ENHANCED DISTANCE PROTECTION FOR SERIES COMPENSATED TRANSMISSION LINES

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ABSTRACT

A variety of factors such as rapid increase in electricity demand, rights-of-way, delays in implementing new transmission facilities and interconnection of new generation facilities such as large scale wind-farms have led to more widespread use of series capacitors on transmission lines. 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, Real Time Digital Simulator*

INTRODUCTION

Transmission lines are a critical element in the electrical power system. Any faults associated with the transmission system need to 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. Apart from that, non-liner operation of series capacitors and other associated components (such as MOV, air-gap, etc.) during faults, 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].

In literature, several attempts have been reported to overcome the aforementioned challenges [2-4]. 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 larger 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 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.

MAIN CONTENTS

Challenges in Protecting Series Compensated Transmission Lines

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.

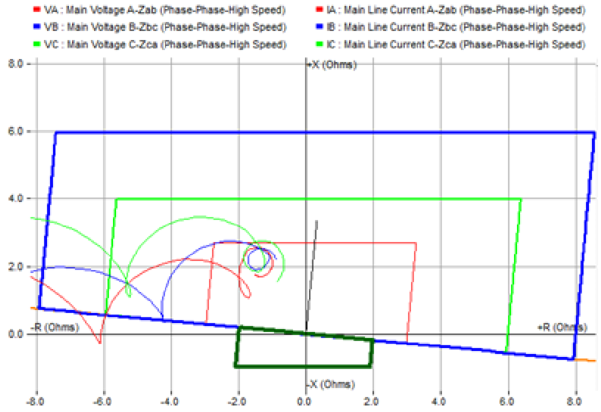

FIGURE 1: Mis-operation distance relay during voltage inversion.

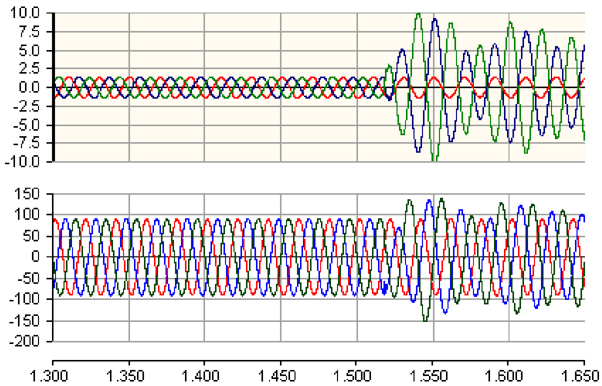

FIGURE 2: Typical sub-harmonic waveform [11]

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 capacitor [10].

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. Apart from that, significantly high amount of sub-harmonics can also affect directionality.

Proposed Method

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.

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.

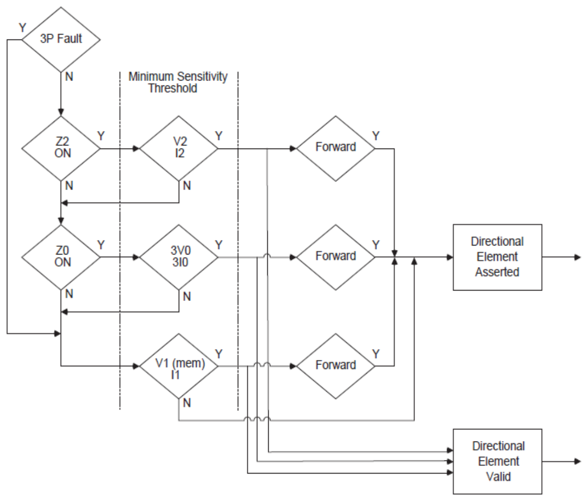

FIGURE 3: Directional element logic

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 above).

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.

