The impacts of series compensated EHV lines on distance protection, and a proposed new mitigation solution

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Abstract

Series compensation is extensively applied to the transmission lines to increase the power transfer capability of transmission lines, reduce transmission losses, improve voltage profiles, and improve power oscillation damping and transient stability of power systems. But it modifies the apparent impedance of the transmission lines during fault conditions and might cause the distance protection of transmission lines to encounter directional discrimination issues and reach problems. The non-linear characteristic of metal oxide varistor in series compensation model creates further complexity to the fault analysis and might affects the performance of conventional distance protection scheme. The distance protection issues in the series compensated lines need to be addressed for the reliable and sustainable operation of power system.

The directional discrimination issues related to current inversion and voltage inversion phenomenon, and reach problems related to sub-synchronous oscillation phenomenon are addressed in this thesis report. This report aims to analyse the impacts of series compensation on the performance of conventional distance relays, and proposes a new protection solution to mitigate the shortcomings of distance relays in the series compensated lines. The proposed new protection solution includes: new tripping characteristic of quadrilateral distance relays to cope with the steady-state reach problems due to current or voltage inversion, and a new high-pass filtering technique to handle the transient reach problems due to SSO.

The proposed new protection algorithm is developed in MATLAB. The performance of new protection algorithm is evaluated by simulating a 500 kV two-source power system with a 200 km series compensated line in EMTDC/ PSCAD (Manitoba Hydro). The proposed new protection solution is found to be beneficial.

Keywords: Series compensation, metal oxide varistor, voltage inversion, current inversion, sub-synchronous oscillation, quadrilateral characteristic distance relay, digital high-pass filter.
Abstrakt

Seriekompensation tillämpas i stor utsträckning på överföringsledningarna för att öka överföringsförmågan hos överföringsledningar, minska överföringsförfluster, förbättra spänningsprofiler och förbättra effektdämpning och övergående stabilitet hos elsystem. Men det ändrar transmissionslinjernas uppenbara impedans under felförhållanden och kan orsaka att distansskydd för överföringsledningarna stöter på diskrimineringsproblem och uppnår problem. Den icke-linjära egenskapen hos metalloxidvaristor i seriekompensationsmodell skapar ytterligare komplexitet för felanalysen och kan påverka prestandan hos konventionella distansskyddssystem. Distansskydd problemen i seriekompenserade linjer måste lösas för en pålitlig och hållbar drift av elsystemet.

De riktningsdiskrimineringsproblem som är relaterade till det aktuella inversions- och spänningsinversionsfenomenet och uppnår problem relaterade till subsynkron oscillationsfenomenet tas upp i denna avhandlingsrapport. Denna rapport syftar till att analysera effekterna av seriekompensation för prestanda hos konventionella distansreläer och föreslår en ny skyddslösning för att mildra bristerna i distansreläerna i seriekompenserade linjer. Den föreslagna nya skyddslösningen innefattar: Ny utlösningskaraktäristik för fyrsidig distansreläer för att klara avståndet med stillastående / räckvidden på grund av ström- eller spänningsinversion och en ny högpassfiltrengsteknik för hantering av övergående över- Nå problem på grund av SSO.

Den föreslagna nya skyddsalgoritmen har utvecklats i MATLAB. Utförandet av den nya skyddsalgoritmen utvärderas genom simulering av ett 500 kV två-källa kraftwerk med en 200 km serie kompenserad linje i EMTDC / PSCAD (Manitoba Hydro). Den föreslagna nya skyddslösningen har visat sig vara fördelaktig.

Nyckelord: Seriekompensation, metalloxidvaristor, spänningsinversion, ströminversion, subsynkron oscillation, fyrsidig karakteristiskt distansrelä, digitalt högpassfilter.
DEDICATION

I would like to dedicate this piece of work to my family and spouse for their love and support throughout this journey, specially to my cute and loving kids Syed Taqwim Arif, Syed Ibrahim Arif and Syed Abdul Ahad for their endless love.
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This thesis report is the result of degree project work in EI270X Electrotechnical Theory and Design, which is the fulfilment of Master degree program in Electric Power Engineering at Kungliga Tekniska Högskolan (KTH) Royal Institute of Technology Stockholm-Sweden. This project is a cooperation between KTH and ABB. The project work is carried out at ABB Corporate Research Center (SECRC) under Power System Development Team in Västerås-Sweden.

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I am grateful to my supervisor Jianping Wang at ABB who introduced me into the real research world and provided me an opportunity to carry out this interesting and challenging project in the world’s leading relays manufacturing, automation and power company ABB under his kind supervision.

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**List of Abbreviations**

<table>
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<th>Description</th>
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<tbody>
<tr>
<td>FSC</td>
<td>Fixed Series Capacitor</td>
</tr>
<tr>
<td>TCSC</td>
<td>Thyristor Controlled Series Compensator</td>
</tr>
<tr>
<td>SC</td>
<td>Series Compensation</td>
</tr>
<tr>
<td>MOV</td>
<td>Metal Oxide Varistor</td>
</tr>
<tr>
<td>EHV</td>
<td>Extra-High Voltage</td>
</tr>
<tr>
<td>UHV</td>
<td>Ultra-High Voltage</td>
</tr>
<tr>
<td>PMU</td>
<td>Phasor Measurement Unit</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>SSO</td>
<td>Sub-Synchronous Oscillation</td>
</tr>
<tr>
<td>VT</td>
<td>Voltage Transformer</td>
</tr>
<tr>
<td>CT</td>
<td>Current Transformer</td>
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<td>SIR</td>
<td>Source to line Impedance Ratio</td>
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Chapter 1

Introduction and Literature Survey

This chapter begins with the brief introduction of series compensation in long transmission corridors and its impacts on existing distance relays, followed by a literature review showing the huge research on the protection issues in the series compensated lines. Existing industrial distance protection solutions for series compensated lines are also addressed in this chapter. This chapter also includes the brief definition of problem, aim and objectives, and methodology of this degree project. Finally, the chapter is concluded with an overview of simulation results and scenarios.

1.1 Background

The world's population is expected to reach 7 billion people, and the energy demand is anticipated to increase by 71% between 2012-2040 in non-OECD (Organisation for Economic Co-operation and Development) countries [1]. This drives power engineers to generate and transmit maximum possible power through the long transmission lines to meet the fast-growing demands of electric power. The strong public and political opposition as well as high infrastructure costs for building new transmission lines drives the power engineer to install Series Compensation (SC) in Extra High Voltage/ Ultra High Voltage (EHV/ UHV) transmission lines. SC is achieved by integrating a Fixed Series Capacitor (FSC) or Thyristor Controlled Series Compensator (TCSC) in series with the transmission line, each with its own advantages [2].

The benefits of SC include: enhanced power transfer capability of bulk transmission corridors, improved voltage profile over the transmission lines, reduced transmission losses, enhanced power flow control over the transmission lines, and improved power oscillation damping and transient stability of power system [3-6].

High fault current through the series capacitor causes overvoltage across it. A series capacitor is sensitive to overvoltage and it is uneconomical to design the series capacitor to withstand such overvoltage during fault conditions. Therefore, a series capacitors is always accompanied by metal oxide varistor (MOV). A MOV takes the advantages of non-linear resistance characteristic of zinc oxide to protect the series capacitor against overvoltage during fault conditions [7-8].

A numerical distance relay is one of the feasible and reliable protection solutions to protect EHV/ UHV transmission against any fault type [9-10]. Distance relays use the local voltage and current at the relay position to compute the apparent impedance, and detect the fault conditions by comparing the computed apparent impedance with the relay setting [11].

The integration of SC in transmission line brings several protection challenges and problems including directional discrimination issues and reach problems for distance relays [3, 6, 8, 12, 13-16].
It is possible to correct and adjust the setting of the distance relays for series compensated lines if the series capacitor always remains in the fault loop, but the operation of the non-linear MOV modifies the apparent impedance of the transmission line during fault conditions, which affects the performance of the distance protection scheme and adds further complexity to the fault analysis and distance relay operation. During high-current fault conditions, the MOV conducts and bypasses the series capacitor thereby changing the apparent impedance of transmission line from its compensated impedance to its uncompensated impedance. During low-current fault conditions, MOV does not conduct and the series capacitor remains in the fault loop, thereby modifying the apparent impedance of the transmission lines. Low-current fault conditions might cause under-reach and over-reach problems, and directional discrimination issues for conventional distance relays.

Thus, a series compensated line affects not only the performance of a distance protection scheme but also presents technical challenges to protection engineers and researchers to find new protection solutions and mitigation techniques to handle such problems.

1.2 Literature review

Reviews showing the impacts of series compensated line on distance protection are presented in [3], [6], [8], [13-14].

Adaptive protection scheme to correct the tripping boundary of distance relays in MOV protected series compensated lines is proposed in [17-19], based on compensation of voltage drops across series capacitors. This protection scheme is one of the effective approaches to handle the limitation of distance relays in the series compensated lines but this scheme requires additional Voltage Transformer (VT) across the SC. A slightly different adaptive protection algorithm is proposed in [20], which considers the compensation voltage in the impedance calculation of the fault loop depending upon the direction of fault current. But this protection scheme needs a reliable communication channel, and voltage and current information at both ends.

Memory voltage polarization uses pre-fault voltage during voltage inversion and is one of the most common solutions to handle directional problems, or voltage inversion issues [3], [8]. However, a new directional relaying algorithm based on voting technique using an integrated approach is proposed in [21] to handle directional issues for distance relay. A slightly different approach to cope with directional problems is used in [22], based on the phase change in positive sequence current and magnitude change in positive sequence voltage.

Current or voltage inversion leads to directional discrimination issues [12], [22] for conventional distance relays. Sub-Synchronous Oscillation (SSO) leads to transient over-reach problems for conventional distance relays [8], [23] which might slow down the operation for distance relays [16].

Prony algorithm based filtering technique is proposed in [15] to cope with impedance measurement errors due to SSO.
A backup distance protection scheme for the series compensated lines based on mutual impedance between phases is proposed in [24]. But this protection scheme considers only un-balanced faults.

A travelling wave based protection scheme is proposed in [25] which offers high speed protection, but the protection scheme faces some limitation during slowly evolving faults. Artificial neural networks based distance protection is proposed in [26-27], but this protection algorithm requires huge and complex training data.

Non-distance protection schemes for series compensated lines include: novel unit protection scheme [28], pilot protection scheme [29], fuzzy logic technique using DC line current [30], and PMU based protection scheme [31].

1.3 Existing protection solutions

Different relay manufacturers already use distance relays for series compensated lines. Table 1-1 outlines the numerical distance relays for series compensated lines by different relay manufacturers.

<table>
<thead>
<tr>
<th>Relay Vendors</th>
<th>Distance relays</th>
</tr>
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<tbody>
<tr>
<td>General Electric (GE)</td>
<td>GE D90Plus [16]</td>
</tr>
<tr>
<td>Schweitzer Engineering Labs, Inc. (SEL)</td>
<td>SEL-421-5 [3]</td>
</tr>
<tr>
<td>ABB</td>
<td>REL 670 [32]</td>
</tr>
<tr>
<td>Siemens</td>
<td>SIPROTEC 4 7SA522 [33]</td>
</tr>
</tbody>
</table>

Almost all the distance relays use hybrid protection scheme to protect series compensated line.

