Directional Protection Applied to Wind Systems: Challenges and Solutions

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***Abstract*—This paper investigates the applicability of a flexible directional element applied to a distance protection scheme with windfarms. The directional element investigated in this study operates based on sequence components of voltage and current measurements. This directional element provides the flexibility for users to enable/disable sequence elements and change their sensitivity levels depending on the application requirements. In addition, it provides extra security during sub-harmonic conditions. Some case studies are presented covering various applications such as series compensated systems and passive inverter based generating system.**

Keywords— directional element, distance protection, transmission lines, series compensated systems, weak systems

I. INTRODUCTION

The transmission lines are considered 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. Interconnection of complex power system elements such as large scale inverter connected generating facilities and series compensated systems has become more common in modern power systems [1-5]. Although these solutions provide several benefits, they introduce a number of protection challenges as described below.

A. Effect of inverter connected passive sources

Identification of correct fault directionality is essential for correct operation of both primary and back-up protection. The primary protection for majority of the transmission lines is provided through the distance protection elements. In addition, the back-up protection systems involves the use of directional overcurrent elements. Furthermore, use of pilot protection methods such as POTT, PUTT and directional comparison is more common in transmission systems. Operation of directional element applied to all the above protection elements plays an important role in providing a secured and a reliable operation [6].

B. Effect of series capacitors

When large scale windfarms are connected to power systems applicability of series compensation has become common in most of the typical applications. The majority of series compensated transmission systems are still protected using distance relays. The distance relays are designed with the assumption that the protected transmission lines are inductive. Inclusion of capacitors in series with transmission lines makes sections 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. Additionally, 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. All these conditions may lead to several protection issues leading to mis-operations of the distance relays [1].

This paper investigates the applicability of a flexible directional element available in a multi-functional distance protection relay to overcome fault direction identification issues associated with complex systems [7]. Recommended settings for different applications are discussed including some test results.

II. FLEXIBLE DIRECTIONAL ELEMENT

This section provides design details associated with the flexible directional element.

A. Sequence Component

Figure 1 shows the logic of the directional element. The directional element consists of three 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. The negative and zero elements may be disabled but 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

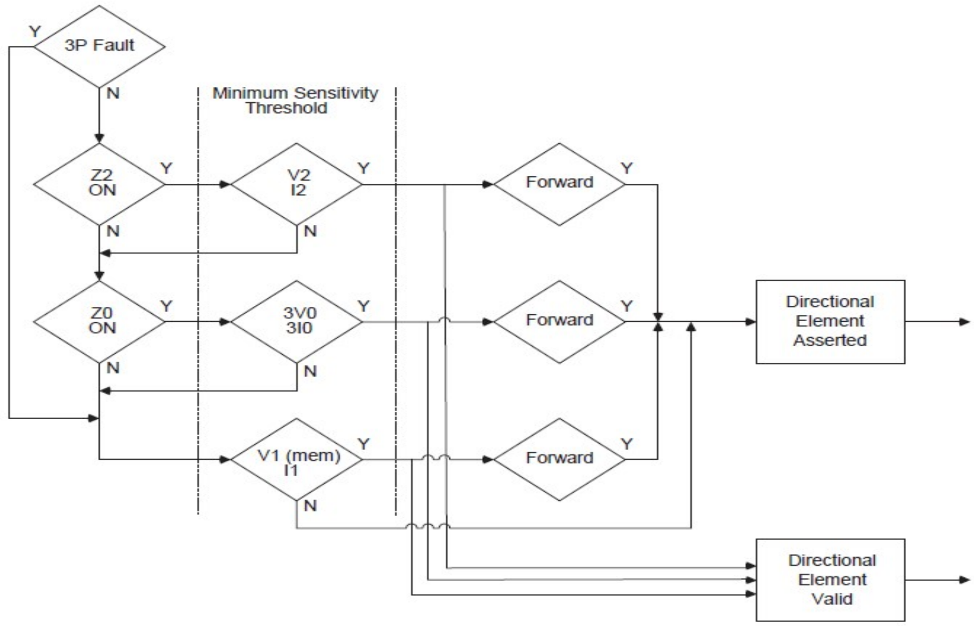


Fig.1. Directional element logic

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.

