based on the impedance reach and directionality (forward/reverse) calculated using voltage and current phasors. Inclusion of the series capacitor closer to voltage measurement (PT location) can significantly change the voltage phase angle. This may ultimately lead to incorrect estimation of both reach and directionality. Figure 1 shows an example of incorrect estimation of reach during a reverse fault.

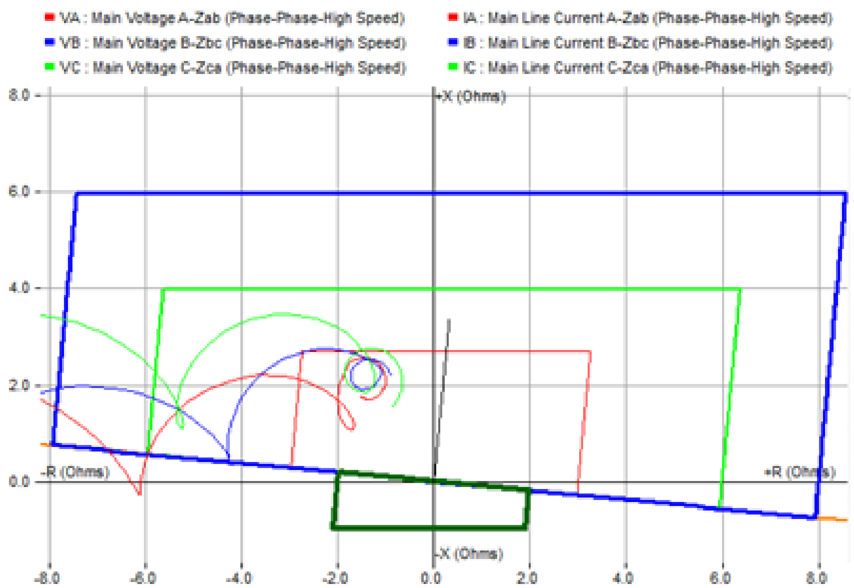

Figure 1: Mis-operation of distance relay during voltage inversion

2.2 Current inversion

When capacitors are connected in series with a transmission line, equivalent system impedance seen at the capacitor side of the fault may appear capacitive while the other side of the fault is inductive. This condition is known as current inversion. Both distance protection and current differential protection may fail under these conditions. Find more details and illustrations about current inversion due to series capacitors [10].

2.3 Sub-harmonics

Interaction of a series capacitor with line inductance can generate sub-harmonic voltage and current signals during switching operation. Figure 2 shows a sub-harmonic condition observed during a phase-to-phase fault in a transmission line with series capacitors. Protective relays operate based on phasor quantities estimated at power frequency. Sub-harmonics generated from capacitors can introduce errors in phasor estimation. This may lead to unexpected operation of distance relays. Impedance over-reach and under-reach are two commonly reported conditions. In addition, a significantly high amount of sub-harmonics can also affect directionality.

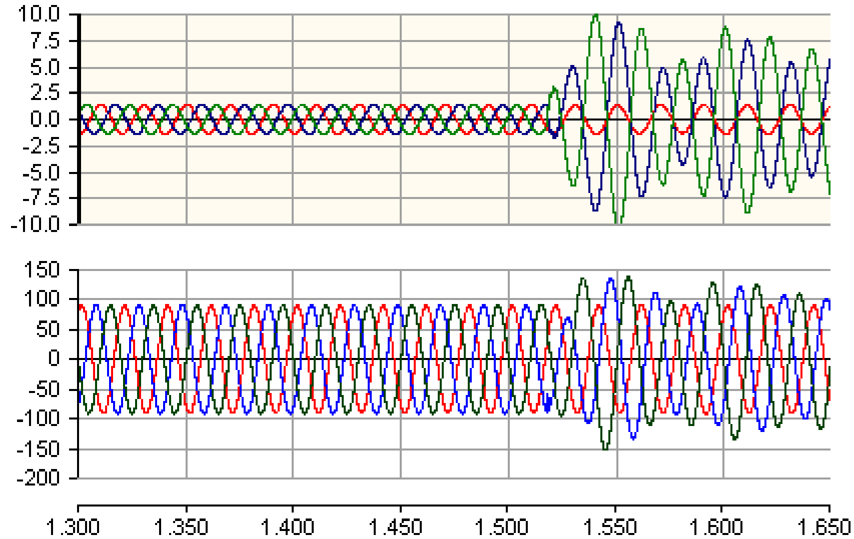

Figure 2: Typical sub-harmonic waveform [11]

3. Proposed methods

The proposed solutions involve the use of a modified directional function to compensate for the effect of the capacitor and a high-pass digital filter to eliminate the effect of the sub-harmonics.

3.1 Enhanced directional element

Figure 3 shows logic of the directional element. The directional element actually consists of 3 separate internal elements: a negative-sequence element, a zero-sequence element, and a positive-sequence element. The negative-sequence and zero-sequence elements use directly measured currents and voltages. The positive-sequence element uses directly measured current, and a memory voltage from the ring filter. The sensitivity for the negative and zero sequence elements may be set by the user, to correctly account for load conditions and system configuration. Both of these elements may be disabled as well. The positive-sequence element is always active.