1.3.1 Memory polarized directional comparator

GE, SEL, ABB and Siemens relay manufacturers use 100% memory polarized directional comparators to handle voltage inversion issues [16], [8]. Memory voltage polarization uses pre-fault voltage during voltage inversion. This guarantees the distance relays to operate during forward faults and fail to pick-up during backward faults which is the disadvantage of using memory voltage polarization.

1.3.2 Multi-input comparator approach and direct trip scheme

GE and SEL relay manufacturers use multi-input comparator approach to handle the current inversion issues. Multi-input comparator approach uses fault-loop current for phase and ground distance protection, and negative and zero sequence currents for the ground element [16]. Since the fault current shifts by more than 90 degree during current inversion, so the distance relays might not operate during current inversion for short period. So, the vendors of these relays recommend to use high speed overcurrent protection for direct tripping during current inversion.
1.3.3 Adaptive dynamic distance reach control strategy

GE and SEL relay manufacturers use adaptive dynamic reach control strategy to handle over-reaching problems [3], [16]. This algorithm adjusts the tripping boundary of the distance relay accordingly using the current magnitude by Eq. (1.1) [3].

\[
Z_{\text{reduced}} = Z_R - \frac{U_L}{|I|} \angle Z_R
\]

Where, \( Z_R \) and \( \angle Z_R \) is the relay set value of complex impedance and phase angle respectively; \( U_L \) is the set value of voltage that is equal to the voltage protection level of SC.

This algorithm reduces the reach sufficiently to handle steady-state/transient over-reaching issues as shown in Figure 1.1. The limitation with this algorithm is that it does not consider high fault resistance. The algorithm fails to detect high impedance faults at the remote end and thus leaves some portion of the line uncovered against faults.

The literature review shows that a lot of research efforts have been made during the past few decades to study the impacts of series compensated lines on distance protection and find some new protection solution to mitigate all the shortcomings associated with series compensated lines to maintain the reliability, selectivity, sensitivity and security of distance relays. But the protection of series compensated lines is still challenging for researchers and protection engineers in both the academic and industrial worlds.

1.4 Problem Definition

The benefits of SC [3-6] brings significant protection challenges including directional discrimination and reach problems [8], [12] for distance protection scheme. The distance...
protective relays might not operate properly during faults on the series compensated lines. An accurate power system model with series compensated line is required to investigate the impacts of series compensation on the voltage and current signal at relay position so that some mitigation techniques or new protection solution is found.

1.5 Aim and Objectives
The overall aim of this degree project is to analyze the impacts of the series compensated EHV transmission line on the performance of distance protection scheme. The objectives are outlined as follows:

- Develop a PSCAD model of a 500 kV two-source power system with series compensated EHV line
- Investigate the impacts of special phenomena associated with series compensation on the voltage and current at relay position
- Analyse the impacts of SC on the performance of a conventional distance protection scheme
- Propose mitigation techniques and a new protection algorithm to handle the shortcomings of the distance relays in series compensated lines

1.6 Methodology
This project considers a 500 kV two-source power system with a 200 km EHV transmission line. Frequency dependent model for transmission line is used to perform accurate transient analysis. Series compensation is considered at sending bus end. The equivalent power system is modeled in EMTDC/ PSCAD (Manitoba Hydro) and transient analysis is performed for different MOV operations and various system operating conditions. The protection algorithm of a quadrilateral distance relay is developed in MATLAB. The simulation data from PSCAD is exported into MATLAB and the impacts of series compensation on distance protection is analyzed. A new setting of the distance relay is proposed to overcome steady-state under-reach and over-reach problems, and a Butterworth high-pass filter is proposed and implemented to cope with transient over-reach problems of distance relays in series compensated lines.

1.7 Scenarios
The impacts of series compensation on distance protection is analyzed for both forward and backward faults under different system operating conditions. The proposed distance relay algorithm and performance of Butterworth high-pass filter is tested for forward-backward faults with different MOV operating conditions, different fault resistance, different fault location, and different source impedance conditions. Since 80% of faults in power system are phase-to-ground faults so the simulation results consider phase-to-ground faults to simplify the analysis however
the protection algorithm works for all type of faults i.e. phase-to-ground, phase-to-phase, and three-phase faults.

The block diagram in Figure 1.2 gives an overall view of simulation results and scenarios to be analyzed.

![Impacts of SC on distance protection](image)

*Figure 1.2: Overview of simulation results and scenarios to be analyzed*

### 1.8 Thesis outline

This report focuses on the effort involved in analyzing the impacts of series compensation on conventional distance protection, and developing new protection algorithm to protect series compensated lines. Directional issues related to the current inversion or voltage inversion phenomenon, and reach problems related to sub-synchronous oscillation are also addressed in this report. This report is organized in eight chapters as follows:

Chapter 1 gives a brief introduction to the background, literature review, problem description, aim and objectives, methodology, and the overview of simulation results followed by thesis outline.

Chapter 2 gives an overview of conventional distance relays as well as the typical protection zones, and tripping characteristic for phase-to-ground/ phase-to-phase faults during both forward/ backward faults.
Chapter 3 presents series compensation model followed by the impacts of MOV operation during different fault conditions.

Chapter 4 explains special phenomena associated with series compensated lines and its impacts on the conventional distance relays.

Chapter 5 shows the impacts of series compensation on the characteristic of line impedance/performance of conventional distance relays for different location of VT or series compensation.

Chapter 6 presents the proposed new mitigation solution to handle the shortcomings and protection issues of distance relays in the series compensated lines.

Chapter 7 focuses on the simulation results to verify the proposed new protection scheme during different phenomena for various forward and backward faults. Finally, the overall conclusions of this report are presented in chapter 8, and this chapter ends with future research and general recommendation of author.
Chapter 2

Principle of Distance Protection

This chapter begins with the brief overview of conventional distance protection scheme, which is then followed by protection zones of typical distance relay. Impedance measurements during both phase-to-ground and phase-to-phase fault loops are explained for both forward and backward faults. The tripping characteristic of typical conventional distance relay is defined as well for forward and backward faults. The chapter ends with the impacts of fault resistance on impedance measurements.

2.1 Overview of distance protection scheme

In order to analyze intelligently the impacts of series compensated transmission lines on distance protection, it is necessary to have firm understanding about the operational principles of conventional distance protection scheme for uncompensated transmission line. It is then easy to extend the knowledge for series compensated transmission line to analyze the impacts of SC on the performance of existing distance relays and resolve the additional relaying problems caused by the integration SC.

Distance relays are widely used to protect long distance transmission lines [9-10]. The operational principle of distance protection scheme is based on calculation of impedance from the voltage and current signal at relay position and compares the computed value of impedance with the pre-determined or set value of relay. Distance relay detects a fault condition if the computed impedance lies inside the characteristic defined by the setting of distance relay. The protection algorithm of distance relay uses six impedance measuring loops to cover all possible and expected forward and reverse faults in transmission line; three impedance measuring loops cover phase-to-ground faults and three impedance measuring loops cover phase-to-phase faults as well as three phase faults [32].

The two most widely and commonly used characteristics of distance relays are; mho and quadrilateral characteristic. Distance relay with quadrilateral characteristic provides adequate coverage to the fault resistance than mho characteristic relay. Quadrilateral characteristic distance relay can easily detect high impedance faults. This project considers distance relay with the quadrilateral characteristic.

2.2 Protection zones

The beauty of distance protection is the multi zones protection which offers primary protection as well as remote backup protection. Distance relay provides instantaneous protection in zone 1 and delayed protection in other zones. The modern distance relay has 3-5 forward zones and one reverse protection zone depending upon the type of relay [32].
This project considers two zones for forward faults and one zone for reverse faults. Typical distance relay protects 80% of protected line in zone-1 and 130% of line in zone-2 against all forward faults. The relay also provides remote backup protection to 80% of the backward line in zone-RV against all reverse faults. Figure 2.1 shows the forward and reverse zones of typical distance relay for typical protected line between bus A and bus B. The quadrilateral characteristic curve of typical distance relay is shown in Figure 2.2.
As mentioned earlier, the protection algorithm of typical quadrilateral characteristic distance relay uses six impedance measuring loops to cover all possible and expected forward and reverse faults in transmission line; three impedance measuring loops cover phase-to-earth faults and three impedance measuring loops cover phase-to-phase faults as well as three phase faults. To analyze the factors affecting the impedance characteristic of the line, it is vital to explain first the impedance measurement of the line during forward/ backward faults in both phase-to-ground and phase-to-phase fault loops.

2.3 Impedance measurements

Consider a typical EHV transmission line between bus A and bus B in a typical two-source power system as shown in Figure 2.3.

![Figure 2.3: Typical two source power system with EHV transmission line](image)

Where, \( U_s \) and \( U_r \) is the source voltage at sending bus S and receiving bus R respectively; \( Z_s \) and \( Z_r \) is the source impedance at sending and receiving end respectively; \( Z_L \) is the impedance of protected EHV transmission line; \( I_s \) and \( I_r \) is the contribution of fault current from two sources; \( U_A \) and \( U_B \) is the phasor voltage at bus A and bus B respectively; R1 is the distance relay installed at bus A.

To calculate the impedance of transmission line during phase-to-ground and phase-to-phase faults for both forward and backward faults, we consider forward fault occurring at P % of protected line impedance from bus A; and backward fault occurring at end of backward line as shown in Figure 2.3. The forward and backward faults occur independently of each other.

2.3.1 Forward Faults

2.3.1.1 Phase-to-ground fault

During phase-to-ground faults, the power system can be modelled as positive, negative and zero sequence network as shown in Figure 2.4.
Where, \((\bar{Z}_{S.1}, \bar{Z}_{S.2}, \bar{Z}_{S.0})\); \((\bar{Z}_{L.1}, \bar{Z}_{L.2}, \bar{Z}_{L.0})\); and \((\bar{Z}_{R.1}, \bar{Z}_{R.2}, \bar{Z}_{R.0})\); is the positive, negative and zero sequence impedance of; sending source; line; and receiving source respectively, such that \(\bar{Z}_{S.1} = \bar{Z}_{S.2}\); \(\bar{Z}_{L.1} = \bar{Z}_{L.2}\); \(\bar{Z}_{R.1} = \bar{Z}_{R.2}\).

\((\bar{i}_{S.1}, \bar{i}_{S.2}, \bar{i}_{S.0})\) and \((\bar{i}_{R.1}, \bar{i}_{R.2}, \bar{i}_{R.0})\) are the sequence currents of sending and receiving source, such that \(\bar{i}_{S.1} = \bar{i}_{S.2} = \bar{i}_{S.0} = \frac{1}{3}\bar{i}_S\); \(\bar{i}_{R.1} = \bar{i}_{R.2} = \bar{i}_{R.0} = \frac{1}{3}\bar{i}_R\); and \(R_f\) is the fault resistance.

During phase-to-ground fault, the apparent impedance seen by distance relay R1 at bus A is given by Eq. (2.1).

\[
\bar{Z}_{PG} = \frac{\bar{U}_A}{\bar{i}_S} = p \cdot (\bar{Z}_{L.1} + \bar{Z}_{L.n}) + k_R \cdot R_f
\]  

(2.1)

Where, \(\bar{Z}_{L.n} = \frac{\bar{Z}_{L.0} - \bar{Z}_{L.1}}{3}\) [33]; and \(k_R = 1 + \frac{\bar{i}_R}{\bar{i}_S}\)

In general, the apparent impedance of transmission line during phase-to-ground fault without SC is given by Eq. (2.2).

\[
\bar{Z}_{NSC} = \bar{Z}_{L.1} + \bar{Z}_{L.n}
\]  

(2.2)

Figure 2.4: Positive, negative and zero sequence model of power system during phase-to-ground fault
2.3.1.2 Phase-to-phase fault

During phase-to-phase fault, the three-phase system can be represented by Figure 2.5. Assume the fault between phase “a” and phase “b”.

