Protection of Series Compensated Transmission Lines Using L-PRO Distance Relays

Introduction

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. A majority of transmission systems are protected using distance relays. Although distance relays are used in almost all protection schemes, their performance is less satisfactory in series compensated transmission systems. 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. The distance relays used to protect series compensated transmission lines may mis-operate under these conditions. 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. These conditions may lead to under-reach or over-reach problems [1-3]. This application paper provides an overview of recent enhancements provided in ERLPhase distance relays to overcome the aforementioned issues associated with series compensated lines and basic guidelines to develop settings for typical applications.

Solutions

The solutions for series capacitor compensated transmission lines involve the use of a modified directional function to compensate the effect of the capacitor and a high-pass digital filter to eliminate the effect of the sub-harmonics [4].

Enhanced Directional Element

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.

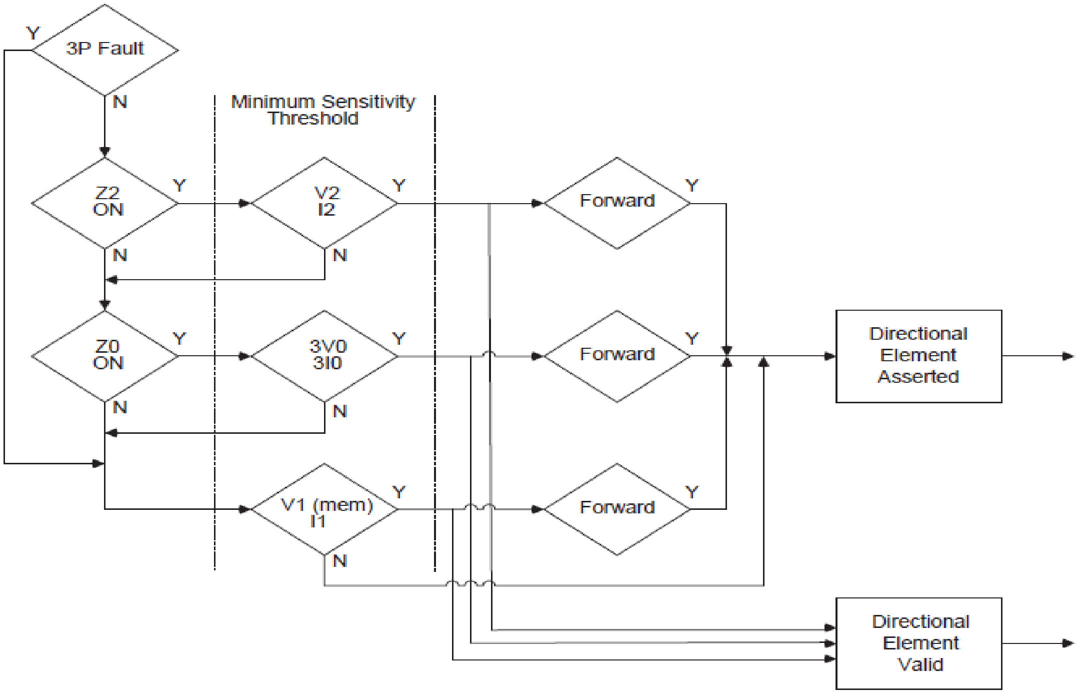


Fig 1: Directional element logic

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 and 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.
When the series capacitor is located at the end of the line ('End-A' relay shown in Fig 2), bus voltages calculated using the line side voltage measurements and the line currents were used to derive the memory voltage calculations and sequence voltage calculations). The relay located at 'End-B' does not need a modification to the directional element.

Fig 2: Series capacitor located at the end of the line

When the series capacitor is located at the middle of line (scenario shown in Fig 3), modifications to the directional element settings is not necessary for the relays located at both ends.