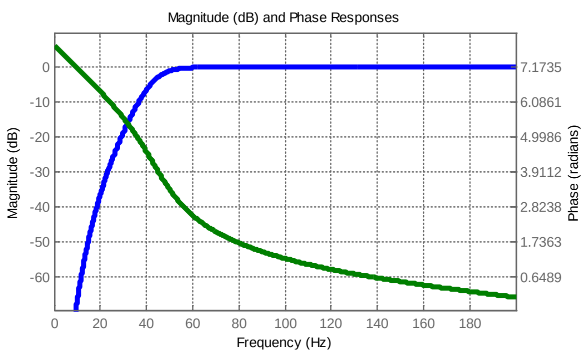

FIGURE 4: Sub-harmonic removal filter response (50 Hz system) [11]

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.

Test system

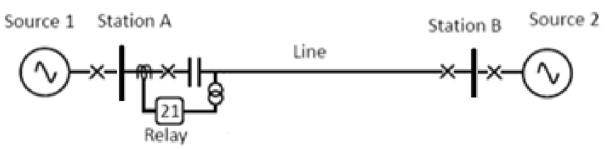

FIGURE 5: Test System

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

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

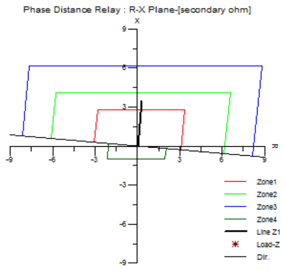

FIGURE 6: Impedance settings

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 leads 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 modified algorithm during a three phase fault simulated at 90% of the line. As it can be seen from the results relay operated correctly without zone-1 over-reach. Figure 9 shows the operation of non-modified algorithm that resulted in over-reach of zone-1.

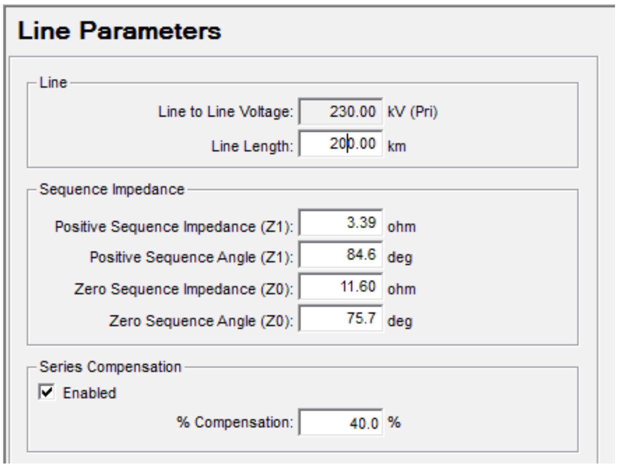

FIGURE 7: Line parameter settings

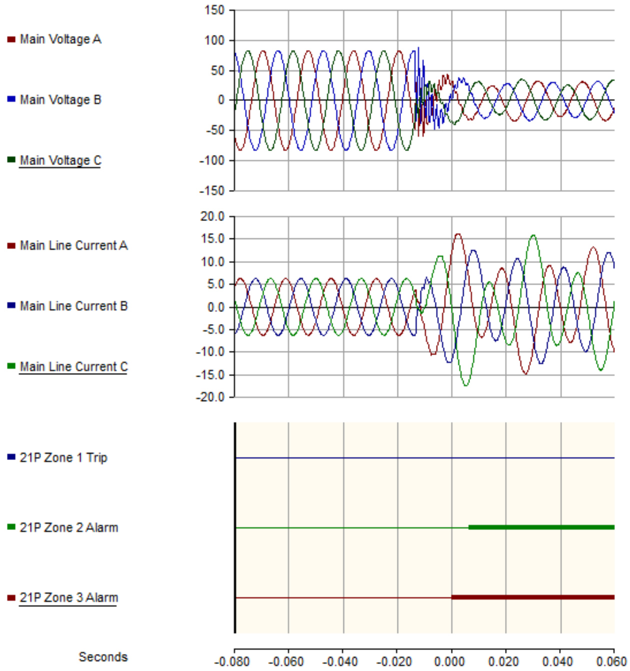

FIGURE 8: Overcoming zone-1 over-reach due to sub-harmonics (modified algorithm)

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].