For 3-phase faults, the directional element will only use the positive-sequence element. For all other faults, the directional element will be considered in the following order:

- negative-sequence calculation
- zero-sequence calculation
- positive sequence calculation

The directional element will only move from one calculation to the next calculation if insufficient sequence voltages and currents exist to make a valid calculation.

The negative-sequence calculation determines the angle between the measured negative-sequence impedance, and the positive-sequence line impedance angle entered in settings. The zero-sequence calculation determines the angle between the measured zero-sequence impedance the zero-sequence line impedance angle entered in settings. The positive-sequence calculation determines the angle between the measured positive-sequence impedance (based on measured current, and the memory voltage) and the positive-sequence line impedance angle entered in settings.

Detailed time simulation based investigations showed that the above algorithm may mis-operate for reverse faults and forward high impedance faults when series capacitors are connected at the end of line, with a line side PT. In order to overcome these mis-operations, estimated bus voltages using line side voltage were used for memory voltage calculations and sequence voltage calculations (in directional element described above).

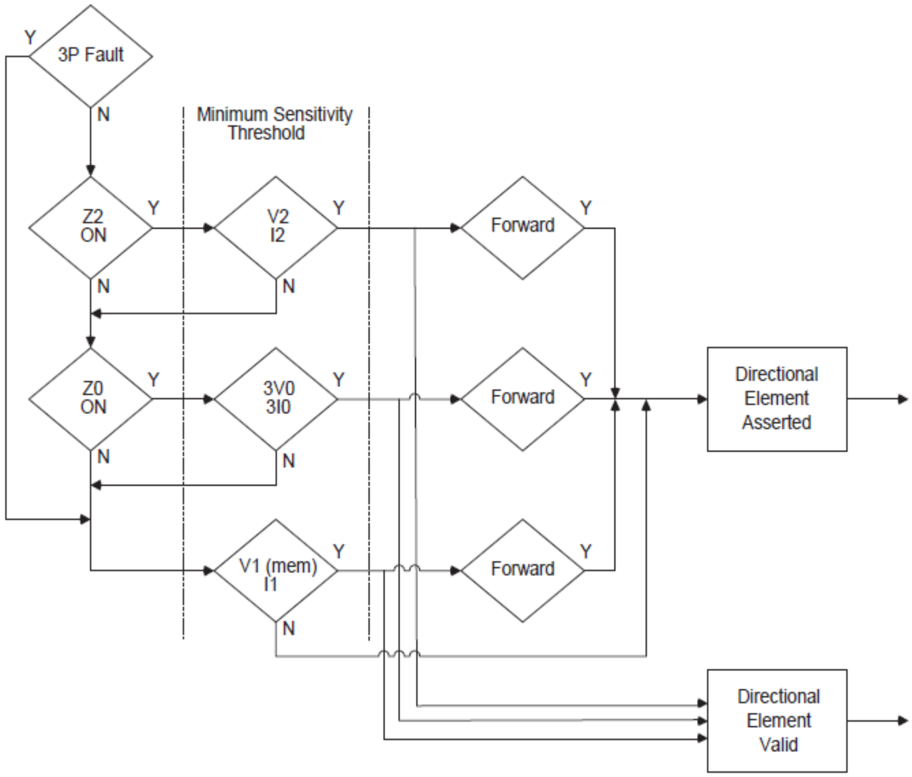

Figure 3: Directional element logic

3.2 Sub-harmonic removal filter

Sub-harmonics make impedance reach estimation challenging, especially for short duration faults. A high pass filter to remove these sub-harmonics is designed so that the pass band has a constant gain with a sharp edge, yet the time delay is not too large. To accomplish this, a 5th order Butterworth high pass filter with a cutoff of frequency of 45 Hz was used for a 50 Hz system. For a 60 Hz system it is set to 55 Hz. The output response of the selected filter at 50 Hz system frequency is shown in Figure 4.

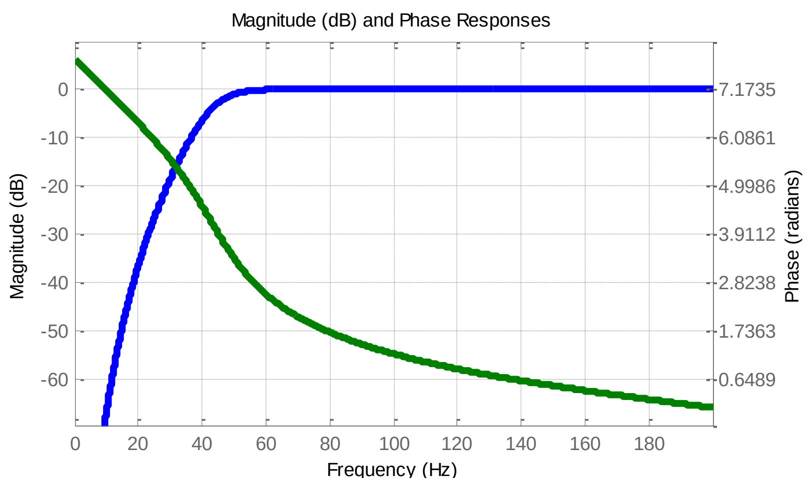

Figure 4: Sub-harmonic removal filter response (50 Hz system) [11]

4. Simulations

The effectiveness of the proposed solution is evaluated under different practical scenarios using a Real Time Digital Simulator (RTDS). This section describes the simulation models used in this study, the relay settings and the simulation results observed under different test scenarios.

