KTH ROYAL INSTITUTE
OF TECHNOLOGY

Doctoral Thesis in Electrical Engineering

Distance Protection of Transmission Lines with High Levels of Series Compensation

A study on frequency and time domain communication independent distance protection for series compensated lines

MD TANBHIR HOQ

Stockholm, Sweden 2023

Distance Protection of Transmission Lines with High Levels of Series Compensation

A study on frequency and time domain communication independent distance protection for series compensated lines

MD TANBHIR HOQ

Academic Dissertation which, with due permission of the KTH Royal Institute of Technology, is submitted for public defence for the Degree of Doctor of Philosophy on Friday 3rd March 2023, at 10:00 p.m. in F3, Lindstedtsvägen 26, Stockholm.

Doctoral Thesis in Electrical Engineering
KTH Royal Institute of Technology
Stockholm, Sweden 2023

ISBN 978-91-8040-480-8
TRITA-EECS-AVL-2023:14

Printed by: Universitetsservice US-AB, Sweden 2023

Abstract

Series capacitors are used in electric transmission lines to increase their power transfer capacity. They compensate for the inductive reactance of the line. They offer a useful alternative to building new lines, in view of economic and environmental constraints. However, during transmission line faults, the presence of series capacitors causes problems for distance protection relays. Distance protection is the most widely used protection method in transmission lines, due to its relatively simple working principle and its ability to work with only local measurements of voltage and current. As the number of series compensated transmission lines is increasing, and the typical compensation level is also increasing, it has become essential to investigate protection methods that can be employed in place of traditional distance protection in series compensated lines.

This thesis addresses the problems associated with line protection in the presence of series capacitor compensation. The first part is an assessment of the performance of traditional distance relays in cases with high levels of series compensation. This was based both on simulation studies and on published works describing research studies and industry experience with series capacitor projects and the related line-protection issues. It is concluded that traditional distance protection cannot be used reliably with high levels of series compensation. The second part of the thesis describes some alternative protection methods that are developed and studied as candidates for better single-ended protection of series-compensated lines. These are based on incremental quantities, Lissajous curves and RL/RLC line models. These methods show positive results for single ended protection of series compensated lines. The incremental-quantity based method is fast and operates reliably, but faces under-reach problems with fault resistance. The Lissajous-curve based method can be used as an alternative to the Fourier transform and has some advantages in overcoming inversion situations, but it requires at least a cycle of data to operate. The RL- and RLC-model based solutions can also operate fast, but lose accuracy with higher fault resistances. All the proposed protection methods are extensively tested, using data from fault test cases generated with PSCAD, and algorithms developed in Matlab.

Keywords: Series capacitor, Series compensation, Transmission line, Distance protection, Incremental quantity, Lissajous curve, RL model, RLC model

Sammanfattning

Seriekondensatorer används i elektriska transmissionsledningar för att öka deras kraftöverföringskapacitet. De kompenserar för ledningens induktiv reaktans. På grund av ekonomiska och miljömässiga begränsningar erbjuder de en användbar alternativ till att bygga nya ledningar. Vid fel i ledningen kan dock seriekondensatorer orsakar problem för distansskyddsreläer. Distansskydd är den mest använda skyddsmetoden hos transmissionsledningar, som konsekvens av sitt relativt enkelt arbetsprincip och av att endast lokala mätningar av spännings och ström behövs. Då det finns ökningar i antalet seriekompenserad transmissionsledningar samt deras kompensationsnivåer, har det blivit väsentligt att utreda skyddsmetoder som kan användas i stället för traditionellt distansskydd.

Denna avhandling tar upp problematiken av reläskydd hos seriekompenserade ledningar. Den första delen är en bedömning av prestationen av traditionella distansskyddsreläer vid fall med höga seriekompenseringsnivåer. Detta baserades både på simuleringsstudier och på publicerade arbeten som beskriver forskningsstudier och branscherfarenhet av skydd hos seriekompenserade ledningar. Man drar slutsatsen att traditionellt distansskydd inte kan användas på ett tillförlitligt sätt med höga seriekompenseringsnivåer. Den andra delen av avhandlingen beskriver några alternativa skyddsmetoder som utvecklas och studeras som kandidater för bättre skydd av seriekompenserade ledningar. Dessa är baserade på inkrementella storheter, Lissajous-kurvor och RL/RLC ledningsmodeller. Dessa metoder visar positiva resultat för kommunikationsoberoende skydd av seriekompenserade linjer. Metoden baserad på inkrementella storheter är snabb och fungerar tillförlitligt, men den har problem med underräckning vid högre felmotstånd. Den Lissajous-kurvabaserad metoden kan användas som ett alternativ till fourier transform och har vissa fördelar för att övervinna inversionssituationer, men den kräver minst en period av data. Den RL- och RLC-modellbaserade metoderna kan också fungera snabbt, men de förlorar noggrannhet med högre felmotstånd. Alla föreslagna skyddsmetoder är utförligt testad med data genererade från PSCAD simuleringar och algoritmer utvecklade i Matlab.