Figure 2.5: Phase-to-phase fault phase “a” and phase “b”

Where, \((\overline{U}_{A,a}, \overline{U}_{A,b}, \overline{U}_{A,c})\) and \((\overline{U}_{B,a}, \overline{U}_{B,b}, \overline{U}_{B,c})\) are the three phase voltages at local bus A and remote bus B respectively; \((\overline{I}_{S,a}, \overline{I}_{S,b}, \overline{I}_{S,c})\) and \((\overline{I}_{R,a}, \overline{I}_{R,b}, \overline{I}_{R,c})\) are the three phase currents at local bus A and remote bus B respectively.

During phase-to-phase fault, the apparent impedance seen by distance relay R1 at bus A is given by Eq. (2.3).

\[
\overline{Z}_{pp} = \frac{\overline{U}_{A,a} - \overline{U}_{A,b}}{\overline{I}_{S,a} - \overline{I}_{S,b}} = p \cdot \overline{Z}_{L-1} + k_{R1} \cdot \frac{R_f}{2}
\]  

(2.3)

Where, \(k_{R1} = 1 + \frac{\overline{I}_{R,a}}{\overline{I}_{S,a}}\); and \(k_{R2} = 1 + \frac{\overline{I}_{S,a}}{\overline{I}_{R,a}}\)

In general, the apparent impedance of transmission line during phase-to-phase fault without SC is given by Eq. (2.4).

\[
\overline{Z}_{NSC} = \overline{Z}_{L-1}
\]  

(2.4)

Figure 2.6 shows the impedance characteristic of transmission line in R-X diagram with effect of fault resistance (a) during phase-to-ground faults and (b) phase-to-phase faults.
Figure 2.6: Impedance characteristic of line in R-X diagram (a) during phase-to-ground faults and (b) phase-to-phase faults

Figure 2.7 shows the zone-1 tripping boundary of quadrilateral characteristic distance relay defined by Eq. (2.5).

$$\bar{Z}_{zone 1} = 0.8 \cdot \bar{Z}_{NSC} + k_R \cdot R_f$$

(2.5)

Figure 2.7: Zone-1 tripping boundary of quadrilateral characteristic distance relay
2.3.2 Backward Faults

Now consider backward fault occurring at the end of backward line as shown in Figure 2.3. Since both active and reactive power reverses its direction during backward faults, so the distance relay R1 sees the apparent impedance of backward line in 3rd quadrant.

By the same analysis as performed for forward faults, the apparent impedance seen by distance relay R1 during phase-to-ground and phase-to-phase backward faults is given by Eq. (2.6) and Eq. (2.7) respectively.

\[
\tilde{Z}_{PG_{-}RV} = -\tilde{Z}_{S_{-}1} - \tilde{Z}_{S_{-}n} - k_R \cdot R_f \tag{2.6}
\]

\[
\tilde{Z}_{PP_{-}RV} = -\tilde{Z}_{S_{-}1} - k_R \cdot \frac{R_f}{2} \tag{2.7}
\]

Where, \( \tilde{Z}_{S_{-}n} = \frac{\tilde{Z}_{S_{-}0} - \tilde{Z}_{S_{-}1}}{3} \); \( k_R = 1 + \frac{I_S}{I_R} \)

Figure 2.8 shows the impedance characteristic of backward line in R-X diagram with effect of fault resistance (a) during phase-to-ground; (b) phase-to-phase backward faults.

**Figure 2.8: Impedance characteristic of backward line in R-X diagram with effect of fault resistance (a) during phase-to-ground; (b) phase-to-phase backward faults**

Figure 2.9 shows the zone-RV tripping boundary of quadrilateral characteristic distance relay for backward faults in general.
2.4 Impacts of fault resistance

Fault resistance is always associated with the occurrence of fault. Fault resistance is basically the combination of arc resistance, tower resistance and tower footing resistance given by Eq. (2.8).

\[ R_f = R_{arc} + R_{tower} \]  \hspace{1cm} (2.8)

Where, \( R_f \) is fault resistance; \( R_{arc} \) is arc resistance, and \( R_{tower} \) is tower resistance.

Arc resistance can be calculated by Warrington’s formula given by Eq. (2.9) [34].

\[ R_{arc} = \frac{28707 \cdot L}{(I)^4} \]  \hspace{1cm} (2.9)

Where, \( L \) is length of arc (meter) and \( I \) is the RMS value of arc current (amperes).

However, in comparison with Warrington’s formula, a new formula for arc resistance is derived in [35] given by Eq. (2.10) and Eq. (2.11).

\[ R_{arc-1} = \frac{1080.4 \cdot L}{1350.5 \cdot I} \]  \hspace{1cm} (2.10)

\[ R_{arc-2} = \left( \frac{855.3}{I} + \frac{4501.6}{I^2} \right) L \]  \hspace{1cm} (2.11)
The contribution of fault currents by both sending and receiving end source in two-source power system introduce the complex quantity in fault resistance. The fault currents of both sources in the fault resistance produce the capacitive or inductive effects depending upon the phasor relationship of both currents. Thus, the overall impact of fault currents by both sources on fault resistance is complex quantity thereby yielding the fault impedance as a resultant quantity given by Eq. (2.12). The fault impedance sometime causes over-reach problems if both currents are out of phase.

\[ Z_f = \left( 1 + \frac{I_R}{I_S} \right) R_f \]  

(2.12)
Chapter 3

Impedance Locus and Series Compensation Model

The overall objective of this chapter is to present a brief overview of Series Compensation (SC) in long transmission corridors, followed by the power transfer capability of series compensated lines. This chapter also gives a brief overview showing the impacts of a series capacitor on the characteristic of transmission lines. SC model including protective circuit for a series capacitor is also addressed in this chapter. The chapter is finally concluded on the impacts of MOV operation during different fault conditions.

3.1 Overview of SC

In 1928, the world first SC system was installed on the emerging US transmission grid by GE, while ABB has implemented the first SC in 1950 and continued to refine and develop this technology in such a way that today ABB leads the world in SC and effective power transmission. The basic objective of SC is to reduce the inductive reactance of transmission line and increase the power transfer capability of transmission line [6] [36]. SC reduces the cost significantly for the transmission lines typically greater than 200 miles as compared to the building of a new equivalent transmission lines [6]. Other advantages of SC include: improved voltage profile, power flow control over the transmission lines, reduced transmission losses, improved power oscillation damping and transient stability of power system [3-6]. The advantages of SC are associated with phenomena: current inversion, voltage inversion, and SSO which leads to directional discrimination issues and reach problems for conventional distance relays [8] [12].

3.2 Power transfer capability

To see the impacts of a series capacitor on the power transfer capability, consider a simple two-source power system with EHV transmission line (a) without SC; and (b) with SC as shown in Figure 3.1.

Figure 3.1: EHV transmission line in a simple two-source power system: (a) without SC; and (b) with SC
Where, $U_s \angle \theta_s$ and $U_r \angle \theta_r$ is the phasor voltage at local bus A and remote bus B respectively; $Z_L$ is the impedance of transmission line; $X_C$ is the capacitance of a series capacitor; $I_s$ is the current flowing in transmission line.

The active and reactive power flow through the lossless transmission line without SC is given by Eq. (3.1) and Eq. (3.2) respectively.

$$P = \frac{U_s \cdot U_r \cdot \sin(\delta)}{X_L} \tag{3.1}$$

$$Q = \frac{U_s \cdot \Delta U \cdot \cos(\delta)}{X_L} \tag{3.2}$$

Where, $P$ and $Q$ is the active and reactive power flow over transmission line; $\delta = (\theta_s - \theta_r)$ and $\Delta U = (U_s - U_r)$ is the angle difference and voltage difference respectively between local bus A and remote bus B.

Keeping the same voltage phasors at local and remote bus, the power transfer capability of transmission line can be enhanced by reducing the inductive reactance of the line. This is achieved by integrating a series capacitor in transmission line as shown in Figure 3.1(b). The active and reactive power flow through the lossless transmission line with SC is given by Eq. (3.3) and Eq. (3.4) respectively.

$$P = \frac{U_s \cdot U_r \cdot \sin(\delta)}{X_L - X_C} \tag{3.3}$$

$$Q = \frac{U_s \cdot \Delta U \cdot \cos(\delta)}{X_L - X_C} \tag{3.4}$$

The power transfer capability depends upon the degree of series compensation. Degree of series compensation is the ratio of capacitive reactance to the inductive reactance of transmission line and can be expressed mathematically by Eq. (3.5).

$$k = \frac{X_C}{X_L} \tag{3.5}$$

Eq. (3.3) can also be expressed in terms of compensation level by Eq. (3.6).

$$P = \frac{U_s \cdot U_r \cdot \sin(\delta)}{X_L (1 - k)} \tag{3.6}$$

The power transfer doubles for 50% compensation level.
3.3 Locus of load and line impedance in R-X diagram

The locus of load impedance in R-X diagram depends upon the direction of active and reactive power flow. The direction of active and reactive power flow depends upon the sign of $\delta$ and $\Delta U$ respectively. Positive active/ reactive power flow means the power flowing from local bus A to remote bus B. Positive active power flow occurs, if the voltage at local bus A leads the voltage at remote bus B, i.e. $\delta > 0$. Positive reactive power flow occurs; if the magnitude of voltage at local bus A is greater than the magnitude of voltage at remote bus B, i.e. $\Delta U > 0$.

The direction of active and reactive power defines the locus of impedance in R-X diagram during both normal load and fault conditions. Figure 3.2 shows the overview of impedance locus in R-X diagram depending upon the direction of active/ reactive power.

![Figure 3.2: Impedance locus in R-X diagram](image)

Where, $Z_L$ and $Z_{Load}$ represents the impedance of transmission line and load respectively; $\phi$ and $\theta_{Load}$ is the power factor angle of line impedance and load impedance respectively.

The line characteristic lies in 1st quadrant if both active and reactive power flows are positive and the line characteristic lies in 4th quadrant if reactive power changes the direction which might occurs during current or voltage inversion phenomenon.

This project considers the locus of load impedance in 1st quadrant during normal operating condition. This means that both active and reactive power flows from local bus A to remote bus B.
under normal operating condition. The series capacitor modifies the characteristic of line impedance in R-X diagram as shown in Figure 3.3 (left). The characteristic of line impedance depends upon the compensation level. Higher the degree of compensation, more the impedance characteristic will be shifted into 4th quadrant as shown in Figure 3.3 (right).

*Figure 3.3: left: Characteristic of line impedance; without (black) and with (red) series capacitor, right: impacts of compensation level on line characteristic*

Normally, the conventional distance relays measure the line impedance in 1st quadrant. However, the integration of series compensation in transmission line shifts the impedance locus into 4th quadrant which causes steady-state under-reach problems or directional discrimination problems for conventional distance relays depending upon the strength of feeding source.

The setting of distance relays can be adjusted for series compensated lines to provide adequate protection if a series capacitor always remains in the fault loop, but this is not true always due to the presence of non-linear MOV device in series compensation model which sometimes bypasses the series capacitor depending upon the level of fault current. Thus, the MOV creates further complexity for fault analysis and operation of distance relays.