B. Sub-harmonic Removal Filter

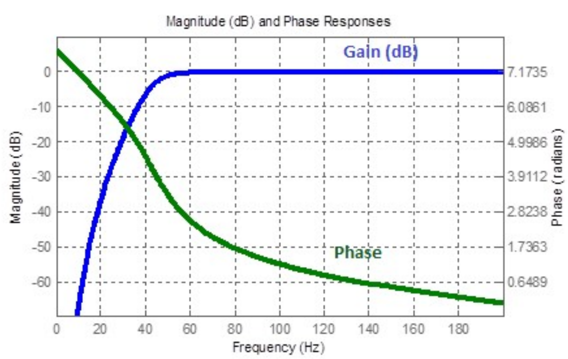
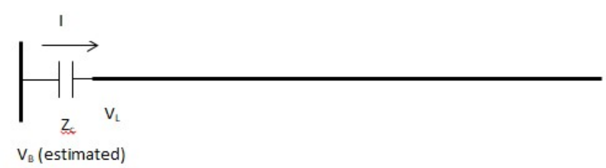


Fig.2. Sub-harmonic removal filter response (50 Hz system)

Sub-harmonics make phasor estimations challenging. A high pass filter to remove these sub-harmonics is designed so that the pass band has a constant gain with a sharp edge and a time delay that 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 2.

C. Voltage Compensation for Series Capacitors

When the series capacitors are located near the end of the line, in order to ensure correct reach calculations it is a common practice to use voltage measurements from line side PTs/CCVTs. This results in incorrect operation of the directional element during reverse faults. However, under such applications the use of bus side voltages for the directional element provides secured operation. The proposed directional element provides the flexibility to use derived the bus side voltages based on line side voltage measurements.



$$V_B\,(estimated) = V_L + Z_c{*}I = V_L + 1/(jX_c){*}I$$

Fig 3: Bus side voltage estimation

Figure 3 shows the process of bus side voltage estimation using line side voltage measurements. It should be noted current measurement (I) and amount series compensation (Zc) are available to the relay [7].

D. Relay Settings

As shown in Figure 4, the distance relay has been provided with two settings for series compensated line applications and the details are discussed below.

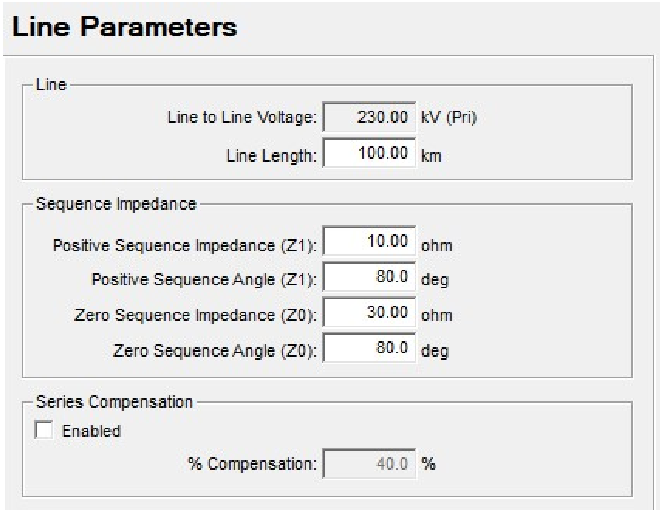


Fig 4: Series compensated settings

III. CASE STUDY -1

This case study covers the directional protection issues related to large wind system connected to a transmission system. Figure 5 shows the 230 kV, 60 Hz test system with the wind farm used in this simulation. The transmission line parameters are given in Table-6. Source-1 and Source 2 are simulated with active sources. The wind farm is simulated as a Type-III model. The transmission line is simulated using a frequency dependent transmission line model. The CT and PT ratios are 1000 and 2000, respectively. The distance relay protecting the transmission line at Station-A is selected for this study.