Acknowledgement

This thesis marks the end of the PhD project "Distance protection of transmission lines with high levels of series compensation". The work was funded as project FPS12 in the Swedish Center for Smart Grids and Energy Storage (SweGRIDS) by Swedish Energy Agency, Hitachi Energy and Svenska kraftnät. I thank all of these organizations for sponsoring the project.

I thank my supervisor, Nathaniel Taylor, for allowing me to work on this project. For always being there whenever I needed any guidance. For being a calming influence and reasonable. I am thankful to my co-supervisor, Jianping Wang, for his input on the direction of the thesis and for helping streamline the work.

I am thankful to everyone at the division of electromagnetic engineering (EME) at KTH for making the last four years enjoyable. Thanks to all HR, IT and service support for their help with the everyday problems of PhD students. I am grateful to Rajeev Thottappillil and Martin Norgren, the division heads during the project, for all their support during my stay at EME. I am grateful to Hans Edin for being a guardian and mentor at KTH since starting my M.Sc. in 2012. I want to thank Patrik Hilber for reviewing my thesis and giving valuable feedback for improvement.

I am grateful to Zakaria for making my life easier in every way possible, listening to my frustrations, and sharing the office for the last four years. Thanks to Mrunal, Toan, Yang, Mauricio, Sanja and Wadih for the pleasant discussions.

Thanks to my current employer Hitachi Energy and Michele Luvisotto for the smooth transition from PhD studies to industry research. For being flexible and accommodating in completing my thesis.

I am thankful to my friends in Sweden for their unrelenting support. Thanks to Jewel, Zerin, Aunik, Nova and Pitom for your kindness and company. I am thankful to Monjur, Ahsan and Murad for supporting me and guiding me in academic research and to Masum, Rokon, Anas and Mirza for making my life easier in 2017.

I am thankful to my family, my sisters Kakon, Nupur and my parents for loving me unconditionally. Your sacrifices made me who I am today. Thanks to my parents-in-law for their support and to Ruba, Shukhon, Hannan, Rasel, Sumon and Jashim for lending me your hands in my difficulties.

Finally, thanks to my wife, Mumu, for always being there, understanding, enduring hardships together and giving me our Nureen.

To my dearest Mumu & Nureen.

'The impediment to action advances action.
What stands in the way becomes the way.'
Marcus Aurelius

Contents

List of Figures

List of Tables

Acronyms

HVDC	High voltage direct current
AC	Alternating current
VT	Voltage transformer
CT	Current transformer
CB	Circuit breaker
FSC	Fixed series capacitor
MOV	Metal oxide varistor
SC	Series capacitor
TD	Time domain
DP	Distance protection
POTT	Permissive over-reaching transfer trip
PUTT	Permissive under-reaching transfer trip
DUTT	Direct under-reaching transfer trip
IQ	Incremental quantity
CSGE	Conic section general equation
DFT	Discrete fourier transform
DWT	Discrete wavelet transform

List of Appended Publications

List of publications included in this thesis

The following publications are summarised in this thesis.

1 **M. T. Hoq**, J. Wang, and N. Taylor, "The Impact of Current Inversion on Line Protection in High Voltage Transmission Lines with Series Compensation", presented at the Conference on Energy, Power Systems and Power- and Industrial Electronics, Narvik, Norway, 2019.

2 **M. T. Hoq**, J. Wang, and N. Taylor, "Impact of High Levels of Series Compensation on Line Distance Protection", presented at the 15th International Conference on Developments in Power System Protection, Liverpool, UK, 2020.

3 **M. T. Hoq**, J. Wang, and N. Taylor, "Review of recent developments in distance protection of series capacitor compensated lines", Electric Power Systems Research, vol. 190, p. 106831, 2021.

4 **M. T. Hoq** and N. Taylor, "Distance Protection of Series Capacitor Compensated Lines: Practical Considerations, Industrial Status and Development", Electricity, vol. 2, no. 2, pp. 168–186, 2021.

5 **M. T. Hoq**, J. Wang, and N. Taylor, "An Incremental Quantity Based Distance Protection with Capacitor Voltage Estimation for Series Compensated Transmission Lines", IEEE Access, vol. 9, pp.164493-164502, 2021.

6 **M. T. Hoq**, J. Wang, and N. Taylor, "An Incremental Quantity Based Protection with Capacitor Voltage Estimation for Mid-Line Series Compensation", presented at the 16th International Conference on Developments in Power System Protection, Newcastle, UK, 2022.

7 **M. T. Hoq**, J. Wang, and N. Taylor, "Series Compensated Transmission Line Distance Protection Using Lissajous curves and Conic Section General Equation".

All articles are available in diva portal

8 **M. T. Hoq**, J. Wang, and N. Taylor, "Time Domain Distance Protection for Series Compensated Transmission Lines Using RL and RLC Line Models".

9 **M. T. Hoq**, J. Wang, and N. Taylor, "Assessing Distance Protection Methods for Series Compensated Transmission Lines".