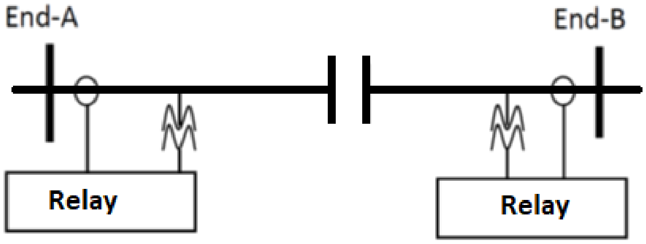


Fig 3: Series capacitor located at the middle of the line

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 and a time delay that is not too large. To accomplish this, a 5th order Butterworth high pass filter with a cutoff frequency of 45 Hz was used for a 50 Hz system. For a 60 Hz system, cutoff frequency is set to 55 Hz. Figure 4 shows the output response of the selected filter at 50 Hz system frequency.

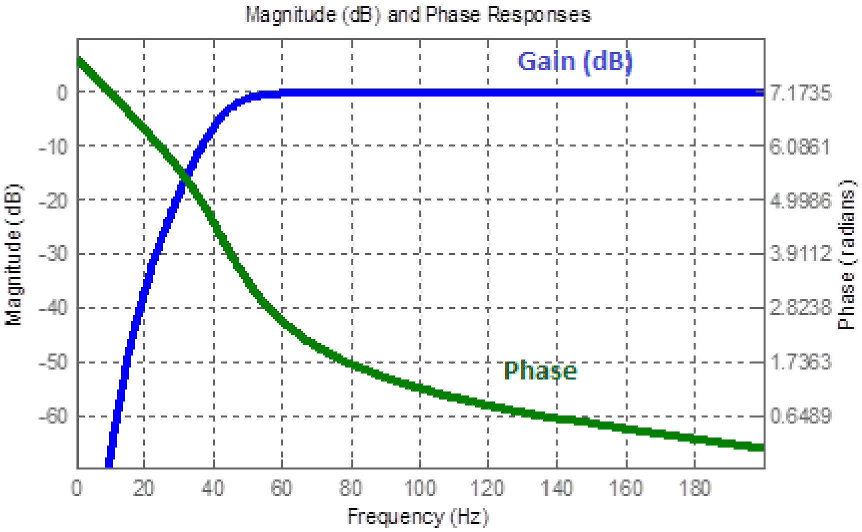
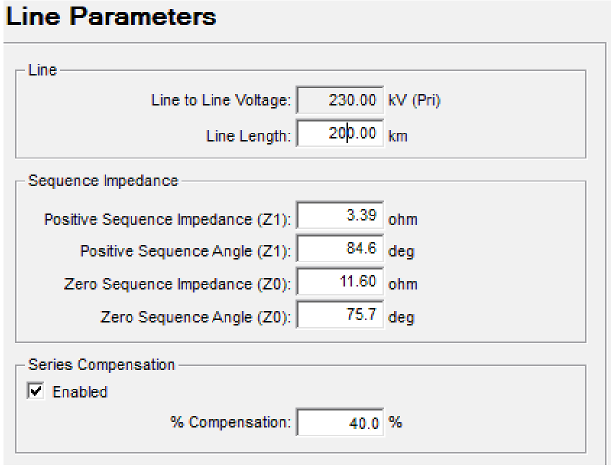


Fig 4: Sub-harmonic removal filter response (50 Hz system)

Relay Settings

As shown in Figure 5, the distance relay has been provided with two settings for series compensated line application.



Line Parameters

Line

Line to Line Voltage: 230.00 kV (Pri)

Line Length: 200.00 km

Sequence Impedance

Positive Sequence Impedance (Z1): 3.39 ohm

Positive Sequence Angle (Z1): 84.6 deg

Zero Sequence Impedance (Z0): 11.60 ohm

Zero Sequence Angle (Z0): 75.7 deg

Series Compensation

☑ Enabled

% Compensation: 40.0 %

Fig 5: Series compensated settings on L-PRO relay

Setting 1: Enable/Disable

This setting will:

- Enable/disable sub-harmonic filters
- Modify the direction element settings based on line side PT/CVT, line current and % compensation setting (setting-2). It should be noted that this is applicable for end of the line capacitor applications only.

Setting 2: % of Series Compensation

This is the percentage of series capacitor compensation as a percentage of positive sequence line impedance. This setting is applicable when the relay is located closer to the series capacitor with line side PT/CVT measurement. For other applications, this should be set to zero.