4.1 Test system

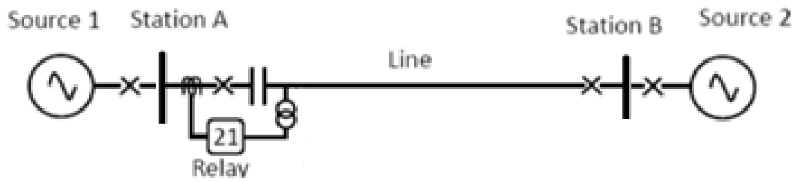

Figure 5: Test system

Figure 5 shows the 230 kV, 60 Hz test system used in this study. Transmission line parameters are given in Table-1. Source-1 is simulated with different source to line impedance ratios (SIR) while keeping the source-1 impedances constant at SIR=1. The transmission line is simulated using a frequency dependent transmission line model. CT and PT ratios are 200 and 3636.36, respectively. Series capacitor compensation level was assumed as 40%. Series capacitors were modeled with MOVs to protect capacitors by limiting excessive voltages across the capacitors during severe faults.

Table-1

Sequence	Impedance (ohms)
Positive	61.7 <84.6
Zero	210.9 <75.7

4.2 Relay settings

Impedance zone settings and line parameter settings are shown in Figure 6 and Figure 7, respectively. Zones 1 to 3 were set to operate in the forward direction while zone-4 was set to operate in the reverse direction for both phase and ground elements. Quadrilateral characteristics were assumed.

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Enabled	☑	☑	☑	☑	☐
Type	Quad	Quad	Quad	Quad	Quad
Forward Reach (ohm)	2.72	4.00	6.00	0.00	20.00
Reverse Reach (ohm)			0.00	1.00	0.00
Left Reach (R1) ohm	3.00	6.00	8.00	2.00	15.00
Right Reach (R2) ohm	3.00	6.00	8.00	2.00	15.00
Mho Char. Angle (deg)	90.0	90.0	90.0	90.0	90.0
Pickup Delay (s)	0.00	0.50	1.50	1.00	1.50
Id Supervision (A)	1.0	1.0	1.0	1.0	1.0

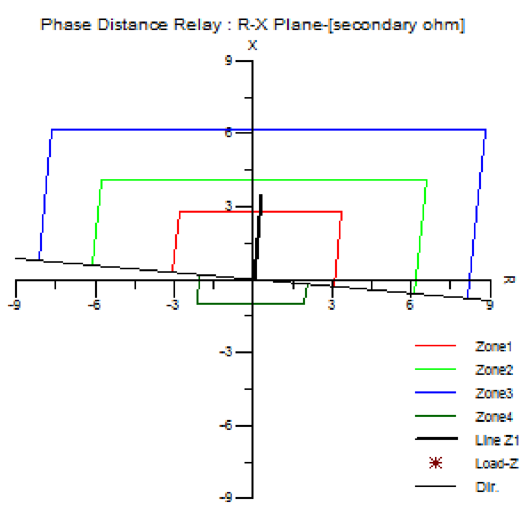

Figure 6: Impedance settings

4.3 Performance during sub-harmonics

As explained in Sec 2.1, inclusion of series capacitors may generate sub harmonics in voltage and current signals during fault conditions. These sub-harmonics can introduce errors in fundamental phasor estimation that lead to over-reach and under-reach issues. In order to investigate the effectiveness of the modified algorithm, different types of faults were simulated at 90% of the line (10% above the zone-1 reach). Source-1 was simulated with SIR=2.0. Figure 8 shows the operation of the modified algorithm during a three phase fault simulated at 90% of the line. As seen from the results, the relay operated correctly without zone-1 over-reach. Figure 9 shows the operation of the non-modified algorithm that resulted in over-reach of zone-1.