Md Tanbhir Hoq is the main author for all included publications. The literature review, simulation, calculation and drafting were conducted by Md Tanbhir Hoq before comments from the supervisors J. Wang and N. Taylor. For publications **1** to **3**, the concepts were developed as a team in collaboration with J. Wang and N. Taylor. The idea of the publication **4** was developed along with N. Taylor. The whole concepts of publications **5** to **9** were initially proposed by Md Tanbhir Hoq and then assessed by J. Wang and N. Taylor.

List of publications by the author not included in the thesis

The following papers were authored during doctoral studies but are not included in the thesis.

i **M. T. Hoq**, M. Z. Habib, E. Shayesteh, and N. Taylor, "Reliability Assessment of Protection Schemes for Series Compensated Transmission Lines", in 4th International Conference on System Reliability and Safety (ICSRS), Rome, Italy, 2019.

ii M. Z. Habib, **M. T. Hoq**, S. Duvnjak Žarković, and N. Taylor, "Impact of the fault location methods on SAIDI of a resonant-earthed distribution system", in IEEE International Conference on Power Systems Technology (POWERCON), Bangalore, India, 2020.

Chapter 1

Introduction

1.1 Background

One-fifth of the total global final energy consumption is in the form of electricity [1]. Electricity is consumed primarily by industry, residential, commercial and public services [1]. Unlike other major energy forms, such as coal, oil and natural gas, electricity cannot be stored on a large scale. Therefore, the production and consumption of electricity must be continuously balanced. The electric power system has been developed for this purpose. The power system today is one of the largest and most complex human constructions [2].

Power Transmission Lines

The role of the power grid is to connect energy generation with energy consumption. Electric power is generally generated at up to 21 kV in power plants [3]. In order to transmit power efficiently, the voltage is increased by step-up transformers. The transmission lines are then used for bulk power transfer over longer distances. Despite the increased HVDC connections in recent decades, overhead AC lines are the most common choice for power transfer in transmission systems. Transmission systems are critical infrastructures and, in many countries, are owned by government utilities. Distribution systems connect from points in the transmission system down to end users of the system, using shorter lines at successively lower voltages.

Transmission Line Protection

Transmission lines are the backbone of the power grid. Along with their traditional role of transferring power from a source to a load point, transmission lines are now integral to electricity trading and synchronously connecting different power systems. The role of transmission line protection is to detect and isolate faults with high selectivity, so that faults in one line are isolated without causing danger or preventing operation of the system. Transmission line protection failure is one of the

leading causes of power system collapse, and blackout [4]. Electricity powers almost all of the technologies and services used by modern society. Blackouts therefore have severe negative direct and indirect consequences on every aspect of life from economy to national security. Line protection is one of the most critical aspects of power system protection concerning network performance and investment costs; therefore, utilities and manufacturers spend significant resources on the design and maintenance of line protection systems [5].

Distance and differential relays are the two most commonly used transmission line protection methods. In their traditional forms, both use fundamental-frequency voltages and/or currents to protect transmission lines. Before elaborating on these, it is essential to get familiarised with a single-line diagram of a transmission line with components relevant to protection, as shown in Figure 1.1. Two sources represent the grid on the sending and receiving sides. There are distance and differential relays in each bus with a voltage transformer (VT), current transformer (CT) and circuit breaker (CB). The relays get the relevant measurement from the VT and CT, take decisions based on the available data and send the trip signal to the CB. In the case of the differential relay, there is necessarily a communication channel between the two line terminals.

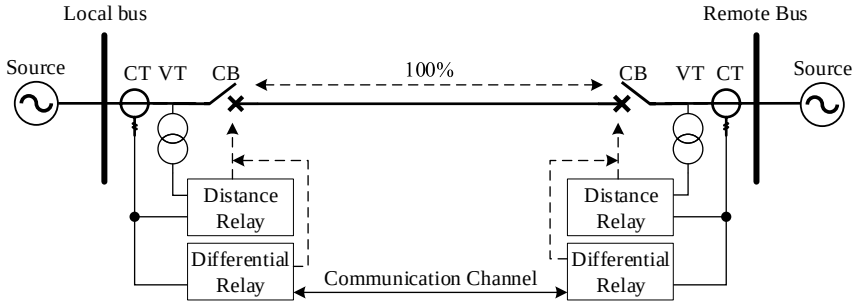


Figure 1.1: Single line diagram of a transmission line

Distance Protection

Distance protection is the most commonly used protection in transmission lines. It can work with local measurement only, without communicating with the other line terminal, and is relatively simple to implement in numerical relays. A distance relay calculates fault impedance from the local measurement of voltage and current, and compares this with a preset impedance to determine whether the fault is within its operating region. The fault distance is inferred from the impedance since the line length is proportional to the distance, hence the name distance protection. In a

three phase system, a distance protection relay can account for different fault types using six measurement loops.