### 3.4 Series Compensation Model

The series capacitor is very sensitive to overvoltage across it and it is uneconomical to design a series capacitor to withstand high overvoltage during fault conditions. Typically, the series capacitor is capable to handle overvoltage up-to 2-3 times the normal rated capacitor voltage. The series capacitor is therefore protected by the parallel connected non-linear MOV device against overvoltage conditions. In 1970, the very first MOV was used to protect a series capacitor [4]. The
MOV has specific energy rating, and limited capability to absorb energy during fault conditions. Therefore, MOV is protected by the high-speed bypass circuit breaker before the critical energy rating of MOV has reached [4].

Figure 3.4 shows the (a) typical series compensation model; (b) non-linear characteristic of MOV. The typical overvoltage protection system of a series capacitor consists of MOV, spark gap, high-speed circuit breaker and damping reactor. The function of damping reactor is to limit discharge current of a series capacitor during triggering of spark gap or circuit breaker closure.

![Diagram of MOV compensation model](image)

**Figure 3.4:** (a) Typical series compensation model; (b) Non-linear characteristic of MOV

MOV takes the advantages of non-linear resistance characteristic of zinc oxide to protect the series capacitor against overvoltage [7]. MOV basically maintains the voltage across the series capacitor below the protective voltage level. MOV conducts if the voltage across the series capacitor exceeds the protective voltage level and stops to conduct if the voltage falls below protective voltage level.

### 3.4.1 MOV setting

Protective voltage level of a series capacitor is normally specified above peak voltage, power swing and normal operating voltage conditions [4] [7]. The MOV protective voltage level is typically the multiple (2-2.5 times) of the rated capacitor voltage and is calculated by Eq. (3.7).

\[
U_p = 2\sqrt{2} \cdot I_R X_C
\]

(3.7)
Where, $U_p$ is the protective voltage level; $I_R$ is the rated capacitor current; and $X_C$ is the capacitive reactance.

The protective current level can be computed by Eq. (3.8).

$$I_p = 2\sqrt{2} \cdot I_R$$  \hspace{1cm} (3.8)

MOV conducts when the level of fault current reaches the protective current level and dissipate energy. MOV has specific energy rating. This means that MOV operates and sends closing signal to high-speed circuit breaker and bypasses the series capacitor before critical energy rating has reached. In this project MOV operates in 20 milliseconds (ms) when MOV energy rating or MOV protective current level is reached. The energy rating, protective current level, and protective voltage level of typical MOV is defined in Appendix-3.

3.4.2 Equivalent impedance of SC model

The parallel combination of MOV and a series capacitor in a series compensation model presents an equivalent impedance to the fault loop during fault conditions. Figure 3.5 shows the equivalent impedance of SC model during fault conditions.

Mathematically, the equivalent impedance of SC model during fault conditions is given by Eq. (3.9).

$$\bar{Z}_{MOV, SC} = R_{MOV} \parallel X_C = R_{eq} - j \cdot X_{eq}$$  \hspace{1cm} (3.9)

MOV changes the equivalent impedance in the fault loop depending upon the level of fault current. This means that the operation of MOV modifies the apparent impedance of fault loop. Therefore, it is very necessary to analyze the impacts of MOV on the characteristic of line impedance.
3.5 Impacts of MOV

The operation of MOV mainly depends upon the level of fault current. The level of fault current depends upon the source impedance, location of fault and fault resistance. The faults can be classified as high-current, medium-current and low-current faults depending upon the operation of MOV/ protective current level. In this project, the protective current level of MOV is assumed to be 10 kA. This project considers the typical range of fault current for different fault conditions depending upon the protective current level or MOV operating time. Table 3-1 presents the typical range of fault current for different fault conditions.

<table>
<thead>
<tr>
<th>Fault conditions</th>
<th>Fault current (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-current faults</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Medium-current faults</td>
<td>10-20</td>
</tr>
<tr>
<td>High-current faults</td>
<td>&gt;20</td>
</tr>
</tbody>
</table>

3.5.1 High-current faults

During high-current faults, the MOV operates within 20 ms thereby bypassing the series capacitor. This means that during high-current faults, the MOV conducts which shifts the apparent impedance slightly to the right and modifies the compensated impedance into uncompensated impedance within 20 ms. Usually high-current faults are not problematic for conventional distance relay. High-current faults occur if SC is installed near strong feeding source.

The typical simulation results in Figure 3.6 shows the impacts of MOV during high-current faults. Figure 3.6 shows (left top to bottom): the fault current (black), voltage across a series capacitor (red), and energy absorbed by MOV (green), and (right top to bottom): current through MOV (black), series capacitor (red) and circuit breaker (blue).
It can be seen by Figure 3.6 that during typical high-current fault, the MOV bypasses the series capacitor in 20 ms and the fault current mainly flows through the circuit breaker.

### 3.5.2 Medium-current faults

During medium-current faults, some of the fault current flows through a series capacitor and some fault current through the MOV. This reduces the level of series compensation in the equivalent impedance model during fault conditions, and shifts the impedance locus slightly to the right too. During medium-current faults, the delayed MOV operation might cause the conventional distance relay to be blind for faults near SC. A new protection algorithm is required for fast detection of medium-current faults.

The typical simulation results in Figure 3.7 shows the impacts of MOV during medium-current faults. Figure 3.7 shows (left top to bottom): the fault current (black) voltage across a series capacitor (red), and energy absorbed by MOV (green), and (right top to bottom): current through MOV (black), series capacitor (red) and circuit breaker (blue).

It can be seen by Figure 3.7 that during typical medium-current fault, part of fault current flows through both the MOV and a series capacitor for longer time (120 ms in this case). MOV operates at 120 ms and hence fast operation of conventional distance relays is not possible under such conditions.
3.5.3 Low-current faults

In low-current faults, the level of fault current is usually below the protective current level. The MOV acts as open circuit and the fault current mainly flows through a series capacitor thereby modifying the apparent impedance of the transmission lines. Low-current faults in series compensated lines lead the distance relays to encounter directional discrimination issues and reach problems. Low-current faults usually occur at remote end or if SC is installed near weak feeding source but also can occur during strong feeding source with impedance faults.

The typical simulation results in Figure 3.8 shows the impacts of MOV during low-current faults. Figure 3.8 shows (left top to bottom): the fault current (black), voltage across a series capacitor (red), and energy absorbed by MOV (green), and (right top to bottom): current through MOV (black), series capacitor (red) and circuit breaker (blue).

![Figure 3.8](image)

*Figure 3.8: (left top to bottom): the fault current (black), voltage across a series capacitor (red), and energy absorbed by MOV (green), and (right top to bottom): current through MOV (black), series capacitor (red) and circuit breaker (blue)*

It can be seen by Figure 3.8 that during typical low-current fault, the fault current mainly flows through a series capacitor and the current through MOV or circuit breaker is almost zero.

By the above analysis and discussion, it can be concluded that the non-linear characteristic of MOV modifies the characteristic of line impedance depending upon the type of fault, location of fault, source impedance and fault resistance. Thus, the operation of MOV has significant impacts on the performance of conventional distance relays. During high-current faults, the MOV bypasses a series capacitor in 20 ms and therefore not a big issue for conventional distance protection after 20 ms, but low-current faults causes under-reach and over-reach problems, and directional issues for conventional distance protection. The impacts of SC on the characteristic of line impedance is shown later in upcoming chapter.

This project considers high-current and low-current faults to analyze the impacts of SC on the performance of conventional distance relays for different MOV operating conditions.
Chapter 4

Special phenomena in series compensated lines

This chapter presents a brief explanation of special phenomena associated with the faults in the series compensated lines such as current inversion, voltage inversion, and Sub-Synchronous Oscillation (SSO) and its impacts on conventional distance protection scheme. Current or voltage inversion leads to directional discrimination issues [12] [22]. SSO causes transient over-reach problems and slows down the operation of conventional distance relays [8] [13].

To illustrate these phenomena, consider a typical two-source power system with series compensated line as shown in Figure 4.1. At 0.3 seconds (s) the fault occurs at p% of total line impedance.

Where, $X_s$, $X_c$, and $X_L$ is the source reactance at sending end, capacitive reactance of SC, and inductive reactance of protected line respectively. The factors affecting the characteristic of line impedance in the fault loop are listed as follows:

- Source impedance
- Degree of SC
- Location of fault

There are three possible combinations of reactance that may occur in series compensated lines during fault conditions as given by Eq. (4.1), Eq. (4.2), and Eq. (4.3). These three conditions are the basic factors behind different phenomenon during faults in the series compensated lines. Special phenomena in series compensated lines and its impacts on conventional distance protection are explained in the next section.

Condition for current inversion: 

$$X_c > X_L + X_s$$  (4.1)

Condition for voltage inversion: 

$$X_c \begin{cases} > & X_L \\ < & X_L + X_s \end{cases}$$  (4.2)

Condition for SSO:

$$X_c < X_L + X_s$$  (4.3)

It can be concluded by the above equations that both current inversion and SSO phenomenon cannot occur simultaneously. However, voltage inversion can occur together with SSO phenomenon.
4.1 Current inversion

Current inversion occurs if the net reactance from source to fault point becomes capacitive. This implies that current inversion occurs if condition in Eq. (4.4) is satisfied.

\[ X_C > X_S + pX_L \]  

\[ (4.4) \]

Where, \[ X_L = \begin{cases} X_{L_{-1}} + X_{L_{-n}} & P-G \text{ Faults} \\ X_{L_{-1}} & P-P \text{ Faults} \end{cases} \]

\[ X_S = \begin{cases} X_{S_{-1}} + X_{S_{-n}} & P-G \text{ Faults} \\ X_{S_{-1}} & P-P \text{ Faults} \end{cases} \]

It is necessary to analyze the impacts of current inversion on voltage, current and power factor angle at relay position.

Figure 4.2 shows two diagrams: the left diagram presents pre-fault voltage (blue) and fault voltage (red) and the right diagram presents pre-fault current (blue) and fault current (red) at relay position during current inversion. It is observed that the fault voltage increases and lags the pre-fault voltage at relay position during current inversion. The fault current also increases but leads the pre-fault current at relay position during current inversion.
Figure 4.2: Left: Pre-fault voltage (blue) and fault voltage (red); Right: Pre-fault current (blue) and fault current (red)

Figure 4.3 shows the pre-fault and post fault power factor angle at relay position during current inversion. It is experienced that the current lags the voltage by load power factor angle during normal load condition. However, the current inversion occurs at 0.3 s and causes the current to leads the voltage at relay position during fault condition. In simple words, current inversion leads the inductive current to becomes capacitive current during fault condition which flows from a series capacitor towards the source. This might cause directional issues or under-reach problems.