Application Examples

This section provides guidelines for creating settings for various types of applications (five typical configurations for series compensated lines).

Case 1: Single circuit with capacitor located at the end of the line

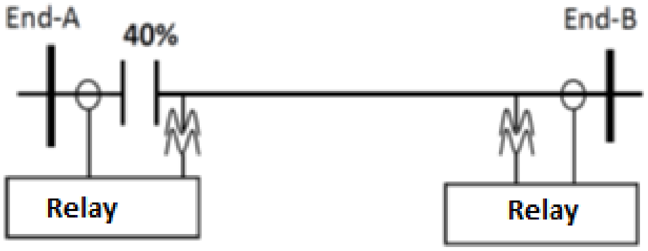


Fig 6: Single circuit with series capacitor located at the end of the line

Table 1: Typical Settings

Setting		End-A	End-B
Series capacitor	Enable/Disable	Enable	Enable
	% Compensation	40%	0%
Forward reach	Z1	Use typical	48%
	Z2	Use typical	Use typical
	Z3	Use typical	Use typical
Reverse reach	Z4	40%	Use typical

Case 2: Single circuit with capacitor located at the middle of the line

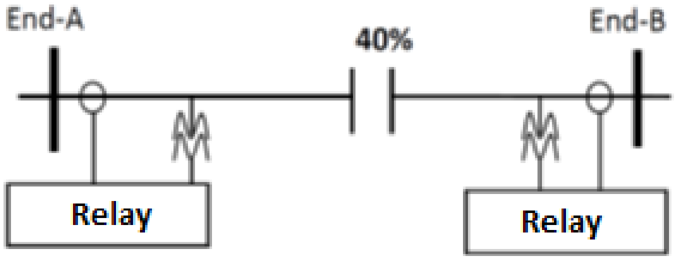


Fig 7: Single circuit with series capacitor located at the middle of the line

Table 2: Typical Settings

Setting		End-A	End-B
Series capacitor	Enable/Disable	Enable	Enable
	% Compensation	0%	0%
Forward reach	Z1	48%	48%
	Z2	Use typical	Use typical
	Z3	Use typical	Use typical
Reverse reach	Z4	Use typical	Use typical

Case 3: Double circuit with capacitors located at the end of the line

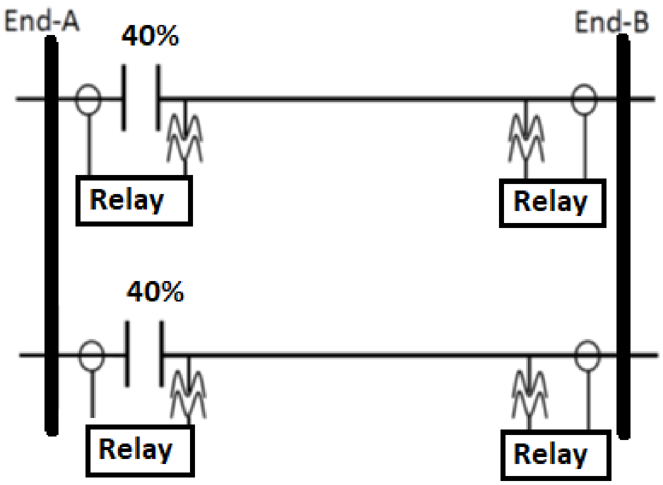


Fig 8: Double circuit with series capacitor located at the end of the line

Table 3: Typical Settings

Setting		End-A	End-B
Series capacitor	Enable/Disable	Enable	Enable
	% Compensation	40%	0%
Forward reach	Z1	Use typical	48%
	Z2	Use typical	Use typical
	Z3	Use typical	Use typical
Reverse reach	Z4	40%	Use typical