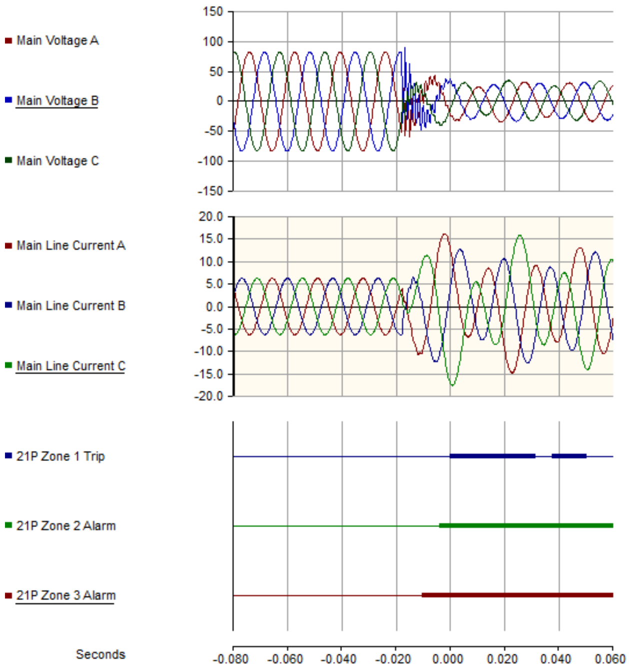

FIGURE 9: Zone-1 over-reach due to sub harmonics (no-modified algorithm)

Performance during voltage inversion As explained in Sec 2.1, 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.

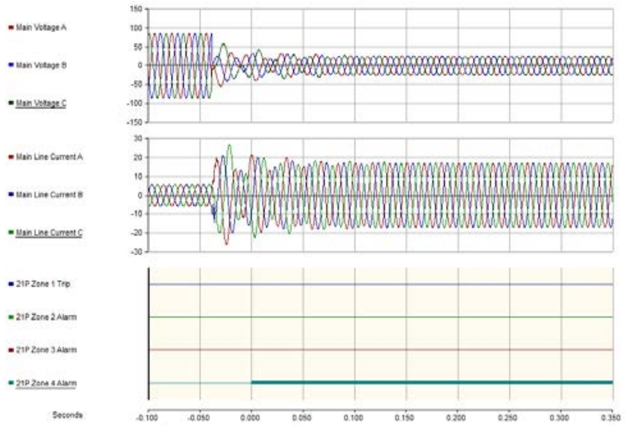

FIGURE 10: Correct zone operation during reverse faults (modified algorithm)

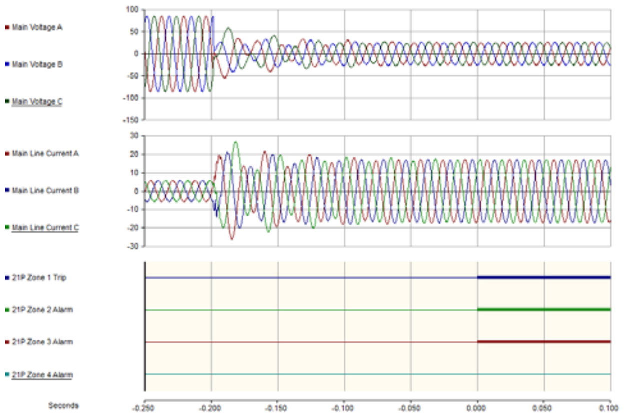

FIGURE 11: Zones mis-operation during reverse faults (no-modified algorithm)

Performance during current inversion As explained in Sec 2.1, 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 ohm, 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.