Figure 4.3: Pre-fault and post fault power factor angle at relay position during current inversion

The overall impact of current inversion can be illustrated by the phasor diagram shown in Figure 4.4. During normal load condition, the pre-fault current (solid red line) lags pre-fault voltage (solid blue line) at relay position; whereas during current inversion, the fault current (dotted red line) leads the fault voltage (dotted blue line) at relay position.
4.1.1 Impacts of current inversion on conventional distance relay:

The capacitive current during current inversion causes the reactive power to flow in reverse direction. The positive active power and reversed reactive power shifts the locus of line impedance from 1st quadrant into 4th quadrant. Figure 4.5 shows the locus of line impedance during current inversion for the phase-to-ground impedance fault \( R_f = 30 \Omega \) at terminal of a series capacitor in typical two-source power system with 50% series compensated line and positive sequence source impedance is \( Z_{S,1} = 5 \Omega \). This leads the conventional distance relay to encounters steady-state under-reach problems as shown in Figure 4.5. A new distance protection algorithm is thus required to handle such issues and provide adequate protection to the series compensated line during current inversion.
4.2 Voltage inversion

Voltage inversion occurs if the reactance from relay position to fault point becomes capacitive but the net reactance from source to fault point but is still inductive. Voltage inversion occurs if both conditions in Eq. (4.5) are satisfied depending upon the location of VT.

\[
\begin{align*}
X_C > pX_L \\
X_C < X_S + pX_L
\end{align*}
\] (4.5)

Voltage inversion is always associated with SC and it can occur both in strong and weak grid.

It is necessary to analyze the impacts of voltage inversion on voltage, current and power factor angle at relay position.

Figure 4.6 shows two diagrams: the left diagram presents pre-fault voltage (blue) and fault voltage (red) and the right diagram presents pre-fault current (blue) and fault current (red) at relay position during voltage inversion. It is observed that the fault voltage decreases and lags the pre-fault voltage by an angle slight less than 180 degree at relay position during voltage inversion. The fault current also increases but lags the pre-fault current at relay position during voltage inversion.

![Figure 4.6: Left: Pre-fault voltage (blue) and fault voltage (red); Right: Pre-fault current (blue) and fault current (red)](image)

Figure 4.7 shows the pre-fault and post fault power factor angle at relay position. Clearly, the voltage inversion occurs at 0.3 s, which changes the power factor angle from lagging to leading.
The overall impact of voltage inversion can be understood by the phasor diagram shown in Figure 4.8. During normal load condition, the pre-fault current (solid red line) lags pre-fault voltage (solid blue line) at relay position; whereas during voltage inversion, the fault current (dotted red line) leads the fault voltage (dotted blue line) at relay position.

4.2.1 Impacts of voltage inversion on conventional distance relay

Figure 4.9 shows the locus of line impedance during voltage inversion for the phase-to-ground bolted fault \( R_f = 0 \, \Omega \) on typical series compensated line at 10 km from relay position with positive sequence source impedance of \( Z_{s,1} = 20 \, \Omega \). This leads the conventional distance relay to encounters directional discrimination issues or steady state under-reach problems depending upon the value of source impedance and fault resistance. A new distance protection algorithm is thus required to handle such issues and provide adequate protection to the series compensated line during voltage inversion.
4.2.2 Conditions for the voltage inversion

The probability of voltage inversion greatly depends upon the location of VT. If VT is installed before SC, then both voltage inversion and current inversion cannot occur simultaneously during forward faults. If VT is installed behind SC, then current inversion causes voltage inversion during forward faults.

To illustrate it analytically, consider two locations “C” and “D” for VT in the typical two-source power system as shown in Figure 4.10. The power system is assumed to be lossless.

Figure 4.9: Impacts of voltage inversion on conventional distance relay

Figure 4.10: Typical two-source power system with two locations for VT
The current through the line during forward fault condition is given by Eq. (4.6).

\[
\bar{I}_S = \frac{\bar{U}_S}{j(X_S + pX_L - X_C)}
\]  

(4.6)

As per Eq. (5.6), current inversion occurs if the condition \( X_C > X_S + pX_L \) is satisfied.

**4.2.2.1 VT installed at location “C”**

The voltage at point “C” during forward fault can be expressed by Eq. (4.7).

\[
\bar{U}_C = (pX_L - X_C) \cdot \bar{I}_S
\]  

(4.7)

As per Eq. (4.7) that the voltage inversion occurs if following conditions are met:

\[
X_C > pX_L
\]

\[
X_C < X_S + pX_L
\]

It can be concluded that both current and voltage inversion cannot occur simultaneously if VT is installed before SC.

**4.2.2.2 VT installed at location “D”**

The voltage at point “D” during forward fault can be expressed by Eq. (4.8).

\[
\bar{U}_D = pX_L \cdot \bar{I}_S
\]  

(4.8)

As per Eq. (4.8) that the voltage inversion occurs if following condition is met:

\[
X_C > X_S + pX_L
\]

It can be concluded that both current and voltage inversion occurs simultaneously if VT is installed behind SC.

This project considers VT at location “C” for forward faults analysis.

**4.2.3 Impacts of source impedance on current and voltage inversion**

The source impedance determines the strength of source whether strong or weak as well as the level of fault currents. Strong source means low-source impedance thereby resulting high-current faults and weak source means high-source impedance thereby resulting low-current faults.

The probability of current inversion is more as compared to the voltage inversion if the feeding source is strong. This means that during current inversion, the level of fault current is enough to operates MOV and bypasses SC thereby modifying the characteristic of line from compensated impedance to uncompensated impedance. However, impedance fault reduces the level of fault current below the protective level and the series capacitor always remain in the fault loop. Strong
feeding source shifts the locus of line impedance slightly to the right during fault conditions. It can be concluded that current or voltage inversion leads to steady state under-reach problems for existing distance relays if the feeding source is strong.

The probability of voltage inversion increases with increase in source impedance. During high-source impedance/ weak source the probability of voltage inversion is maximum while the probability of current inversion is almost zero. During low-current faults, the fault current mainly flows through SC. Low current-fault conditions in the weak feeding source modify the line characteristic in such a way that the line characteristic enters the reverse tripping zone of conventional distance relay and the relay trips wrongly in reverse zone during the forward faults. This phenomenon is explained in more detail in the next chapter. In short, voltage inversion leads to directional discrimination issues for conventional distance relay if the feeding source is weak.

4.3 Sub-Synchronous Oscillation (SSO)

SSO occurs if the net reactance from source to fault point in a series compensated line becomes inductive. SSO occurs if the condition in Eq. (4.9) is satisfied.

\[ X_C < X_S + pX_L \]  \hspace{1cm} (4.9)

The integration of the series capacitor in a transmission line sets up series resonant resistive-inductive-capacitive circuit which introduces signal with natural frequency in power system. The natural frequency of series resonant circuit can be computed by Eq. (4.10).

\[ f_n = \frac{1}{2\pi \sqrt{LC}} = f \sqrt{\frac{X_C}{X_S + pX_L}} \]  \hspace{1cm} (4.10)

Where, \( f \) is the fundamental frequency of power system (50 Hz in Sweden), and \( f_n \) is natural frequency of series resonant circuit.

It can be seen by Eq. (4.10) that a fault on series compensated line introduce high or low frequency components in power system depending upon the source impedance, degree of series compensation and location of fault.

If the fault occurs on series compensated line such that \( X_C > X_S + pX_L \), the series resonant circuit introduces high frequency components in the power system. If the fault occurs on series compensated line such that \( X_C < X_S + pX_L \), the series resonant circuit introduces low frequency components called subharmonics in the power system. These sub-harmonics superimposes on the fundamental component of voltage and current phasors and introduce distortion in voltage and current. Figure 4.11 shows the RMS value of fundamental component of voltage (red) and current (blue) during SSO for the bolted fault occurring at 0.3 s on typical series compensated line at remote end (200 km from relay position). Clearly, the SSO creates harmonics and distortions in current and voltage signal, and leads to an error in the impedance measurement.
4.3.1 Impacts of SSO on conventional distance relay

The conventional numerical distance relays use a sliding window based Fast Fourier Transform (FFT) as filtering technique to extract fundamental frequency component. FFT eliminates DC and high frequency integer components but cannot remove low frequency components/sub-harmonics. Consequently, sub-harmonics in the voltage and current create error in the impedance measurements and produce signal envelops which results impedance characteristic to follow logarithmic spiral during fault conditions. Figure 4.12 shows the impact of SSO on conventional distance relay during phase-to-ground bolted fault at remote end (200 km from relay position) on typical series compensated line. It has been seen that conventional distance relay encounters transient over-reach problems due to the oscillatory spiraling impedance characteristic. This leads the conventional distance relay to miss-operate in zone 1 for the faults in zone 2 on series compensated lines. A new mitigation solution is thus required to handle such issues and provide adequate protection to the faults on series compensated lines during SSO phenomenon.
SSO phenomenon occurs during faults at remote end if the feeding source is strong and might cause transient over-reach problems. However, SSO phenomenon can also occur during faults at terminal of a series capacitor if the feeding source is weak.

By the above analysis, it can be concluded that current or voltage inversion leads to directional discrimination issues or steady-state under-reach problems for conventional distance relays depending upon the parameters of fault loop. SSO phenomenon causes transient over-reach problems for conventional distance relays. Thus, a new protection solution is required to handle these issues, and maintain the reliable operation of power system.
Chapter 5

Impacts of Series Compensation on Distance Relays

This chapter describes the impacts of SC on the apparent impedance of transmission line. This chapter also shows how the non-linear MOV modifies the impedance characteristic of line during fault conditions. This chapter also includes the impacts of SC on the performance of conventional distance relays. Finally, the chapter is concluded with the problems of SC on distance relays.

5.1 Impacts of a series capacitor on the impedance measurements

Consider a typical two source power system as shown in the Figure 5.1. A series capacitor is integrated at the beginning of EHV line and the fault occurs on EHV line at P % of total line impedance from local bus A as shown in the Figure 5.1.

Figure 5.1: Typical two source power system with series compensated EHV line

Where, $X_C$ is the capacitive reactance of the series capacitor.

To see the impact of a series capacitor on the apparent impedance of transmission line during phase-to-ground faults and phase-to-phase faults, we consider phase-to-ground and phase-to-phase fault loop.

5.1.1 Phase-to-ground fault

During phase-to-ground faults, the power system with a series capacitor can be modelled as positive, negative and zero sequence network as shown in Figure 5.2.
Figure 5.2: Equivalent sequence model of power system during phase-to-ground fault

The apparent impedance of transmission line seen by distance relay R1 at bus A during phase-to-ground fault is given by Eq. (5.1).

$$\overline{Z}_{pg} = \frac{U_{A-a}}{I_{S-a}} = p \cdot (\overline{Z}_{L_{-1}} + \overline{Z}_{L_{-n}}) - jX_C + k \cdot R_f$$

(5.1)

Where, $\overline{Z}_{L_{-n}} = \frac{\overline{Z}_{L_{-0}} - \overline{Z}_{L_{-1}}}{3}$ [32]; and $k = 1 + \frac{I_{R-a}}{I_{S-a}}$

In general, the apparent impedance of series compensated EHV line during phase-to-ground fault is given by Eq. (5.2).

$$\overline{Z}_{sc} = \overline{Z}_{L_{-1}} + \overline{Z}_{L_{-n}} - jX_C$$

(5.2)

5.1.2 Phase-to-phase fault

Consider the phase-to-phase fault between phase “a” and phase “b” as shown in the Figure 5.3.

Figure 5.3: Phase-to-phase fault between phase “a” and phase “b”
The apparent impedance of transmission line seen by distance relay R1 during phase-to-phase fault is given by Eq. (5.3).

\[
Z_{pp} = \frac{U_{A_a} - U_{A_b}}{I_{S_a} - I_{S_b}} = p \cdot Z_{L_1} - jX_C + k \cdot \frac{R_f}{2}
\]  

(5.3)

In general, the apparent impedance of series compensated line during phase-to-phase fault is given by Eq. (5.4).

\[
Z_{SC} = Z_{L_1} - jX_C
\]  

(5.4)

The setting and tripping boundary of distance relay can be adjusted if the series capacitor always remain in the fault loop but the presence of non-linear MOV modifies the characteristic of line impedance depending upon the level of fault current or source impedance. It is therefore necessary to see the impact of MOV operation on the impedance measurement.