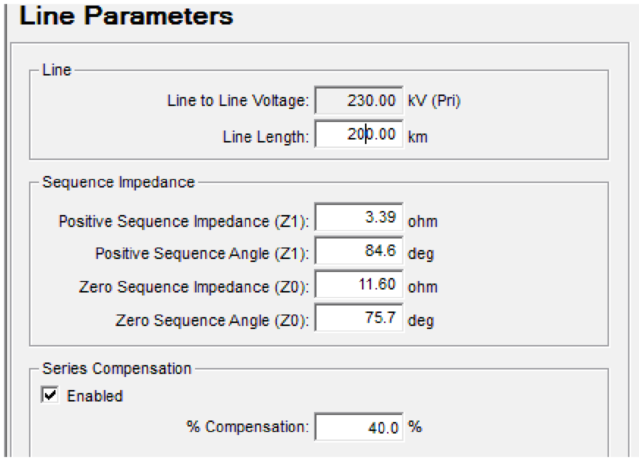

Figure 7: Line parameter settings

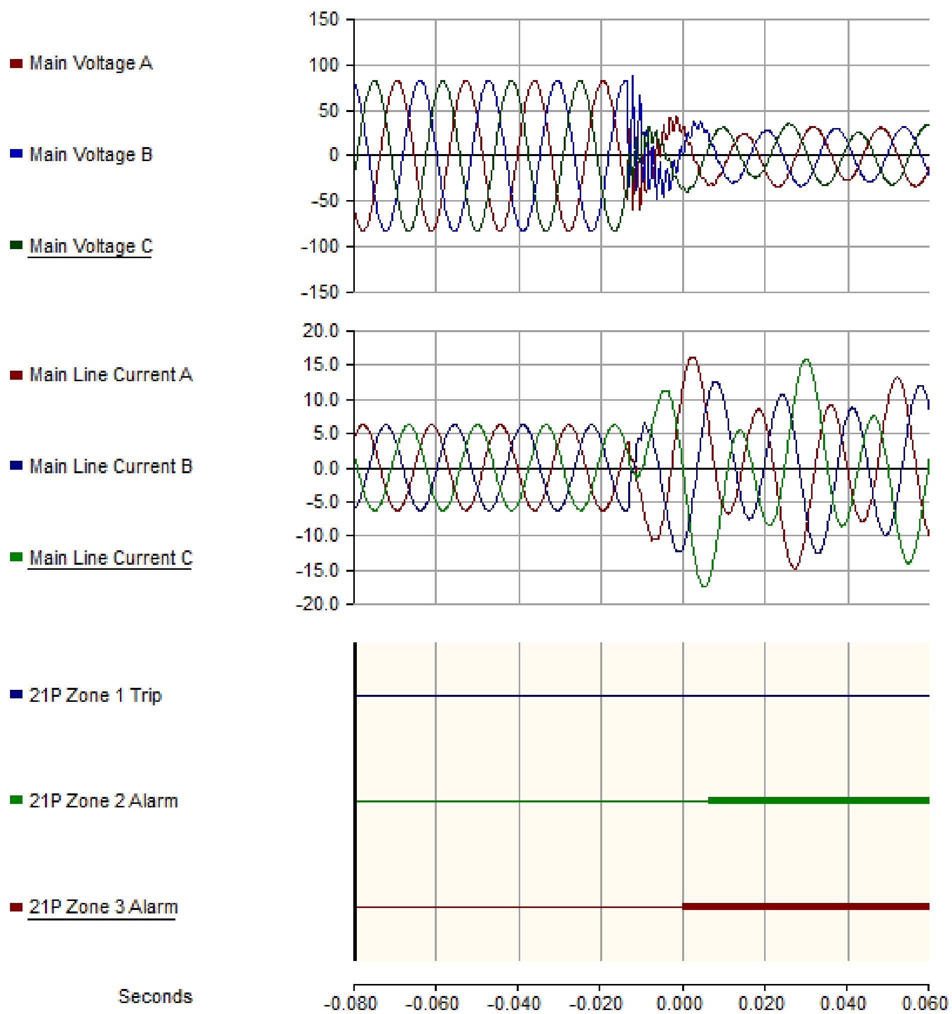

Figure 8: Overcoming zone-1 over-reach due to sub-harmonics (modified algorithm)

Apart from the over-reach issue, fault location estimation may also be affected due to sub-harmonics. Effectiveness of the proposed filter for fault location estimation was also investigated in another study. Results showed improved fault location estimations. Details can be found in [11].