Distance protection is a non-unit type of protection, meaning that the reach of the protection is not strictly limited within the protected line segment. Distance relays are designed to operate with different zones. The zone 1 is usually set at around 80% of the line length, usually set to be instantaneous (no deliberate delay). The zone 2 and the zone 3 are usually set at 120% and 220% of the line length, with added delay. Zone 2 ensures that the protected line is entirely covered, in case of faults beyond zone 1. Its delay gives time for a fault just beyond the line end to be cleared by protection relays closer to the fault. Zone 3, where used, provides a backup to other protection relays.

Differential Protection

Differential protection operates on Kirchhoff's current law, that the current entering the local bus should be equal to the current exiting the remote bus under normal conditions. Differential protection, therefore, requires fast communication between two terminals of the protected line for transmitting measurement data. It is a unit-type protection, provides excellent selectivity, and is immune to many different system changes. However, in practice, differential protection always needs backup protection due to the possibility of communication channel failure. Analysis of relay failures in various utilities revealed that communication failures were one of the leading causes of relay failure [6], [7]. Distance protection is the usual choice for backup to differential protection, as it can operate without a communication channel between line terminals. Differential protection is less common than distance protection in high-voltage transmission networks due to higher cost associated with the high speed communication channel. However, they are used in situations where distance protection becomes unreliable. The current differential relay works with comparing two quantities per phase: the differential current I_{diff} and the bias current I_{bias}. There are many different ways of defining the bias current, but a generic definition is given in Equation 1.1, where I_{l} and I_{r} are the currents measured into the line at the local and remote buses, and m is the slope of the restraint curve.

$$\begin{aligned} I_{\text{diff}} &= |I_{\text{l}} + I_{\text{r}}| \\ I_{\text{bias}} &= m \times |I_{\text{l}} - I_{\text{r}}| \end{aligned} \tag{1.1}$$

Series Capacitor Compensation

Long transmission lines have a significant inductive reactance, which is the main part of their series impedance at power frequency. Therefore, adding a capacitor in series with the line reduces the overall line impedance and allows a higher current flow. This arrangement is called series capacitor compensation. Series capacitors increase power transfer ability and improve voltage stability and angular stability

[8]. They are an economical option for building new transmission lines when more power is required to be transferred [8].

There are many different types of series capacitive compensation devices. However, the simplest form of series compensation is inserting a fixed series capacitor (FSC) in the transmission line. FSC is the lowest cost and most widely used series compensation method in AC transmission lines [9] [10]. As the power system continues to evolve, the transmission grid is asked to transmit more power over longer distances. Series capacitors will continue to be an essential tool for facilitating more power flow within the same transmission infrastructure [10].

The degree of compensation or the compensation level k is used to characterise the proportion of the inductive reactance X_{L} of the line that is compensated by the capacitive reactance X_{C} of the series capacitor, as defined by equation 1.2 and usually expressed in percentage.

$$k = \frac{X_{\mathrm{C}}}{X_{\mathrm{L}}} \times 100\% \tag{1.2}$$

Higher compensation levels mean lower effective line impedance, and consequent higher power transfer ability. It is expected that in the future more series compensated lines will be seen, and with higher compensation levels [10].

Series capacitors are equipped with high-voltage protection. A typical arrangement is shown in Figure 1.2. The metal oxide varistor (MOV) is a strongly non-linear resistance. It is connected in parallel with the capacitor. Under normal load conditions the voltage across the capacitor is low enough that the MOV has a high resistance, carrying negligible current. During faults with higher current, the voltage across the capacitor increases. Once the voltage reaches the MOV's threshold, it carries some of the fault current and thus limits the voltage across the capacitor. The MOV absorbs energy from the fault current. When its energy limit is reached, the bypass CB closes to remove both the MOV and capacitor from the fault loop. The operation of the MOV and CB during faults creates a highly non-linear behaviour during faults.

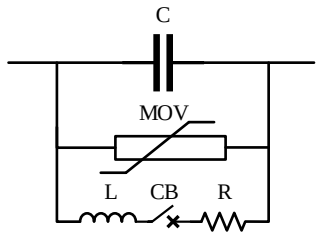


Figure 1.2: Capacitor bank protection scheme

Figure 1.3 shows examples of ways of implementing a series capacitor in a transmission line. Subplot *a* and *b* show the SC in the line terminal and in mid-line. In subplot *c* there are capacitors in both line terminals. In subplot *d*, there are capacitors in each one-third distance of the line. The positions shown in *a* and *b* are most common.