### 5.2 Impact of MOV operation on the impedance measurement

Consider typical two-source power system with MOV protected SC model as shown in Figure 5.4.

![Figure 5.4: Typical two source power system with SC model](image)

As discussed earlier that SC model presents equivalent impedance during fault condition. The apparent impedance seen at relay R1 during fault condition is given by Eq. (5.5).

\[
Z_{R1} = p \cdot Z_L + Z_{MOV,SC} + k \cdot \frac{R_f}{X}
\]  

(5.5)
Where, 
\[
\bar{Z}_L = \begin{cases} 
\bar{Z}_{L-1} + \bar{Z}_{L-a} & P - G \text{ Faults} \\
\bar{Z}_{L-1} & P - P \text{ Faults}
\end{cases}
\]

, \( Z_{MOV\_SC} \) is the equivalent impedance of SC model, and \( x \) is the number of phases involved in the fault. The value of \( x \) is 1, 2, 3 for single phase, two phase and three phase faults respectively.

This project considers SC at beginning of protected line during forward fault analysis but considers SC in the adjacent backward line during backward fault analysis. Thus, the apparent impedance seen by relay during forward and backward faults is given by Eq. (5.6) and Eq. (5.7) respectively.

\[
\bar{Z}_{Forward} = \bar{Z}_L + Z_{MOV\_SC} \quad (5.6)
\]

\[
\bar{Z}_{Reverse} = -\bar{Z}_S - Z_{MOV\_SC} \quad (5.7)
\]

During high current faults, the characteristic of line shifts slightly to the right and decreases the compensation level due to MOV conduction. During low current faults, the series capacitor fully compensates the reactance of line.

High-current faults usually occur if the feeding source is strong and low-current faults occur if the feeding source is weak. It is interesting to analyze the impedance characteristic of line during both strong and weak feeding source. As the distance relay is installed at bus A. The feeding source is Source (S) and Source (R) during forward and backward faults respectively.

The strength of power source can be determined by the source to line impedance ratio (SIR). Strong source has low value of SIR in general while weak source has high value of SIR. Table 5-1 shows the typical SIR value for strong and weak source in this project.

<table>
<thead>
<tr>
<th>Power source</th>
<th>SIR value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong source</td>
<td>2.5 %</td>
</tr>
<tr>
<td>Weak source</td>
<td>50 %</td>
</tr>
</tbody>
</table>

As explained in the previous chapter that voltage inversion depends upon the location of VT. This means that characteristic of line impedance varies with the location of VT in the fault loop. Therefore, it is important to analyze the characteristic of line impedance for both location of VT (before and after SC in the fault loop).

5.3 VT is installed before SC

If VT is installed before SC (Bus A in this case), distance relay sees SC in the forward fault loop only. This modifies the characteristic of line impedance during forward faults depending upon the source impedance or strength of feeding source as shown in Figure 5.5. The impedance characteristic of backward line for reverse faults does not change. Which means that the
conventional distance relay encounter directional and reach problems during forward faults but can provide remote backup protection to the backward adjacent line during backward faults. The fact is that, for such configuration of VT the voltage and current inversion cannot occur simultaneously during forward faults which modifies the impedance characteristic of line during forward faults but voltage and current inversion occurs simultaneously during backward faults which cancel the resultant impacts on the impedance characteristic during backward faults and characteristic of backward line remains the same.

Figure 5.5 shows the impedance characteristic of protected line without SC (black), with SC and strong feeding source (red), with SC and weak feeding source (blue) during forward faults, and backward line (green) during reverse fault.

![Figure 5.5: Impedance characteristic of: protected line without SC (black), with SC and strong feeding source (red), with SC and weak feeding source (blue) during forward faults; and backward line (green) during reverse fault](image)

5.3.1 Impacts on conventional distance relay

5.3.1.1 Strong feeding source (S)

As discussed earlier during high-current faults MOV conducts which shifts the characteristic of line to the right and modifies the line characteristic (red arrowed line) as shown in Figure 5.6. Figure 5.6 shows the impacts of SC installed at strong source on the performance of conventional distance relay if VT is installed at bus A.
During normal load condition, the locus of load impedance is denoted by position (0) in Figure 5.7. If the bolted fault occurs just after SC, the locus of line impedance jumps to 4th quadrant as represented by position (1). The high current causes the MOV to conduct and shifts the impedance locus to position (2) within 20 ms as shown in Figure 5.7 and imposes no problem for conventional distance relay after 20 ms. However, the impedance faults shift the impedance locus to position (3) thereby leading to steady-state under-reach problem for conventional distance relay. The conventional distance relay also encounters steady-state over-reach and transient over-reach problems during faults at remote end/ or next adjacent line. Thus, new distance protection algorithm is required to handle such steady-state and transient reach problems.

5.3.1.2 Weak feeding source (S)

The weak feeding source results low-current faults and the fault current mainly flows through a series capacitor. Low-current faults modify the line characteristic (red arrowed line) as shown in Figure 5.7. Figure 5.7 shows the impacts of SC installed at weak source on the performance of conventional distance relay if VT is installed at bus A. Clearly, the conventional distance relay encounters directional discrimination issues, steady-state under-reach and over-reach problems, and transient over-reach problems.

Figure 5.6: Impacts of SC installed at strong source on the performance of conventional distance relay if VT is installed at bus A
Since the probability of current inversion in a weak feeding source is zero. This means that voltage inversion is the main reason behind directional discrimination issues and under-reach problems in the weak feeding source.

**5.4 VT is installed behind SC**

If VT is installed behind SC (point D in this case), distance relay sees SC in the backward fault loop only. This modifies the characteristic of line impedance during backward faults depending upon the source impedance or strength of feeding source as shown in Figure 5.8. The impedance characteristic of protected line during forward faults does not change. Which means that the conventional distance relay encounters directional and reach problems during backward faults but provides adequate protection to the protected line during forward faults. The fact is that, for such configuration of VT the voltage and current inversion occurs simultaneously during forward faults which cancel the resultant impacts on the impedance characteristic during forward faults and characteristic of protected line does not change, but voltage and current inversion cannot occur simultaneously during backward faults which modifies the impedance characteristic of line during backward faults.
Figure 5.8 shows the impedance characteristic of: protected line (black) during forward faults, backward line without SC (green), with SC and strong feeding source (red), and with SC and weak feeding source (blue) during reverse faults.

5.4.1 Impacts on conventional distance relay

5.4.1.1 Strong feeding source (S)

As discussed earlier that VT is installed at point “D” then distance relay sees SC in the backward fault loop only which modifies the characteristic of backward line but the characteristic of protected line remains the same. In this case the impacts of SC on the performance of conventional distance relay is same as described in the previous section but in opposite direction i.e. the relay encounters steady-state under-reach and over-reach problems, and transient over-reach problems during backward faults as shown in Figure 5.9.
5.4.1.2 Weak feeding source (S)

In the same way as described in the previous section, under this system configuration the conventional distance relay encounters directional discrimination issues, steady-state under-reach and over-reach problems, and transient over-reach problems during backward faults only as shown in Figure 5.10.

Figure 5.6: Impacts of SC installed at strong source on the performance of conventional distance relay if VT is installed at “D”
5.5 Problems of SC for conventional distance relays

The overall problems imposed by series compensation on the performance of conventional distance relays are outlined as follows:

- Steady state under-reach problems
- Steady state over-reach problems
- Directional discrimination issues
- Transient over-reach problems

All the above-mentioned problems occur because of special phenomena as discussed in previous chapter. In simple words, steady-state under-reach problems and directional discrimination issues occur due to current or voltage inversion phenomenon, while transient over-reach problems occur due to SSO phenomenon.
Chapter 6

Proposed New Mitigation Solutions

This chapter presents new mitigation solutions for distance relays in the series compensated lines. New setting of distance relay is proposed to handle steady-state reach problems. This chapter also presents the digital high-pass filtering technique as a new mitigation solution to cope with the transient over-reach problems.

6.1 New mitigation solution

The proposed new mitigation solution includes: new characteristic of quadrilateral distance relay and typical high-pass filter. New characteristic of distance relay defines new tripping boundary by considering the capacitive reactance of SC to handle steady-state under-reach issues related to current or voltage inversion as well as steady-state over-reach problems. Digital high-pass filter is proposed to filter low-frequency signals and damped spiraling impedance oscillation during SSO phenomenon. Digital high-pass filter is new mitigation solution to handle transient over-reach issues related to SSO. The benefits of new mitigation solution include: solution to steady-state and transient under-reach and over-reach problems. In simple words, the proposed protection solution handles current and voltage inversion issues as well as SSO problems.

6.1.1 New characteristic of quadrilateral distance relay

As explained previously that, if SC is installed near strong source, the characteristic of line impedance shifts to the right. The tripping characteristic of distance relay can be modified to handle reach problems. The new tripping characteristic of distance relay depends upon the location of VT and SC in the fault loop. For forward faults analysis, VT is considered before SC in the fault loop. This modifies the setting of distance relay during forward faults only. For backward faults analysis, VT is considered behind SC in the fault loop. This modifies the setting of distance relay during backward faults only.

6.1.1.1 Forward Faults analysis

Figure 6.1 shows the typical power system model for forward faults analysis. Series compensation is installed at local end of protected line as shown in Figure 6.1.
Since the distance relay sees SC in the forward fault loop only, the tripping characteristic of relay would be modified for the forward faults only while the backward characteristic remains the same. Figure 6.2 shows the proposed new characteristic of zone-1/zone-RV quadrilateral distance relay under this system configuration. This project considers this characteristic to perform forward fault analysis. All the parameters and variables are clearly defined in the previous chapter.
6.1.1.2 Backward Fault analysis

Figure 6.3 shows the typical power system model for backward fault analysis. The SC is installed in the backward adjacent line.

Since the distance relay sees SC in the backward fault loop only, the backward tripping characteristic of relay would be modified while the forward characteristic remains the same. Figure 6.4 shows the proposed new characteristic of zone-1/ zone-RV quadrilateral distance relay under this system configuration. This project considers this characteristic to perform backward fault analysis. All the parameters and variables are clearly defined in the previous chapter.

Figure 6.4: New setting of distance relay for backward fault analysis
6.1.2 Digital high-pass filter

High-pass filter is used to allow high frequencies to pass and block lower frequencies. Butterworth and Chebyshev filters are the two most widely used digital filters. The choice of filter depends upon the application. Butterworth filter is maximally flat due to zero ripple in passband and stopband whereas Chebyshev filter has steeper response but possess 3 dB ripple in passband as shown in Figure 6.5. Butterworth filter is used when ripples in passband is not desirable and Chebyshev filter is used when the steep response is required. Moreover, Butterworth filter is the only filter that maintains the same shape for higher order than other types of filters (Chebyshev, Bessel, Elliptic). Higher the order of filter, the frequency response of filter will be closer to ideal filter and hence more will be the attenuation in magnitude of transfer function. This means that there is tradeoff between order of filter and magnitude/phase response of transfer function.