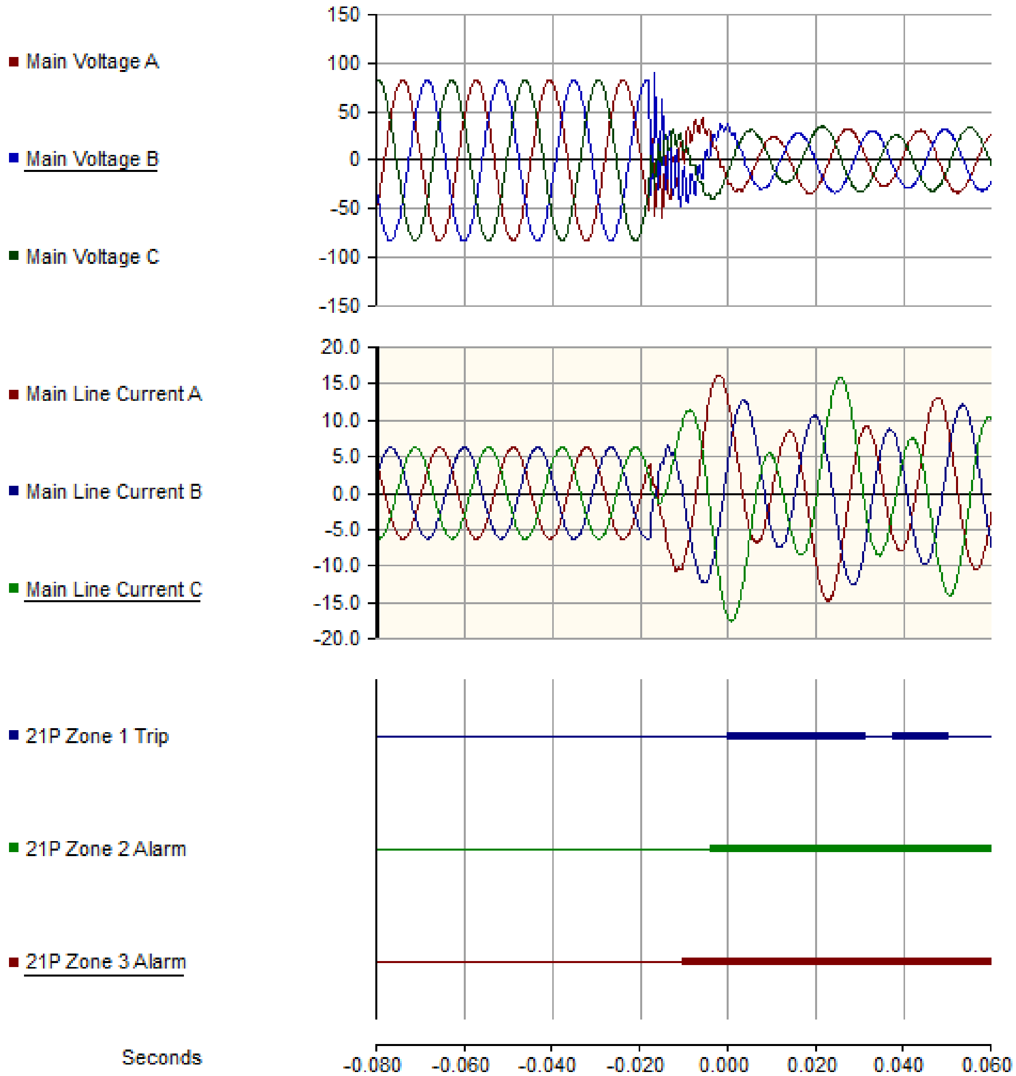

Figure 9: Zone-1 over-reach due to sub harmonics (no-modified algorithm)

4.4 Performance during voltage inversion

As explained above, inversion in voltage phasors occurs during a reverse fault closer to the capacitor. In order to evaluate the performance of the proposed algorithm under voltage inversions, reverse faults were simulated closer to the capacitor. In this simulation study, source-1 was simulated with SIR=2.0. Figure 10 shows the operation of the distance relay using the proposed method which compensates the effect of the series capacitor for a reverse fault simulated very close to the relay. As can be seen in Figure 10, all zones operated correctly for the reverse zone. Figure 11 shows the operation of the conventional (non-modified) distance relay for the same fault where all the zones responded incorrectly. Other types (phase-to-ground, phase-to-phase and phase-to-phase-ground) of faults were also simulated in the reverse direction and the modified algorithm showed correct operation.

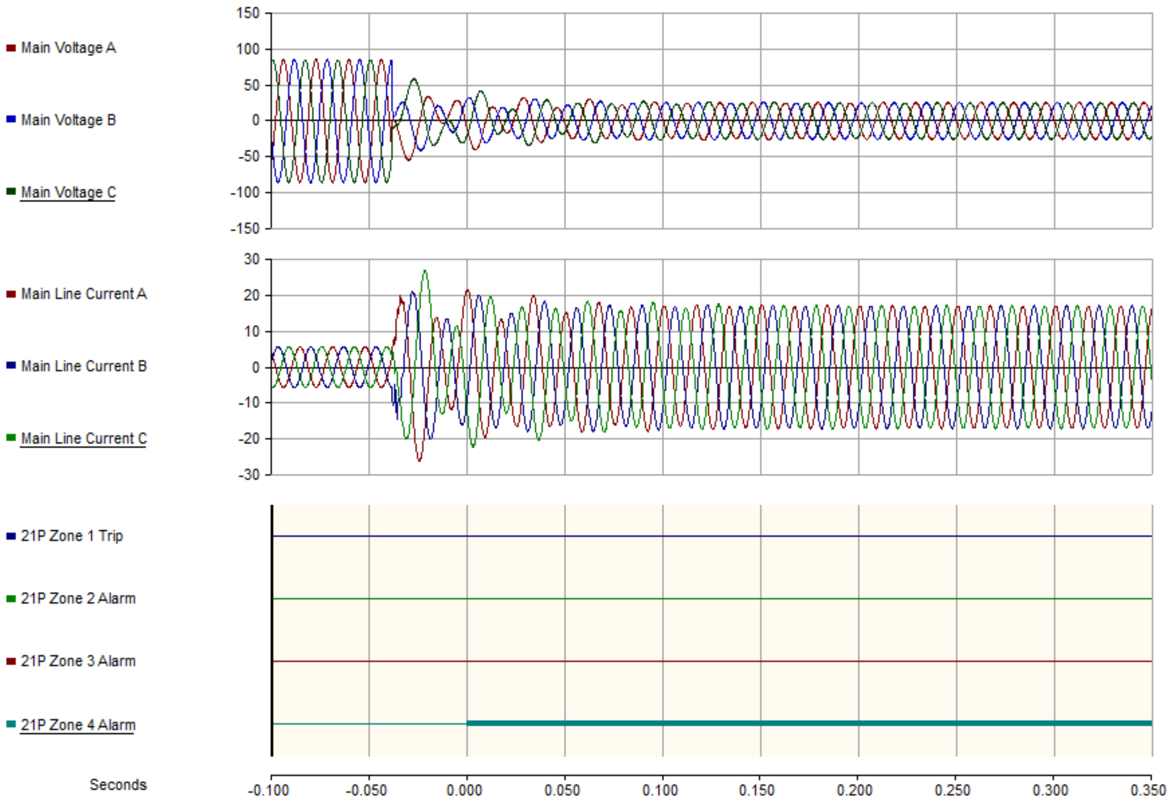

Figure 10: Correct zone operation during reverse faults (modified algorithm)