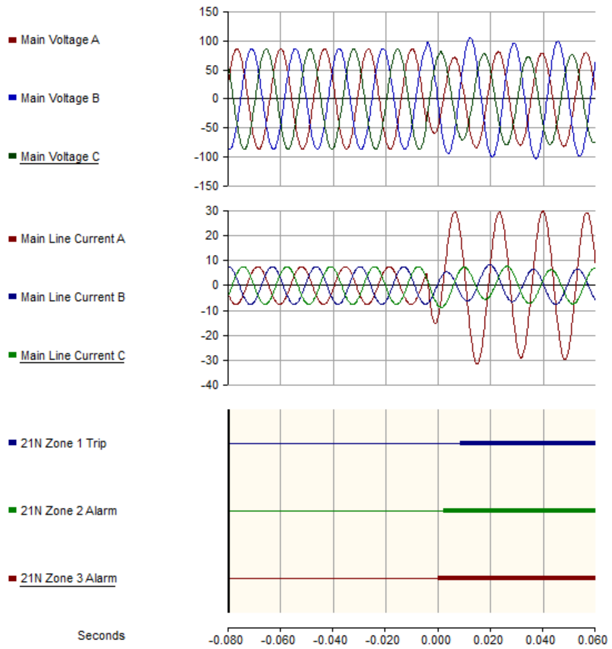

FIGURE 12: Correct zone-1 operation during forward high impedance fault (modified algorithm)

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 shows 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.

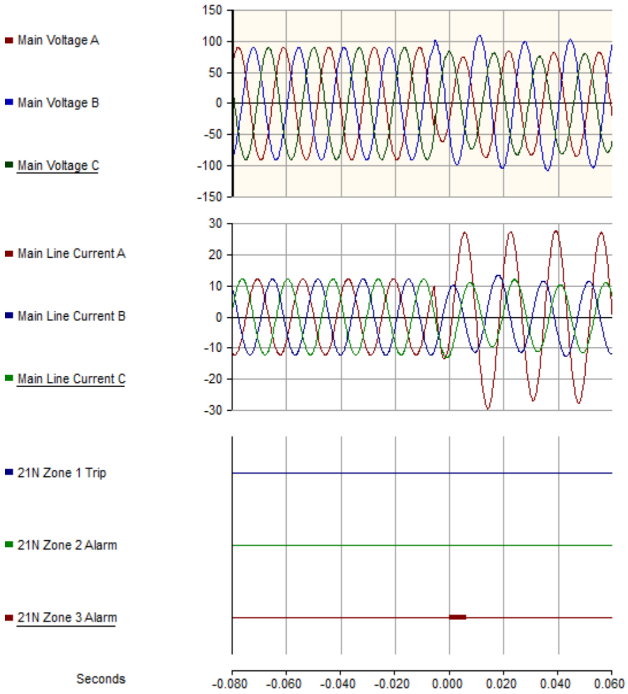

FIGURE 13: Incorrect operation during forward high impedance fault (non-modified algorithm)

Effect of mutual compensation Different types of faults were simulated at different locations on the double circuit transmission line arrangement shown in Figure 14.

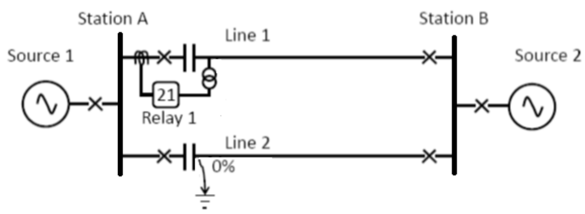

FIGURE 14: Reverse fault on double circuit transmission line

Mutual impedance of 132.5 <69.9 ^{0} ohms (primary) was assumed. Mutual compensation for the relay was provided through an additional current input. The mutual compensation factor used for this simulation is shown in Figure 15.

Different types of faults were simulated at different locations in the system. Results showed correct operation on all simulated fault scenarios. Figure 16 shows the operation of the modified algorithm for a closed in reverse three-phase fault simulated on the other line just after the series capacitor (as shown in Figure 14). Figure 17 shows the operation of the conventional algorithm for the same fault that shows a mis-operation of the forward zones for a reverse fault. In these simulation cases SIR=5 was used.