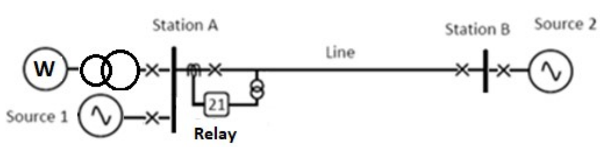


Fig 5: Transmission line connected with a wind system

It should be noted that when the active Source-1 is connected to the system, the distance relay at End-A is expected to work normally during forward faults due to the fault current contributions from the active source. When the Source-1 is out of service, the relay is driven by the fault currents from the wind generator. The lack of zero sequence current or negative sequence current or both zero and negative sequence currents found to be the possible protection challenges associated with such conditions.

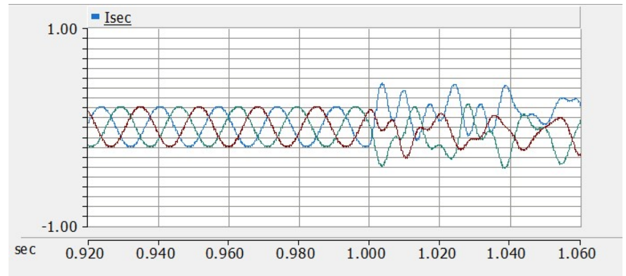


Fig 6: Fault currents seen by the relay during a forward single phase to ground fault

Figure 6 shows the variation of fault currents observed by the relay during a forward single phase to ground fault simulated when Source-1 is out of service. Although the fault is involved with only one phase, the wind generator continues to contribute into all three phases. In addition, the fault currents are lower in magnitude and they are with low frequency harmonics. The weak networks similar to this application are typically protected with POTT schemes with echo back support. However, incorrect fault direction identification at the local end relay (eg. forward faults are classified as reverse) may result incorrect operation of the POTT scheme. Therefore, it is essential to eliminate the possibilities of such mis operations.

In order to ensure secured operation of the directional element, following special settings are applied.

- Enabled the sub-harmonic filtering (shown in Fig. 4. It should be noted that as per the design of this relay, sub-harmonic filter can be enabled by enabling the series capacitor with 0 % compensation)
- Disabled dependencies of negative sequence and zeros sequence components on fault direction identification (shown in Figure 20. Only the positive sequence is used).

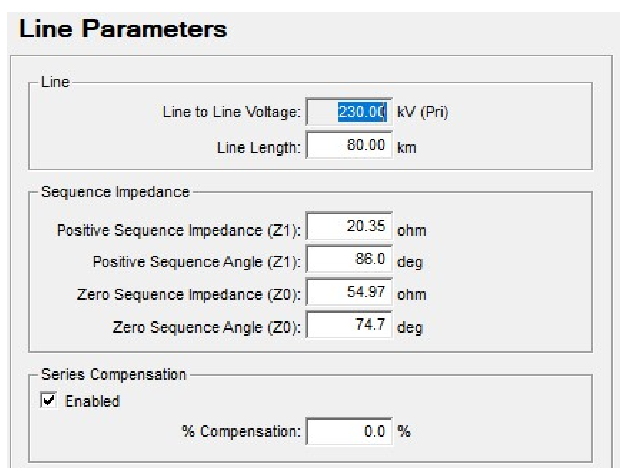


Fig 7: Line Parameters

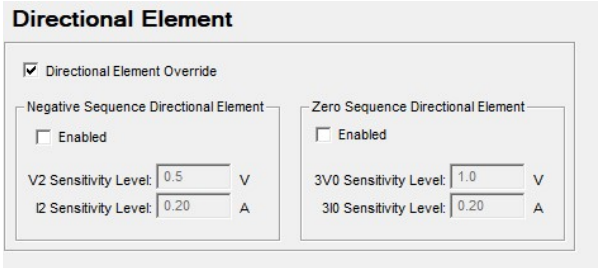


Fig 8: Directional Element Settings

The reach and zone settings associated with 21P and 21N protection functions are shown in Figure 21 and Figure 22 respectively.