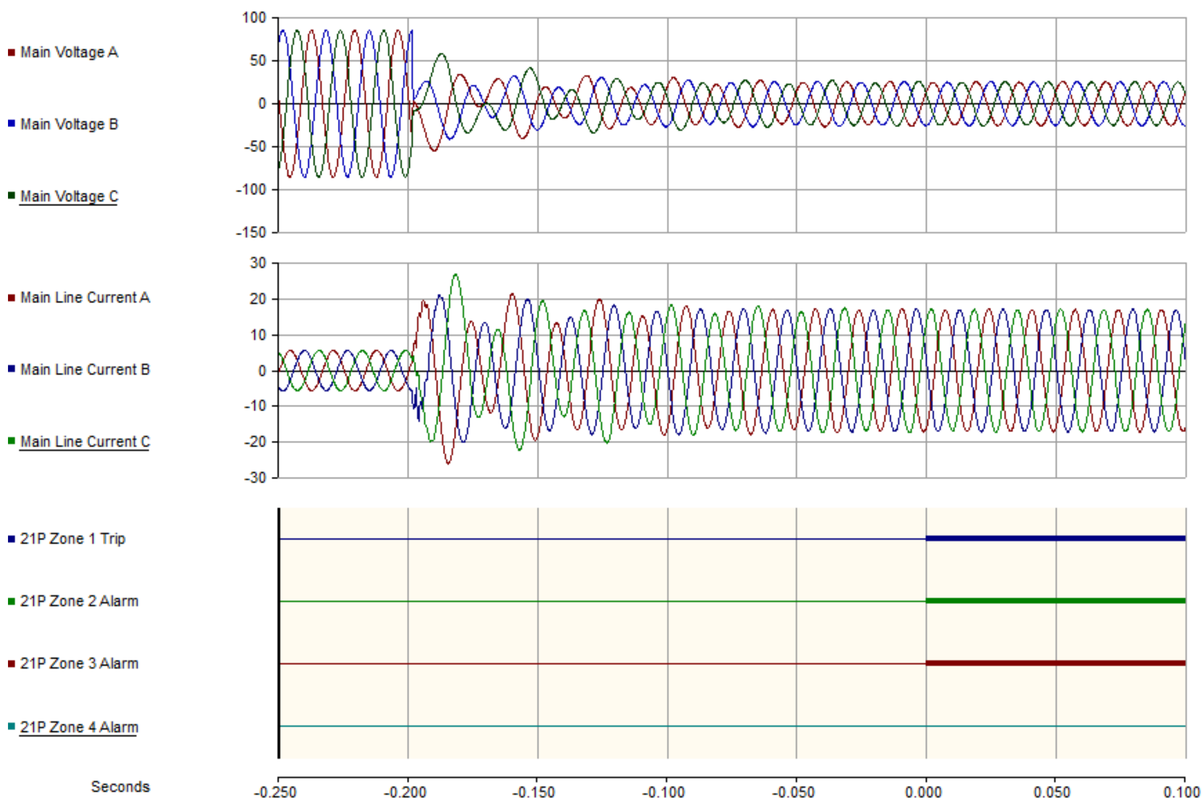

Figure 11: Zone mis-operation during reverse faults (no-modified algorithm)

4.5 Performance during current inversion

As explained above, inclusion of a series capacitor in a transmission line may create inversion of current phase that leads to incorrect operation of distance relay. In order to investigate the operation of the proposed algorithm under such conditions, a high impedance (40 ohms, primary) single phase to ground (A-G) forward fault was simulated at 5% of the transmission line. In this simulation, source-1 was simulated with SIR=0.25.