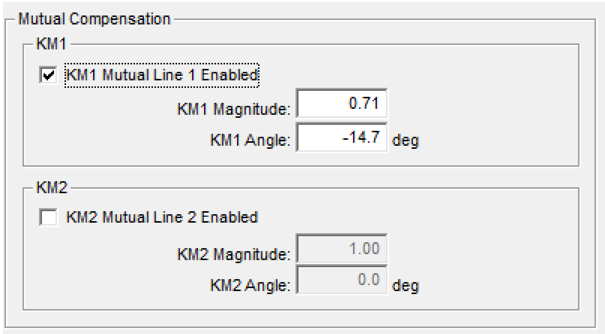

FIGURE 15: Mutual compensation settings

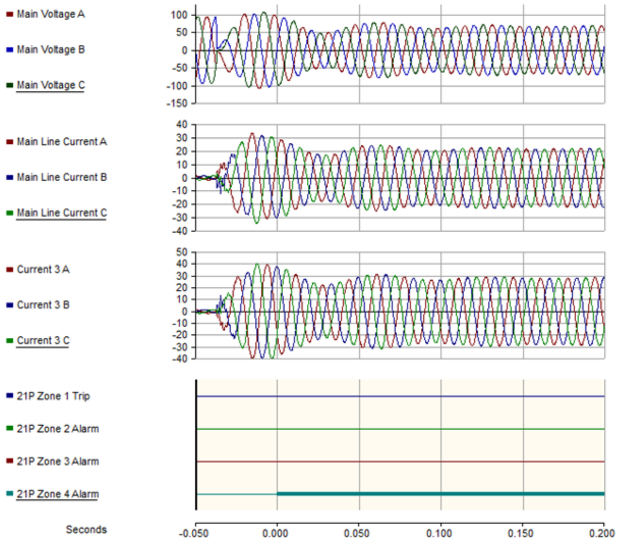

FIGURE 16: Operation of the modified algorithm for reverse fault

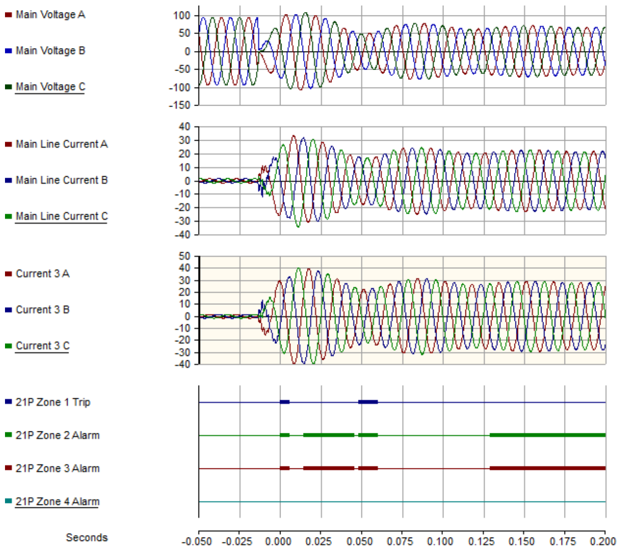

FIGURE 17: Operation of the non-modified algorithm for reverse fault

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 18. This setting will provide enhanced operation during sub-harmonic conditions.

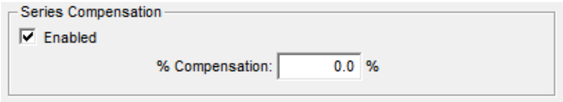

FIGURE 18: Settings for a series capacitor at middle of the line

CONCLUSION

In this paper, an enhanced distance protection method that eliminates dc offsets and sub-harmonic components for series compensated lines is presented. The proposed method involves the use of a modified directional element and a sub-harmonic removal filter. A laboratory prototype of the proposed algorithm was implemented. 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.

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