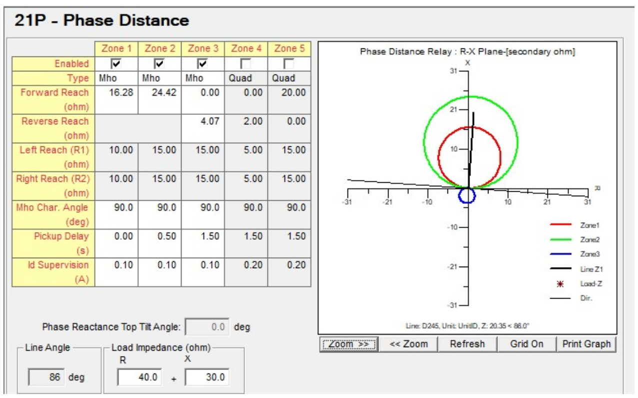


Fig 9: 21P Settings

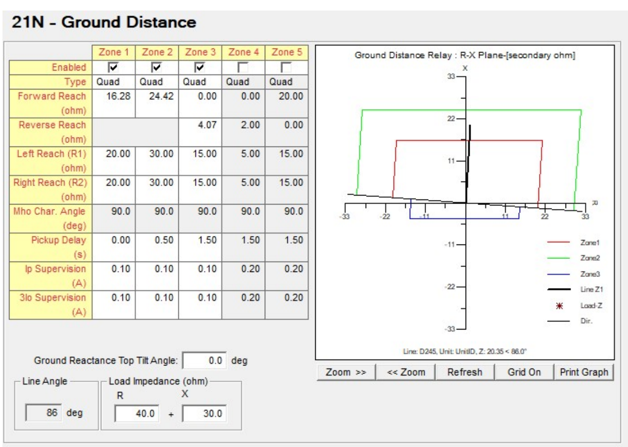


Fig 10: 21N Settings

A. Effect of sub-harmonic filtering

Testing has been carried out to investigate the effect of sub-harmonic filtering. Figure 23 shows the operation the relay during a forward three phase fault without the sub-harmonic filtering (setting disabled). As it can be seen from the results, relay has mis-operated for this fault. Figure 24 shows the operation of the relay for the same fault after enabling the sub-harmonic filtering, which shows the correct operation. Note that this simulation has been carried out assuming that Source-1 is out of service.