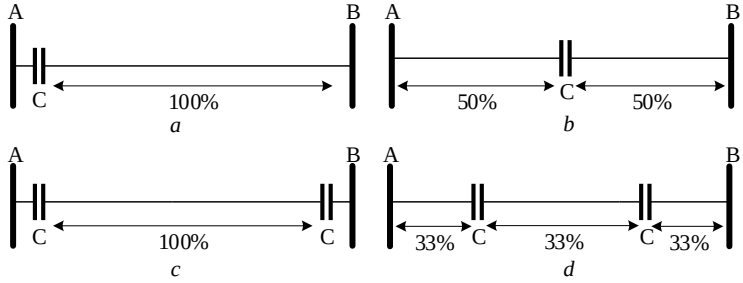


Figure 1.3: Different positions of SC in a line: a) line terminal, b) mid-line, c) both line terminals, d) 33% from each bus

1.2 Motivation

Distance protection is widely used for transmission line protection, as it can operate independently of communication with local measurement. Series compensation is employed for increasing power transfer capacity, improving voltage profile, reducing transmission losses, and improving transient stability. The non-linear behaviour of series capacitor bank protection during faults poses challenges in accurately measuring the line impedance with phasor distance relays. The distance relay faces directional problems and delays in this situation. Existing methods implemented in the distance relays to solve these challenges exist, but these do not fully address the problems and mainly apply to low series compensation levels such as 30%. It requires further research to find the suitability of distance protection on highly compensated lines and to evaluate other potential techniques for using distance protection.

1.3 Sustainable Development and Ethical Aspects

Reliable line protection at reasonable cost is an enabler for implementing more series capacitors with higher compensation levels in the transmission grid. Series capacitors can be used to transmit more power with the existing transmission infrastructure or new lines can be equipped with series capacitors for operating them with higher flexibility. Series capacitors are therefore helpful for integration of renewable energy sources in the existing network or for supplying electricity to remote areas at a lower cost. Thus, work on improving line protection of series compensated lines

can contribute towards achieving UN sustainable development goal 7: Affordable and Clean Energy, specifically with the goal's target 7.1 (ensure universal access to affordable, reliable and modern energy services) and 7.2 (increase substantially the share of renewable energy in the global energy mix) [11]. Additionally, it can also partially influence UN sustainable development goal 9: Industry, Innovation and Infrastructure, target 9.4 (upgrade infrastructure and retrofit industries to make them sustainable) [11]. By reducing the need for new lines to be built, series capacitors contribute to less use of materials and less disturbance to the countryside.

The research presented in this thesis was performed using computer simulations and models. There are no ethical conflicts perceived, related to animals, humans and environment, due to the conduct of this research.

1.4 Objectives

The objectives (O) of this work are listed below. All objectives are in the context of series capacitor compensated transmission line distance protection. The four objectives are referred to in the text with the labels O1, O2, O3 and O4.

O1: Evaluate the performance of traditional distance protection.

O2: Review methods proposed for improving distance protection.

O3: Evaluate other line distance protection methods for SC lines.

O4: Compare performances of new distance protection methods.

1.5 Scope and Limitations

The scope of this work is distance protection of series-compensated transmission lines with high levels of series compensation. Compensation levels over 50% are considered as high. Long, high-voltage power transmission lines are the focus. A maximum sampling rate 10 kHz is assumed to be available for designing and testing protection methods. In all studied cases, a 200 km long transmission line is considered, with rated voltage 500 kV and system frequency 50 Hz. The transmission line is assumed to be fully transposed in all cases. Distance protection methods independent of the communication channel between the two line terminals are considered. Therefore, methods that can operate with only local voltage and current measurements are deemed as valid. Methods involving machine learning and artificial intelligence are not studied; reasons are closely aligned with the views in [12], as the project is aimed at solutions that could be used in transmission systems in the near future.

The capacitor placements at the line terminal and the mid-line are considered as shown in Figure 1.3 *a* and *b*. It is assumed that only bus-side measurements are available. Capacitor bank protection with MOV and CB is considered as shown in

Figure 1.2. It is assumed that the bypass circuit breaker does not operate within the 1 power frequency cycle of 20 ms, even with the highest fault current levels. Two-terminal line models are assessed; therefore, interaction from other parts of the system, such as a parallel line, wind farms or other power electronic converter-based sources, is not evaluated.

1.6 Methodology

Different methodologies have been employed in different publications included in this work. In order to understand the performance of traditional phasor-based distance protection in highly compensated lines, a distance relay algorithm was implemented in Matlab. The algorithm was tested using fault cases generated with PSCAD with high levels of series compensation (publications 1 and 2). An in-depth literature review of relevant academic publications was conducted to understand the state of art research for the protection of series compensated lines (publication 3). Design aspects of series compensation, relay manuals and patent overview were studied to understand the status of series compensated line protection in practice (publication 4). After understanding the characteristic of protection methods required in distance protection of lines with high levels of compensation, different non-traditional distance protection methods were investigated. New distance protection has been tested for suitability in series compensated lines with high compensation levels, and all algorithms were implemented in Matlab. Many different test cases were generated using a Python script and PSCAD automation library to test all distance protection algorithms extensively (publications 5, 6, 7, 8). This allowed testing methods suitable for distance protection of series compensated lines that avoid the problems associated with phasor based distance protection and allowed for investigating their relative strengths and weakness (publication 9).

1.7 Scientific Contribution

The contributions of this work can be divided into the following seven parts, connected with the included publications according to Table 1.1.

C1: **Investigating impact of high levels of compensation**
The Contribution **C1** aims to address the **O1** by studying the impact of compensation levels higher than 50% in transmission line protection. The impact of current inversion on line distance and differential protection is presented in publication **1**. The impact of higher compensation levels on phasor-based distance protection is shown in publication **2**.