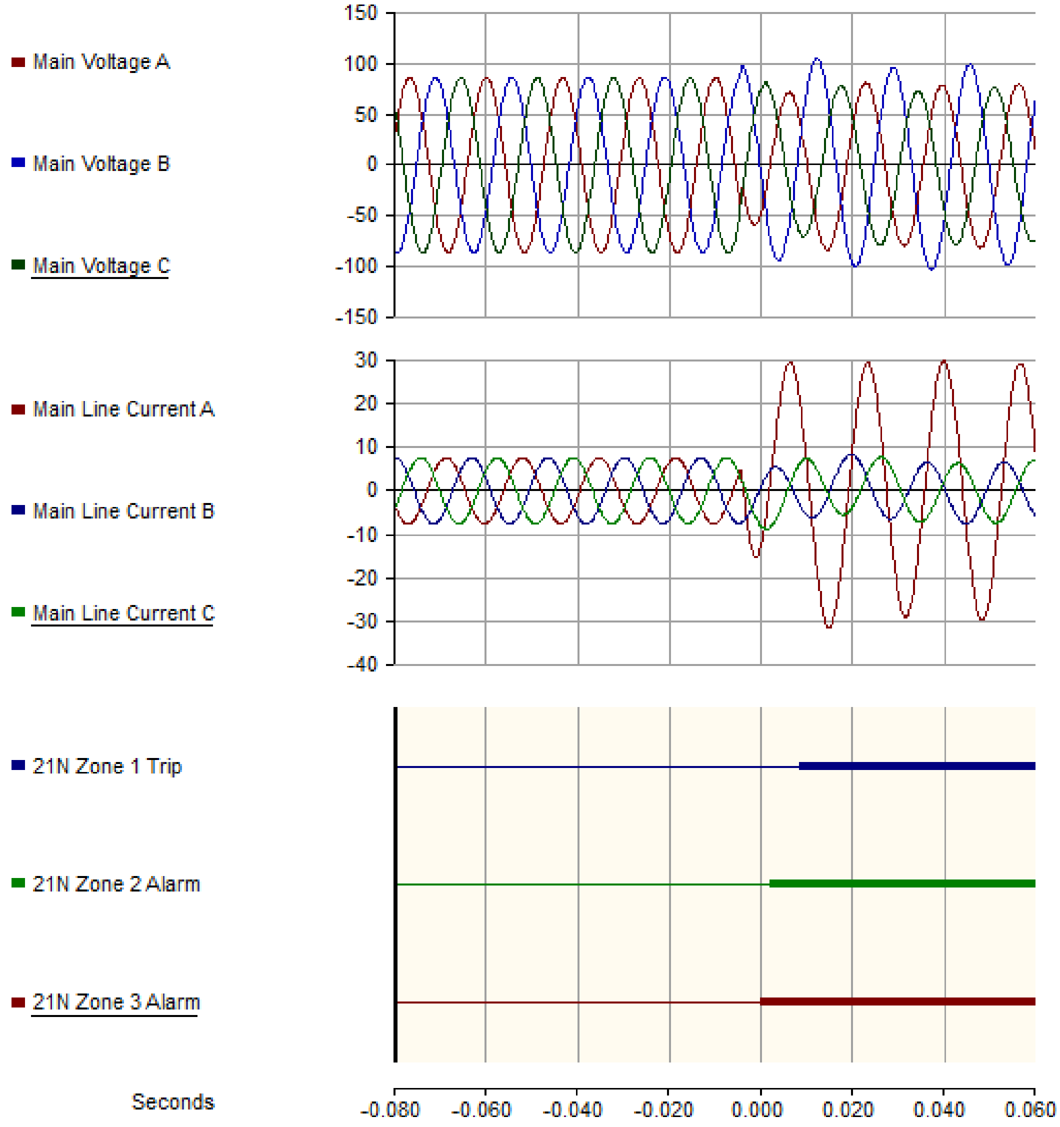

Figure 12: Correct zone-1 operation during forward high impedance fault (modified algorithm)

Figure 12 shows the performance of the modified algorithm during this fault. As seen in results above, the relay shows correct operation in all the forward zones. Operation of the non-modified algorithm for the same fault is shown in Figure 13; zone-1 to zone-3 show incorrect operation.

Simulations are repeated for faults at different locations with different impedances and results showed correct operation for the modified algorithm compared with the non-modified algorithm.