Case 4: Double circuit with capacitors located at the middle of the line

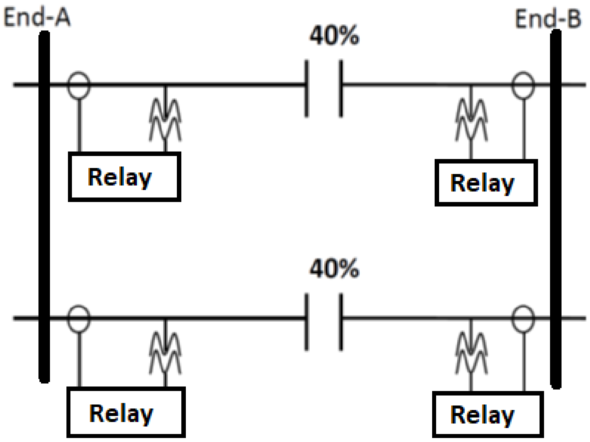


Fig 9: Double circuit with series capacitor located at the middle of the line

Table 4: Typical Settings

Setting		End-A	End-B
Series capacitor	Enable/Disable	Enable	Enable
	% Compensation	0%	0%
Forward reach	Z1	48%	48%
	Z2	Use typical	Use typical
	Z3	Use typical	Use typical
Reverse reach	Z4	Use typical	Use typical

Case 5: Permissive Overreach Transfer Trip (POTT) Scheme

Line current differential schemes are widely used for series compensation lines as they provide secure protection against most practical voltage inversions and sub harmonic conditions. However, the requirement of high-speed communication for line current differential limits applicability in some situations. Of different types of communication aided schemes, POTT schemes are most typically used for providing protection for series compensated lines. For applications using secured operation of POTT schemes, accurate operation of Zone-2 (scheme driven Zone) with forward directional supervision is essential. The POTT scheme can be successfully applied for all the above network configurations. Electromagnetic transient type testing is recommended for validation of protection settings.

Related Considerations

System Interactions

Interaction of series capacitors with other devices such as synchronous generators, power electronic converters, etc. may lead to generation of sub synchronous oscillation (SSO) conditions such as Sub Synchronous Torsional Interaction (SSTI) and Sub Synchronous Controller Instability (SSCI). Secured operation of the distance protection under worse case SSO conditions may not be possible. This is beyond the scope of the line protection level. However, possible SSO conditions should be analyzed at the system study level and precautions shall be taken to eliminate such conditions. If any protection method is used as a solution, it should be coordinated with rest of the protection devices.

Series Capacitor Protection and Transient Recovery Voltages

During trainset faults, voltage across the series capacitors can be significant, which can lead to generation of transient recovery voltage (TRV) conditions which can affect the insulation levels. Use of MOV or air-gap based bypassing is a commonly used approach to eliminate or reduce the possibility of capacitor over voltage and TRV conditions. Even with reduced TRV levels, upgrades to insulation levels may be required. This is beyond the scope of the line protection applications. However, the details of the capacitor by-passing mechanism are essential for determination of optimal settings for line protection relays.

Setting Validation

As described in the above sections, inclusion of series capacitors makes a considerable impact on the power system. Detailed system studies are carried out to determine the system level impacts. The series capacitor bypassing mechanism is one of the key components associated with protection settings. Additionally, system SIR may also have an impact on the performance of protection settings. Therefore, detailed electromagnetic transient type simulation studies (with appropriate modeling of the series capacitors and associated components) are always recommended for validation of protection settings.

Summary

In this paper, applicability of an enhanced distance protection method for series compensated transmission line protection was presented. The proposed method involves the use of a modified directional element and a sub-harmonic removal filter. Applicability for the proposed method for different network configurations was presented. Guidelines and recommendations for developing protection settings for different scenarios such as single circuit lines, double circuit lines and communication aided scheme were presented.

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 Annual Western Protective Relay Conference, 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,” IEE Proceedings - Generation, Transmission and Distribution, Jul 1998, vol. 145, no. 4.
4. N. Perera et al., “Enhanced Distance Protection for Series Compensated Lines”, PAC World 2015, 29 Jun – 02 Jul, 2015; Glasgow, Scotland.
5. L-PRO 4000 Transmission Line Protection Relay User Manual, ERLPhase Power Technologies Ltd. Winnipeg, MB, Canada.
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