C2: **Academic literature review on improving distance protection**
Contribution **C2** aims to address **O2**. Recent and older literature on improving phasor-based distance protection is studied to understand the state of the

art in research and their applicability in higher compensation levels. This outcome is presented in publication **3**.

C3: **Study on practical Considerations, industrial status and development**
Review on different practical aspects of series compensated line protection including design factors, implementation examples, relay manufacturer protection solutions and patent overview. Contribution **C3** aims to address **O2**. This outcome is shown in publication **4**.

C4: **IQ based protection**
IQ-based distance protection is implemented and evaluated for line distance protection with high levels of compensation. The advantages and shortcomings are evaluated in the context of series compensated lines. The **C4** address objective **O3**. The outcome of this are presented in publications **5** and **6**.

C5: **CSGE based protection**
Distance protection using Lissajous curves and CSGE is implemented and evaluated. The advantage of using the Lissajous curve and CSGE-based distance protection in SC compensated line address objective **O3**. This work is presented in publication **7**.

C6: **RL & RLC model-based protection**
RL and RLC model-based time domain distance protection for SC compensated lines are implemented and evaluated to address **O3**. It is presented in publication **8**.

C7: **Comparing different distance protection methods**
Performance comparison of different methods in distance protection is presented in paper **9** by evaluating each of the methods in **C4-C6** in case of series compensated line protection. This addresses objective **O4** and presented in publication **9**.

Table 1.1: Thesis objective, contribution and publication map

		P1	P2	P3	P4	P5	P6	P7	P8	P9
O1	**C1**	•	•							
O2	**C2**			•						
	C3				•					
O3	**C4**					•	•			
	C5							•		
	C6								•	
O4	**C7**									•

1.8 Thesis Outline

Chapter 1: This chapter presents the background, motivation, objectives, limitations and contribution of the thesis.

Chapter 2: The challenges of phasor-based distance protection and line protection methods used by power utilities in series compensated lines are discussed in this chapter (publications 1, 2, 4).

Chapter 3: This chapter presents literature on protection methods that can operate with local measurement only in series compensated lines from both academic research and relay manufacturers (publications 3, 4).

Chapter 4: Methods tested for distance protection in lines with high levels of series compensation, along with the methods for testing the protection methods, are described in this chapter (publications 5, 6, 7, 8).

Chapter 5: Different methods described in chapter 4 is compared in this chapter, and their relative strength and weakness are identified and discussed (publication 9).

Chapter 6: The conclusions of the thesis and the future work scopes are presented in this chapter.

Chapter 2

Protection of Series Compensated Lines

This chapter describes protection challenges associated with phasor based distance protection of series compensated transmission lines, and protection methods used by utilities for the protection of series compensated lines. This chapter contains excerpts from publications 1, 2 and 4.

2.1 Challenges of Distance Protection

This section discusses different challenges for distance relays protecting lines with high levels of series compensation. The discussion is based around a series compensated line with the capacitor placed at a line-terminal, shown as a single-line diagram in Figure 2.1. Resistances are ignored in the simplified diagram as they tend to be small compared to power-frequency inductive reactances for transmission lines. The line terminal where the relay is located is referred to as the local bus, while the line terminal at the other end of the line is referred to as the remote bus. The local and remote source reactance are represented with X_{S} and X_{R}. The reactance of the capacitor is denoted X_{C}, and the reactance of the total line length

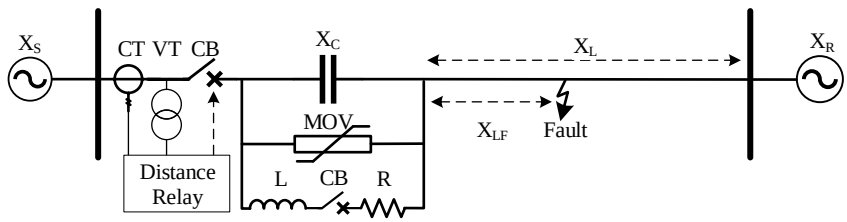
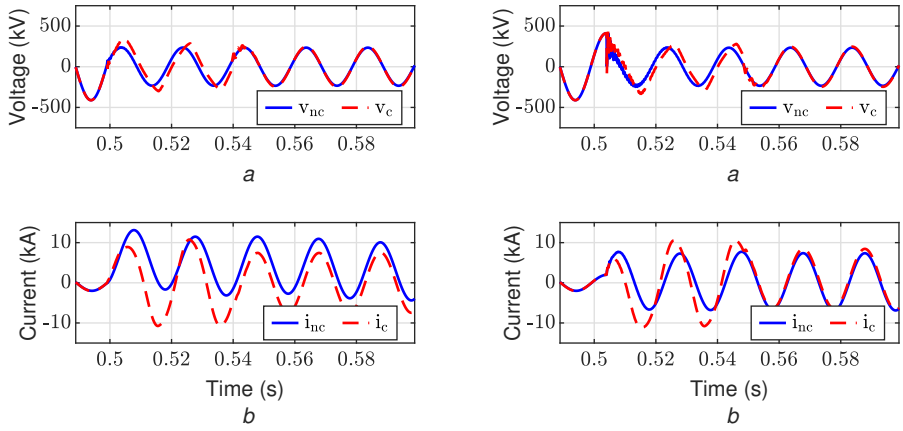