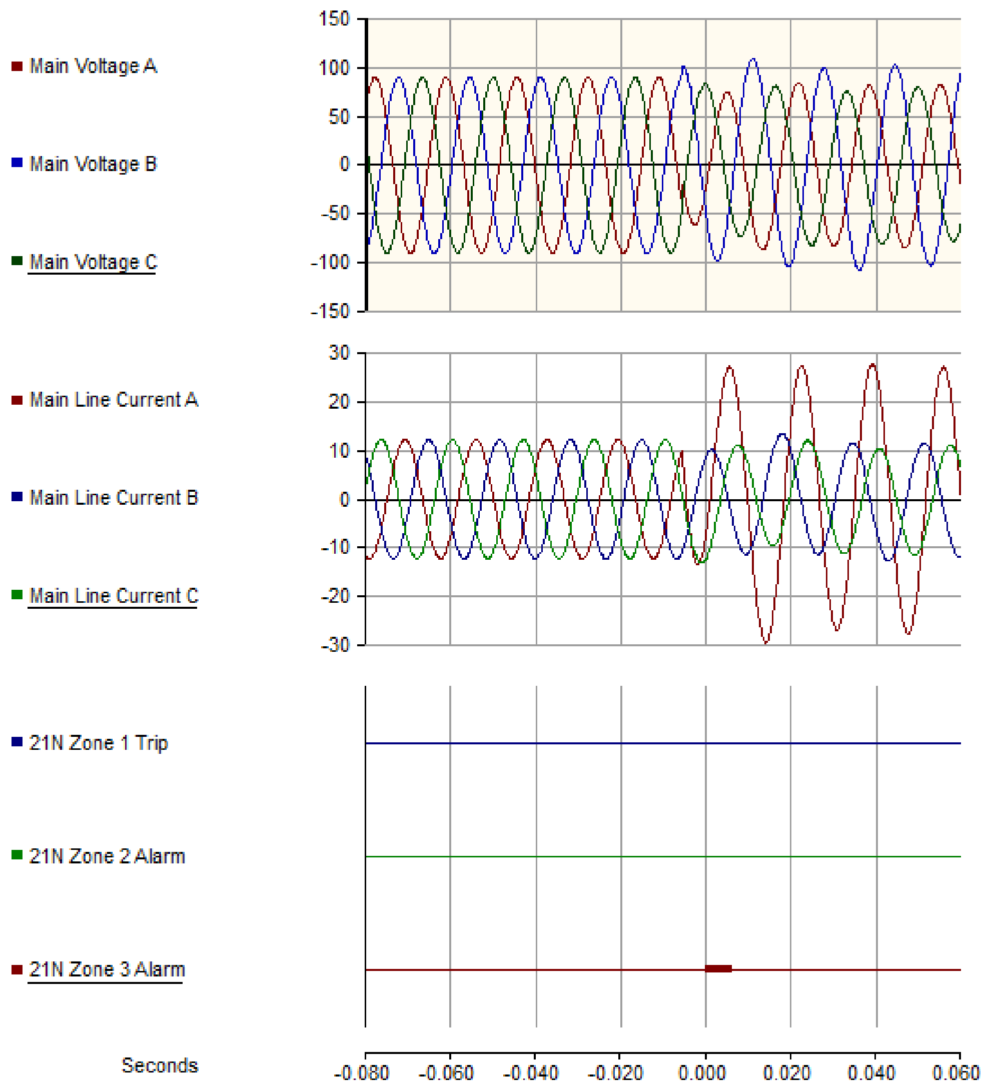

Figure 13: Incorrect operation during forward high impedance fault (non-modified algorithm)

4.6 Effect of capacitor location

Simulation scenarios above assumed that the series capacitors were located at the end of the line. In some applications, series capacitors are located in the middle of the line. In that case, modifications to the directional element are not required as the capacitor is located far from the voltage measurement. However, the inclusion of a sub-harmonic filter is beneficial. Users can achieve this by enabling the series capacitor setting and setting the percentage compensation to zero, as shown in Figure 14. This setting will provide enhanced operation during sub-harmonic conditions.

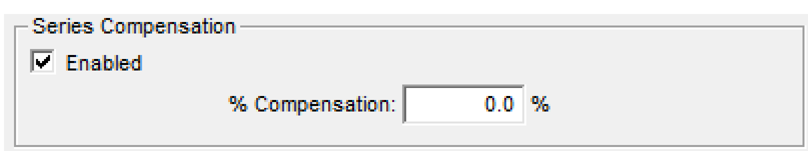

Figure 14: Settings for a series capacitor at middle of the line

5. Conclusions and future work

An enhanced distance protection method that eliminates dc offsets and sub-harmonic components for series compensated lines is presented in this paper. The proposed method involves the use of a modified directional element and a sub-harmonic removal filter. Performance of the proposed algorithm was evaluated under different scenarios such as voltage inversion, current inversion, sub-harmonics, etc. simulated in a Real Time Digital Simulator environment. Results obtained from this study showed that the proposed method is capable of providing enhanced and secured protection against faults and sub-harmonic conditions during the switching operations of a series compensated transmission system.

Further research will be carried out to investigate the performance of the proposed algorithm for mutual compensated transmission lines with series capacitors.

6. References

[1] “IEEE Guide for Protective Relay Application to Transmission-Line Series Capacitor Banks”, IEEE Standard C37.116, 2007.

[2] H. J. Altuve, J. B. Mooney, and G. E. Alexander, “Advances in series-compensated line protection,” presented at the 35th Annu. Western Protect. Relay Conf., Spokane, WA, Oct. 2008.

[3] F. Ghassemi, J. Goodmi, and A. T. Johns, “Method to improve digital distance relay impedance measurement when used in SC lines protected by MOVs,” in Proc. Inst. Elect. Eng., Transm. Distrib., Jul. 1998, vol. 145, no. 4.

[4] P. Jena and A. K. Pradhan, “An integrated approach for directional relaying of the double-circuit line,” IEEE Trans. Power Del., vol. 26, no. 3, pp. 1783–1792, Jul. 2011.

[5] U. B. Parikh, D. Biswarup, and R. P. P. Maheshwari, “Combined wavelet-SVM technique for fault zone detection in a series compensated transmission line,” IEEE Trans. Power Del., vol. 23, no. 4, pp. 1789–1794, Oct. 2008.

[6] A. I. Megahed, A. M. Moussa, and A. E. Bayoumy, “Usage of wavelet transform in the protection of series-compensated transmission lines,” IEEE Trans. Power Del., vol. 21, no. 3, pp. 1213–1221, Jul. 2006.

[7] K. Pradhan, A. Routray, S. Pati, and D. K. Pradhan, “Wavelet fuzzy combined approach for fault classification of a series compensated transmission line,” IEEE Trans. Power Del., vol. 19, no. 4, pp. 1612–1618, Oct. 2005.

[8] V. Malathi, N. S. Marimuthu, and S. Baskar, “A comprehensive evaluation of multi—category classification methods for fault classification in series compensated transmission line,” Neural Comput. Appl., vol. 19, pp. 595–600, 2009.

[9] R. Coteli, “A combined protective scheme for fault classification and identification of faulty section in series compensated transmission lines,” Turkish J. Elect. Eng. Comput. Sci., pp. 1–29, 2012.

[10] N. Perera, A. D. Rajapakse, “Series-Compensated Double-Circuit Transmission Line Protection Using Directions of Current Transients”, IEEE Transactions on Power Del., vol. 28, no. 3, pp.1566-1575 , July 2013.

[11] U. Annakage, N. Perera, V. Liyanage, “Enhanced impedance based single ended fault location estimation for distance relays”, Cigre Canada 2013, Calgary, AB.