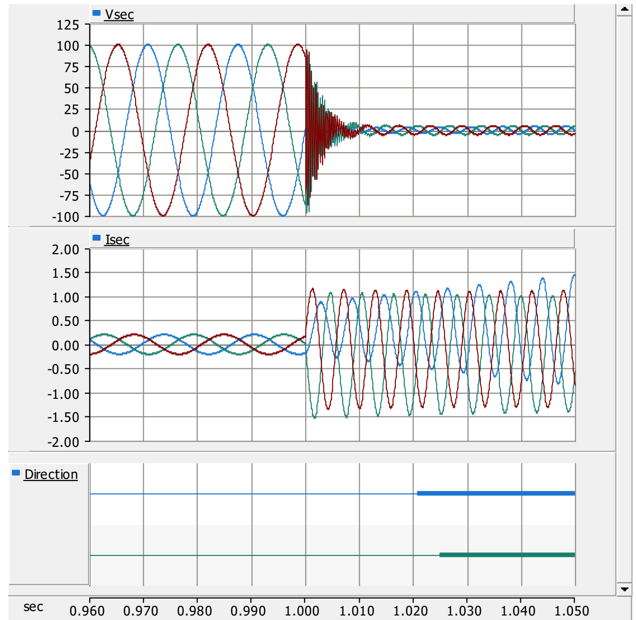


Fig 11: Fault direction identification without sub-harmonic filtering

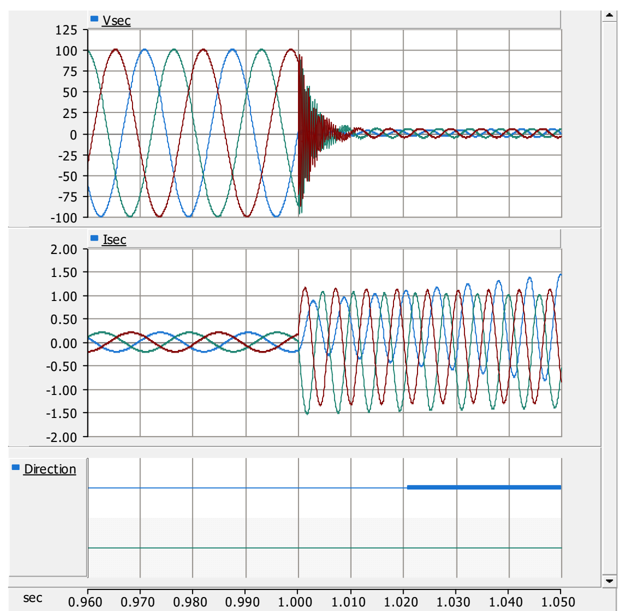


Fig 12: Fault direction identification with sub-harmonic filtering

Different types of fault were simulated at different locations of the network. The directional element showed secured operation for all simulated fault scenarios.

IV. CASE STUDY - 2

This case study covers the conventional directional issues related to series compensated systems. Figure 10 shows the 230 kV, 60 Hz test system used in this study. Transmission line parameters are given in Table-5. 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.

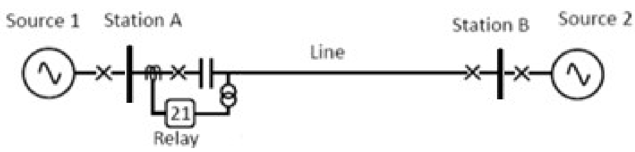


Fig. 13: Series Compensated Test system

Table-1 – System Parameters

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

The impedance zone settings (21P/N) and line parameter settings are shown in Figure 11 and Figure 12, 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. Typical directional element settings were used.

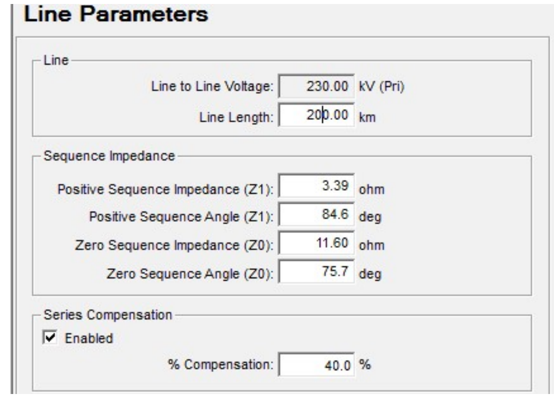


Fig. 14: Line parameter settings

As explained in above sections, 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 13 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 14 shows the operation of a conventional distance relay for the same fault showing Zone-1 trip.