![Figure 6.5: Characteristic of Butterworth and Chebyshev high-pass filter](image)

Since the subharmonics in the voltage and current signal creates errors in the impedance measurements and causes spiraling impedance oscillatory characteristic. Therefore, Butterworth high-pass filter is the best choice.

6.1.2.1 Butterworth high-pass filter

The magnitude and phase response of transfer function of first order Butterworth high-pass filter is given by Eq. (6.1) and Eq. (6.2).

\[
|H(j\omega)| = \frac{(f/f_c)}{\sqrt{1+(f/f_c)^2}}
\]  

(6.1)

\[
\angle H(j\omega) = 180^\circ - \tan^{-1}(f/f_c)
\]  

(6.2)
Where, $H(j\omega)$ is the transfer function at angular frequency $\omega$; $f$ and $f_c$ is the system nominal and cut-off frequency respectively.

The magnitude response in term of dB can be expressed by Eq. (6.3).

$$|H(j\omega)|_{dB} = 20\log|H(j\omega)|$$

$$|H(j\omega)|_{dB} = 20\log(f/f_c) - 20\log\sqrt{1+(f/f_c)^2}$$

Asymptotic behavior of 1st order Butterworth high-pass filter is:

For $f \ll f_c$:

$$|H(j\omega)|_{dB} \approx 20\log(f/f_c)$$ and $\angle H(j\omega) \approx 180^\circ$

For $f \gg f_c$:

$$|H(j\omega)|_{dB} \approx 20\log(f/f_c) - 20\log\sqrt{1+(f/f_c)^2} = 0$$ and $\angle H(j\omega) \approx 0^\circ$

Generally, the transfer function of system can be expressed in terms of zeros and poles as given by Eq. (6.4).

$$H(s) = \frac{(s-z_1)(s-z_2)...(s-z_n)}{(s-\lambda_1)(s-\lambda_2)...(s-\lambda_n)}$$

Where, $z_1, z_2,...,z_n$ are zeros and $\lambda_1, \lambda_2,...,\lambda_n$ are poles of system.

This project considers a typical Butterworth high-pass filter as a solution for SSO.

6.1.2.2 Impacts of Butterworth high-pass filter on distance relay

Figure 6.6 shows the impact of typical Butterworth high-pass filter on the performance of distance relay for phase-to-ground bolted fault at remote end (200 km from relay position) on typical series compensated line.

Clearly, the typical high-pass filter eliminates signal distortion and removes the envelopes and damps the oscillatory spiraling impedance characteristic significantly. The benefit of typical high-pass filter is to make the distance relay trip properly during SSO phenomenon.
Figure 6.6: Impact of typical Butterworth high-pass filter on the performance of distance relay during SSO
Chapter 7

Testing and Simulation Results

This chapter presents the performance of proposed distance protection scheme for the typical series compensated line under different system operating conditions i.e. fault resistance, fault location and source impedance. The proposed protection algorithm provides adequate sensitivity to internal faults and selectivity to external faults. The performance of new distance relay is tested during both forward and backward faults for various MOV operating conditions. The typical two-source power system with series compensated EHV line is modelled in EMTDC/ PSCAD. The detail description of power system PSCAD model is given in appendix-1.

7.1 Performance of proposed distance relay

This project considers phase-to-ground faults to simplify the analysis. However, the proposed protection algorithm provides adequate protection to all type of faults i.e. phase-to-ground/ phase-to-phase/ phase-to-phase-to-ground/ three phase faults.

7.1.1 Forward Faults

For forward faults analysis, the source at sending end (S) in Figure 6.1 is assumed to be strong source. The positive sequence and zero sequence impedance of source (S) is assumed to be \( Z_{s-1} = 5\angle 85^\circ \) and \( Z_{s-0} = 3Z_{s-1} \), respectively. The positive and zero sequence impedance of protected line is \( Z_{l-1} = 0.025 + j0.2759 \Omega/\text{km} \) and \( Z_{l-0} = 3Z_{l-1} \), respectively. The performance of proposed distance relay is verified by testing the operation of relay during special phenomena i.e. current inversion, voltage inversion, and SSO phenomenon.

As discussed earlier, the conditions of different special phenomena occur by varying various system parameters and operating conditions. The conditions of special phenomena during forward faults are listed as under:

- **Condition for current inversion:** \( X_c > X_L + X_S \)
- **Condition for voltage inversion:** \( X_c \begin{cases} > X_L \\ < X_L + X_S \end{cases} \)
- **Condition for SSO phenomenon:** \( X_c < X_L + X_S \)

7.1.1.1 Fault at terminal of SC

Phase-to-ground fault at terminal of SC yields following parameters for fault loop.

\( X_c = 27.6 \Omega, \ X_L = 0 \Omega, \ X_L + X_S = 8.4 \Omega \), which satisfies the condition for current inversion.
Figure 7.1 and Figure 7.2 shows the performance of new distance relay for bolted fault i.e. $R_f = 0 \ \Omega$ and impedance fault i.e. $R_f = 30 \ \Omega$ respectively at terminal of SC. The MOV operates during bolted faults and the locus of line impedance shifts from 4th quadrant to 1st quadrant within 20 ms as shown in Figure 7.1. However, the impedance fault reduces fault current below protective level of current and fault current mainly flows through a series capacitor and the locus of line impedance lies in 4th quadrant as shown in Figure 7.2. Thus, the proposed distance relay provides adequate protection during current inversion phenomenon.

*Figure 7.1: Performance of distance relay during current inversion for bolted fault at terminal of SC*
7.1.1.2 Fault at 47 km from relay position

The phase-to-ground fault at 47 km from relay position yields the following parameters for fault loop. \( X_C = 27.6 \, \Omega \), \( X_L = 23.5 \, \Omega \), \( X_L + X_S = 32 \, \Omega \), which satisfies the condition for voltage inversion.

Figure 7.3 and Figure 7.4 shows the performance of proposed distance relay during voltage inversion for bolted fault i.e. \( R_f = 0 \, \Omega \), and impedance fault i.e. \( R_f = 30 \, \Omega \) respectively at 47 km from relay position. The MOV operates and shifts the locus of line impedance from 4\(^{th}\) quadrant to 1\(^{st}\) quadrant within 20 ms as shown in Figure 7.3. However, during the impedance faults, the fault current mainly flows through a series capacitor and the locus of line impedance lies in 4\(^{th}\) quadrant as shown in Figure 7.4. Clearly, the proposed distance relay algorithm handles voltage inversion issues.
Figure 7.3: Performance of distance relay during voltage inversion for bolted fault at 47 km on line.

Figure 7.4: Performance of distance relay during voltage inversion for impedance fault at 47 km from relay position.
### 7.1.1.3 Fault at 90% of protected line (180 km from relay position)

The bolted phase-to-ground fault at 90% of the line (10% above the zone 1 reach) yields the following parameters for fault loop.

\[ X_C = 27.6 \, \Omega, \quad X_L = 90.3 \, \Omega, \quad X_L + X_S = 98.6 \, \Omega, \] which satisfies the condition for SSO.

Figure 7.4 and Figure 7.5 show the impacts of SSO on the performance of distance relay without and with Butterworth high-pass filter respectively for phase-to-ground fault on 90% of typical series compensated line. This fault occurs in zone 2 of distance relay, but the oscillatory spiraling impedance characteristic related to SSO might lead to transient over-reach problems and might causes false tripping in zone 1 for faults in zone 2. However, the typical Butterworth high-pass filter significantly removes signal envelops and damps the spiraling impedance characteristic efficiently at the cost of 10 ms time delay as shown in Figure 7.5. Thus, the proposed mitigation solution (typical high-pass filter) handles perfectly the SSO problems and ensures the correct operation of distance relay.

**Figure 7.4:** Impact of SSO on the performance of distance relay without Butterworth high-pass filter during fault at 90% of line from relay position.
Similarly, the Figure 7.6 shows the behavior of distance relay during SSO (left): without high-pass filter, and (right): with high-pass filter for phase-to-ground fault on 90% of typical series compensated line. Clearly, the SSO might cause false tripping in zone 1 for fault in zone 2. However, the typical filter damps the oscillatory impedance characteristic significantly to ensure the correct operation of distance relay.

### 7.1.1.4 Impacts of high source impedance

During high source impedance/weak feeding source, the bolted phase-to-ground fault at terminal of SC yields the following parameters for fault loop.

\[ X_c = 27.6 \, \Omega, \quad X_L = 0 \, \Omega, \quad X_L + X_S = 166.6 \, \Omega, \]

which satisfies the condition for voltage inversion as well as SSO.

Figure 7.6 and Figure 7.7 shows the impact of high source impedance on the performance of proposed distance relay during bolted fault at terminal of SC without and with Butterworth high-pass filter respectively. The Butterworth high-pass filter damps the impedance characteristic as shown in Figure 7.7. However, high source impedance shifts the locus of line impedance in reverse tripping zone of distance relay and the reverse zone for remote backup protection of backward line trips incorrectly for forward faults. The distance relay encounters directional discrimination issues due to voltage inversion as shown in Figure 7.7.
Figure 7.6: Impact of high source impedance on the performance of distance relay during bolted fault at terminal of SC without Butterworth high-pass filter

Figure 7.7: Impact of high source impedance on the performance of distance relay during bolted fault at terminal of SC with Butterworth high-pass filter
However, the proposed distance relay provides adequate protection to the impedance faults during high source impedance. Figure 7.8 shows the performance of distance relay during impedance fault i.e. $R_f = 8 \, \Omega$ at terminal of SC with Butterworth high-pass filter.

![Figure 7.8: Performance of distance relay during impedance fault at terminal of SC with Butterworth high-pass filter](image-url)

*Figure 7.8: Performance of distance relay during impedance fault at terminal of SC with Butterworth high-pass filter*
7.1.2 Backward Faults

For backward faults analysis, the source at receiving end (R) in Figure 6.3 is assumed to be strong source. The positive sequence and zero sequence impedance of source (R) is assumed to be $Z_{R-1} = 5\angle 85^\circ$ and $Z_{R-0} = 3Z_{R-1}$ respectively. For backward fault analysis, the following assumption are made. $Z_{L-1} = 0 \Omega$, $Z_{S-1} = 0.025+j0.2759\Omega/km$ and $Z_{S-0} = 3Z_{S-1}$.

The performance of proposed distance relay is tested during backward faults for special phenomena i.e. current inversion, voltage inversion, and SSO phenomenon.

The conditions of special phenomena during backward faults are listed as under:

Condition for current inversion: \[ X_C > X_R + X_L + X_S \]

Condition for voltage inversion: \[ X_C \begin{cases} > & X_S \\ < & X_R + X_L + X_S \end{cases} \]

Condition for SSO phenomenon: \[ X_C < X_R + X_L + X_S \]

7.1.2.1 Fault at terminal of SC

Phase-to-ground backward fault at terminal of SC yields following parameters for fault loop.

\[ X_C = 27.6 \Omega \quad X_S = 0 \Omega, \quad X_R + X_L + X_S = 8.4 \Omega, \] which satisfies the condition for current inversion.

Figure 7.9 shows the performance of distance relay for bolted backward fault i.e. $R_f = 0 \Omega$ at terminal of SC. The MOV operates and shifts the locus of line impedance from 4th quadrant to 1st quadrant within 20 ms as shown in Figure 7.9.
7.1.2.2 Backward fault at 40 km from relay position

The phase-to-ground fault at 40 km on backward line from relay position yields the following parameters for fault loop. \( X_C = 27.6 \, \Omega \), \( X_S = 20.5 \, \Omega \), \( X_R + X_L + X_S = 28.4 \, \Omega \), which satisfies the condition for voltage inversion.