Figure 2.1: Single line diagram of a SC compensated line along with capacitor bank over voltage protection

is denoted X_{L}. During a fault, the reactance of the line from the measurement point up to the fault point is X_{LF}, which is some proportion of X_{L}, depending on the fault location. The combination of the capacitor and MOV during a fault presents an effective capacitive reactance X_{CF} that can be lower than X_{C} if the MOV carries part of the fault current. Current and voltage inversions are explained together here: even though their mechanism is slightly different, their consequences are similar in the context of phasor based distance protection.

The behaviour of the line currents during faults is different in series compensated lines compared to lines without SC. An example of this is shown in Figure 2.2. This shows measured voltages and currents at the local bus in lines with and without a series capacitor in the fault loop for two different fault inception angles for a bolted phase to ground fault at 60 km from the local bus. Subscript 'nc' is for the case without, and 'c' is for the case with a capacitor in the fault loop. The values are plotted until around five cycles after the fault.



(i) 0° inception angle **(ii)** 90° inception angle

Figure 2.2: Voltage and current signals for faults with and without SC with i) 0° ii) 90° fault inception angle

Sub-figures *i* and *ii* show results for fault inception angles of 0° and 90°, respectively. The inception angles are referred to the voltage phase. The voltage behaviour in subplots *a* in both sub-figures are not very dissimilar, one can observe the impact of the capacitor voltage, but the magnitudes are similar. However, the behaviour of the current signals shown in subplots *b* are significantly different in the presence of high levels of series compensation.

With the smaller inception angle a significant DC component is seen in the fault current in cases without series compensation, but the DC component is negligible with the series capacitor present. With a high fault inception angle, the DC component is small in both cases. With SC in the fault loop, the current peak does not

occur immediately after the fault but somewhat later. The fault current magnitude is not severely impacted by the fault inception angle in the presence of SC. The current magnitude decreases after the bypass CB removes the capacitor from the fault loop, around 2 cycles after the fault in both cases.

Current and Voltage Inversion

Current inversion happens when the transmission line becomes capacitive from the source to the fault point during a fault. The reactance of the capacitor during the fault (X_{CF}) is higher than the sum of the reactances of the source (X_{S}) and the line fault loop (X_{LF}). The condition can be expressed by Equation (2.1).

$$X_{\mathrm{CF}} > X_{\mathrm{S}} + X_{\mathrm{LF}} \tag{2.1}$$

This condition arises more easily with a strong source (low X_{S}) or close-in faults (low X_{LF}) or high levels of compensation (high X_{CF}).

Voltage inversion happens when the transmission line becomes capacitive from the measurement to the fault point during a fault, while the total reactance from the source to the fault remains inductive. The capacitor's reactance during the fault (X_{CF}) is higher than the line reactance (X_{LF}) but lower than the sum of line and source reactances ($X_{\mathrm{S}} + X_{\mathrm{LF}}$) as shown in Equation (2.2).

$$X_{\mathrm{S}} + X_{\mathrm{LF}} > X_{\mathrm{CF}} > X_{\mathrm{LF}} \tag{2.2}$$

Voltage inversion has been the most common issue in series compensated lines. Series capacitors have typically been used with moderate levels of compensation (low X_{C}), and in weak systems with substantial source impedance (high X_{S}). Both of these factors work against the condition for current inversion. However, with increasing use of series capacitors in transmission lines, higher levels of series compensation is found, in even stronger systems [13].

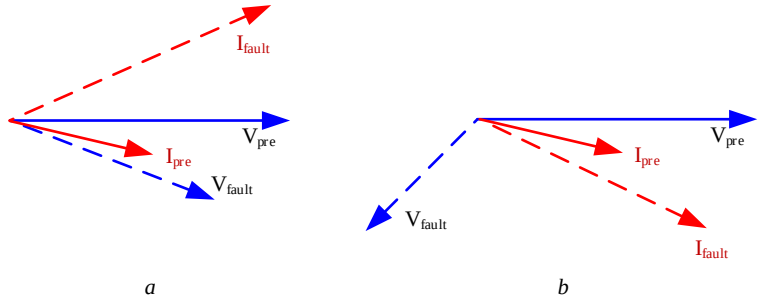


Figure 2.3: Phasor diagram of inversion conditions a) current inversion b) voltage inversion

The effect of current and voltage inversions can be visualised with phasor diagrams shown in Figure 2.3. The subplots *a* and *b* show current and voltage inversion, respectively. During current inversion, the phase angle of the fault current (I_{fault}) leads, and the fault voltage (V_{fault}) lags, relative to the pre-fault voltage (V_{pre}). During voltage inversion, the measured current (I_{fault}) and voltage (V_{fault}) both lag the pre-fault voltage (V_{pre}). In both cases, the fault current leads the fault voltage, leading to calculation of a negative reactance. The current and voltage inversion therefore have similar consequence on the calculation of fault impedance, if the fault voltage is used as a reference.