	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

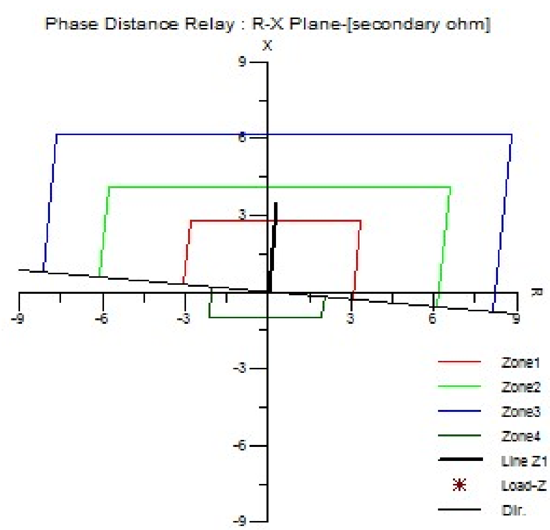


Fig. 15: Impedance settings

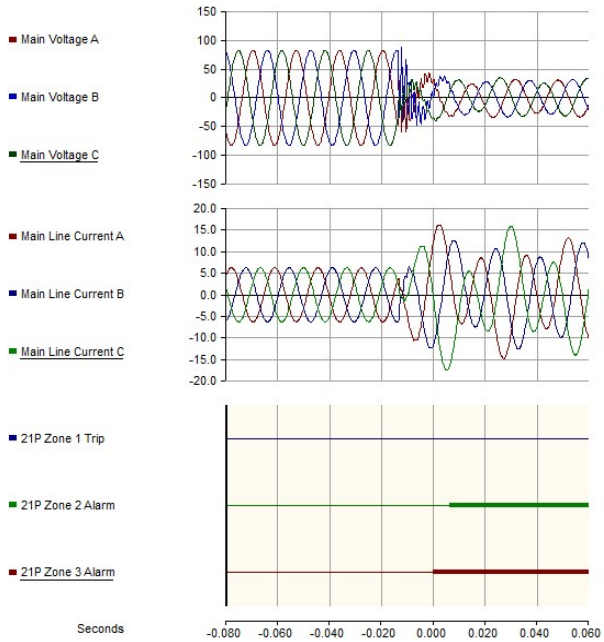


Fig. 16: Effect of sub-harmonics- 90% fault (modified)

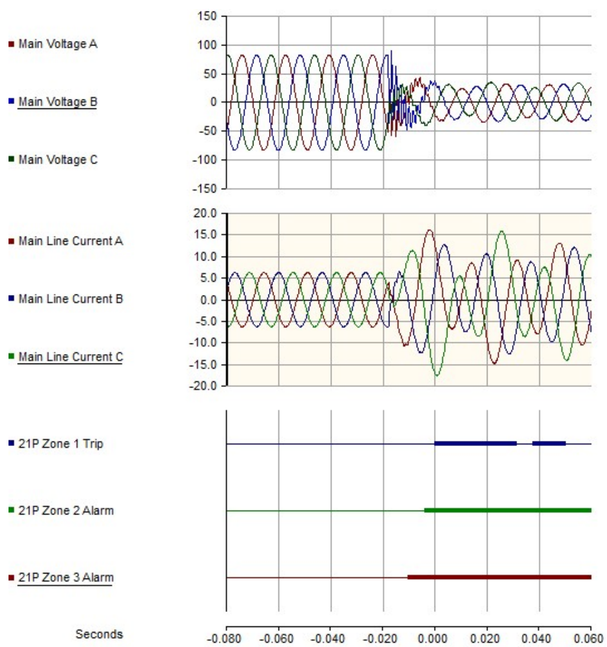


Fig.17: Effect of sub harmonics - 90% (conventional)

In addition to aforementioned sub-harmonic related issues, the common series compensated issues such as voltage inversion, current inversion, etc. are not disused here. More information can be found in [8].

V. Conclusion

In this paper, applicability of a flexible directional element to overcome protection challenges associated with complex network configurations such as inverter connected wind systems was investigated. Applicability of the proposed method for different network configurations was presented including the recommendations for developing basic protection settings. Simulation based testing has also been carried out using simplified networks models to verify the recommended settings. Results presented in this paper demonstrated secured operation for the proposed directional element for the investigated applications based on the proposed changes.

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