Figure 7.10 shows the performance of distance relay for bolted fault i.e. \( R_f = 0 \, \Omega \) at 40 km on backward line from relay position. The MOV operates and shifts the locus of line impedance from 4\(^{th}\) quadrant to 1\(^{st}\) quadrant within 20 ms as shown in Figure 7.10.
7.1.2.3 Fault at remote end (200 km on backward line) from relay position

The phase-to-ground fault at remote end (200 km on backward line) from relay position yields the following parameters for fault loop.

\[ X_C = 27.6 \, \Omega, \quad X_S = 100.3 \, \Omega, \quad X_R + X_L + X_S = 108.4 \, \Omega, \] which satisfies the condition for SSO phenomenon.

Figure 7.11 and Figure 7.12 shows the impacts of SSO on the performance of distance relay without and with Butterworth high-pass filter respectively. This fault occurs on the boundary of zone 1. The spiral impedance characteristic in Figure 7.11 is related to SSO but the typical Butterworth high-pass filter significantly removes signal envelops and damps the spiraling impedance characteristic efficiently as shown in Figure 7.12. But since reverse zone acts as remote backup protection for backward adjacent line so the SSO problem is not a major issue for reverse zone of distance relay.
Figure 7.11: Impact of SSO on the performance of distance relay without Butterworth high-pass filter during fault at remote end of backward line from relay position.

Figure 7.12: Impact of Butterworth high-pass filter on the performance of distance relay during SSO for fault at remote end of backward line from relay position.
Chapter 8

Conclusions

This chapter presents the main conclusion of this master degree project, future research and recommendation of author.

8.1 Main Conclusions

The main objective of this project is to analyze the impacts of SC on the performance of conventional distance relays and propose a new protection solution to mitigate the shortcomings of distance protection scheme during faults on the series compensated lines. The overall conclusion of this project is outlined as follows:

- The probability of current inversion is more if SC is installed at strong source and might cause the conventional distance relay to encounter steady-state under-reach problems depending upon the fault resistance.
- The probability of voltage inversion is more if SC is installed at weak source and might cause the conventional distance relay to encounter directional discrimination issues or steady-state under-reach problem depending upon the fault resistance.
- SSO occurs if the net reactance of fault loop becomes inductive. SSO occurs at remote end if the feeding source is strong but can also occurs near SC if the feeding source is weak.
- SSO phenomenon in series compensated lines causes the conventional distance relay to encounter transient over-reach problems especially for zone 1 setting.
- Current and voltage inversion cannot occur simultaneously if VT is installed before SC in the fault loop and vice versa.
- The condition of current inversion and SSO contradicts with each other. This means that both current inversion and SSO cannot occur simultaneously.
- SSO can occur together with voltage inversion.
- In summary, the integration of SC leads to steady state under-reach and over-reach problems, directional discrimination issues, and transient over-reach problems for conventional distance relays. The conventional relays might encounter false tripping or blinding depending upon the parameters of fault loop.
- New quadraliteral characteristic is proposed for distance relays to handle steady-state under-reach, and over-reach problems.
• Typical digital high-pass filter is designed and implemented as a new solution to cope with SSO problems and handle transient over-reach issues.
• The directional discrimination issue is still challenging during bolted fault near the series capacitor if SC is installed at weak source. However, the new relay algorithm provides adequate protection for impedance faults even if SC is installed at weak source.

8.2 Future research and Recommendation
This project considers SC installed at sending end of protected line. The author of this report put huge efforts and innovative skills to analyze the impacts of series compensation on the performance of conventional distance relay in a very good way. The author of this report also proposed new distance protection solution to handle the protection issues during faults on the series compensated lines. The proposed protection algorithm detects any type of bolted and impedance faults (up to 50 Ω) on series compensated lines within 20 ms. The proposed protection scheme is found to be advantageous. The author intends to explore further research in the same domain by analyzing the impacts of series compensation on the behavior of interconnected power system. For the future research, the author suggests and recommends that it is also necessary to investigate the impacts of series compensation on the performance of distance relays for the following cases.
• SC installed at remote end of the line
• SC installed in the parallel lines
• SC installed in the adjacent backward and forward lines.
Appendix-1

Power System Modeling

Appendix-1 gives an overview of power system modelling in EMTDC/ PSCAD followed by modelling of EHV transmission line. EHV transmission line considers distributed parameter and modelled as frequency dependent phase model in PSCAD to perform accurate transient analysis.

A1.1 PSCAD Model of Power System

Typical two-source power system with series compensated EHV line is modelled in PSCAD as shown in the Figure A1.1. The source “S” and “R” is the sending and receiving end source respectively. This project considers distance relay at bus “A”. For forward fault analysis, the SC is installed after bus A as shown in the Figure A1.1. Backward fault analysis consider SC installed before bus A. The line between bus “A” and bus “B” is EHV transmission line.

![Figure A1.1: PSCAD model of two-source power system with series compensated EHV line](image)

The block diagram of MOV control strategy and distance protection scheme in PSCAD is presented in Figure A2-1 (Appendix-2).

A1.2 Modeling of transmission line

Transmission line can be modelled as lumped parameter or distributed parameter model depending upon the length of transmission line.

Lumped parameter line model produces higher harmonics and distortion in the wave shape and cannot simulate the response of transmission line over high order frequencies present in signal during transient condition [37]. In the transmission line with ground return, the parameters are highly dependent on the frequency. So, the model of transmission line considering the entire
frequency range of signals is very essential for the correct electromagnetic transient simulation [37]. Frequency dependent model of transmission line uses distributed parameter and considers the impact of high frequencies in voltage and current signals during transient conditions.

Consider the simplified frequency dependent model for EHV transmission line as shown in Figure A1.2. The output voltage and current can be represented in term of input voltage and current by Eq. (A1.1) and Eq. (A1.2) respectively [37].

\[
\bar{U}_R = \cosh(\gamma \cdot \ell) \cdot \bar{U}_S - \bar{Z}_C \cdot \sinh(\gamma \cdot \ell) \cdot \bar{I}_S \quad (A1.1)
\]

\[
\bar{I}_R = \frac{1}{\bar{Z}_C} \cdot \sinh(\gamma \cdot \ell) \cdot \bar{U}_S - \cosh(\gamma \cdot \ell) \cdot \bar{I}_S \quad (A1.2)
\]

Where, \(\bar{Z}_C = \sqrt{\bar{Z} \cdot \bar{Y}}\) is characteristic impedance; and \(\gamma = \sqrt{\frac{\bar{Z}}{\bar{Y}}}\) is propagation constant.

\[\bar{Z} = R + j\omega L \text{ and } \bar{Y} = G + j\omega C\]

\(R, L, C, G\) are series resistance, series inductance, shunt capacitance and shunt conductance in per unit length.

Frequency dependent model with distributed parameters \(R, L, C\) and \(G\) gives an accurate estimation of transmission line over a wide frequency ranges present in signal during transient condition. The line can be modelled either by modal technique (Frequency Dependent Mode Model) or by phase technique (Frequency Dependent Phase Model). This project considers Frequency Dependent Phase model for EHV transmission line.

Master library in PSCAD offers Frequency Dependent Model in different conductor configuration. This project considers a typical equally spaced and ideally transposed horizontally configured three phase line model with two ground wires is shown in Figure A1.3. All conductors are at height of 22m from surface of earth, the horizontal spacing between phases is 14m. Each phase has symmetrical four sub-conductors with spacing of 0.4572m.
The system data is given in Appendix-3 which includes: data of power sources at sending/receiving end, rating/specification of MOV and a series capacitor, and data of EHV transmission line. The parameters of line conductor and ground wire used in PSCAD is given in table A3-1 (Appendix-3).
Appendix-2

Appendix-2 gives a short overview of control strategy of MOV and distance protection scheme implemented in PSCAD.

*Figure A2-1: Block diagram of MOV control and distance protection scheme in PSCAD*
Appendix-3

A3.1 System Data
System frequency= 50Hz, Base voltage= 500 kV, Base power= 200 MVA

A3.2 Data of power sources at sending and receiving end

<table>
<thead>
<tr>
<th>Source</th>
<th>Voltage Phasor $(U \angle \theta^0)$ - kV</th>
<th>Positive sequence impedance $(Z_{1 \angle \theta^0})$ - Ω</th>
<th>Zero sequence impedance $(Z_{0 \angle \theta^0})$ - Ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sending end source</td>
<td>$(500 \angle 25^0)$</td>
<td>$(5 \angle 85^0)$</td>
<td>$(15 \angle 85^0)$</td>
</tr>
<tr>
<td>Receiving end source</td>
<td>$(480 \angle -10^0)$</td>
<td>$(100 \angle 85^0)$</td>
<td>$(300 \angle 85^0)$</td>
</tr>
</tbody>
</table>

A3.3 Rating of a series capacitor and MOV
Capacitance of a series capacitor= 115uF (for 50 % SC)
MOV energy level= 23 MJ
MOV protective current level= 10 kA
MOV protective voltage rating= 304 kV
MOV I-V characteristic= PSCAD user defined table

A3.4 Data of EHV transmission line
Frequency Dependent (Phase) Model
Length of line= 200 km
Positive sequence impedance= 0.025+j0.2759 Ω/km
Zero sequence impedance= 0.2515+j0.954 Ω/km

Table A3-1: Parameters of line conductor and ground wire

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor Geometric Mean Radius</td>
<td>0.02034 m</td>
</tr>
<tr>
<td>Conductor DC resistance</td>
<td>0.01 Ω/km</td>
</tr>
<tr>
<td>SAG for all conductors</td>
<td>12 m</td>
</tr>
<tr>
<td>Ground wire Radius</td>
<td>0.005524 m</td>
</tr>
<tr>
<td>Ground wire DC resistance</td>
<td>2.8 Ω/km</td>
</tr>
<tr>
<td>SAG for all ground wires</td>
<td>10 m</td>
</tr>
<tr>
<td>Height of ground wire above conductor</td>
<td>10 m</td>
</tr>
</tbody>
</table>
References


[33] Siemens, SIPROTEC 4 7SA522, Distance protection relay for transmission lines, V-7


**Biography**

**Syed Arif Ullah Shah**, born 1984 in Pakistan, received his BSc degree in Electrical Engineering from UET Peshawar-Pakistan in 2007. During 2007-2008, he worked as apprentice engineer at Fauji Fertilizer Bin Qasim Limited (FFBL) Pakistan. From 2008 to 2015, he worked as research associate at Institute of Space Technology (IST) Islamabad-Pakistan. He has completed the course work of master program in Electric Power Engineering at KTH Royal Institute of Technology, Stockholm- Sweden during 2015-2017. Currently he is doing degree project at ABB Corporate Research Center (SECRc) under Power System Development Team in Västerås-Sweden. He is dealing with the challenges in the field of power system protection. He has also performed interesting projects which includes: “Impacts of distributed generations in the typical Swedish micro grid on the conventional protection, and proposed a new protection solution”, “Impacts of FACTS and HVDC on power system stability and power oscillation damping”, “Smart grid and implementation of protection schema using IEC 61850 substation architecture”, and “Design and implement line differential protection algorithm for typical 220 kV line”.