The impact of inversions are demonstrated in Figure 2.4 for a phase-to-ground bolted fault in a terminal series compensated line with 0° fault inception angle. Subplot *a* shows the voltage and current phase angles from half-cycle before the fault to two cycles after the fault. The fault inception time is marked with the grey horizontal line. The subplot *b* shows the impedance trajectory in the R-X plane for the same fault and at the same time frame. The pre-fault point is marked with a circle (∘). The voltage leads the current before the fault. After the fault, the current phase angle becomes higher than the pre-fault voltage angle and the voltage angle decreases, this is a current inversion, and it continues for around half-cycle after the fault. After around half-cycle post fault, the current and voltage angles decrease further, and voltage inversion conditions can be observed from around 0.51 ms onward. Current inversion usually lasts for a short while, and voltage inversion follows it [14]. As mentioned earlier, in both current and voltage inversion, the current phase angle leads to the voltage phase angle. The consequence of this is a capacitive reactance measured by the relay. It is demonstrated in the R-X diagram in subplot *b*. The impedance trajectory is in the negative reactance region after around 2 cycles post-fault. If the distance relay decides within this time, it will detect a reverse fault instead of a forward fault [15]. Moreover, if the relay waits for longer until voltage and current inversion situations are gone, it would take a long time to operate, which is also unacceptable [15].

Sub-synchronous Oscillation

The line inductance, along with the series capacitor, has a natural frequency of oscillation, and it can be excited by transient situations [16]. The natural frequency of the circuit can be expressed by Equation 2.3 during a fault.

$$f_n = f\sqrt{\frac{X_{\text{CF}}}{X_{\text{S}} + X_{\text{LF}}}} \tag{2.3}$$

When X_{CF} is slightly lower than the sum of X_{S} and X_{LF}, then frequencies slightly lower than the fundamental frequency are excited. Oscillations close to and lower than fundamental frequency cause problems in phasor estimation and are hard to eliminate with filters. These oscillations are called sub-synchronous oscillations (SSO). The condition for SSO can be expressed by Equation 2.4.

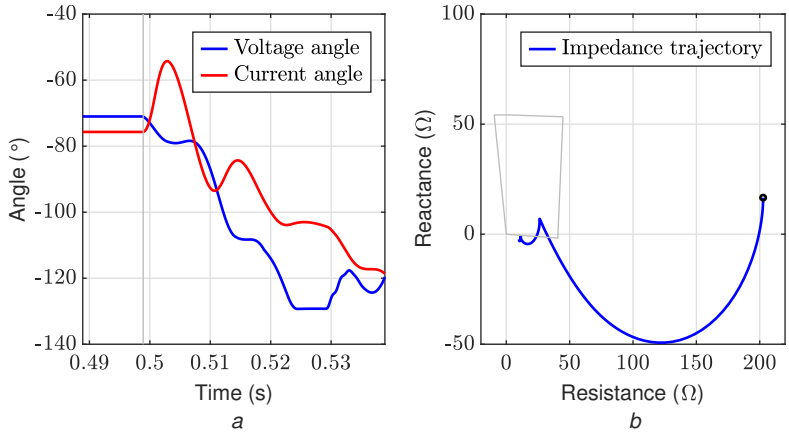


Figure 2.4: Impact of inversion on phasor based distance relay in a) phase angle of voltage and current b) impedance trajectory in R-X plane

$$X_{\mathrm{S}} + X_{\mathrm{LF}} > X_{\mathrm{CF}} \tag{2.4}$$

The impedance at the relay takes many cycles to reach a steady state value in the presence of SSO. Therefore, the relay takes longer to operate and can over- or under-reach. The effect of SSO can be observed if the capacitor remains in the fault for longer period after fault. With higher levels of series compensation, fault distances causing worst cases of SSO move further away from the local bus. As X_{C} increases, to fulfill Equation 2.4, the fault must be further away (higher X_{LF}). High levels of series compensation can be advantageous for line protection, with regard to SSO, as faults in the protected line will not cause extreme levels of SSO.

The impact of SSO is shown in Figure 2.5 for a bolted phase to ground fault 180 km from the local bus. Subplot *a* shows the resistance and reactance with time for 10 cycles after the fault. The fault inception time is marked with the grey horizontal line. Subplot *b* shows the R-X plot for the same fault with the same time frame. The pre-fault point is marked with a circle (○). The oscillatory behaviour is seen in both subplots. The impedance trajectory in *b* does not settle to a point, even at 10 cycles after the fault.

Capacitor Bank Operation

The non-linear behaviour of the capacitor bank protection is one of the significant challenges in series compensated line protection. The capacitor protection behaves in different ways for different fault current levels, as demonstrated in the following Figure 2.6. Three subplots show the current through the capacitor, MOV and the bypass breaker for three fault current levels. Subplot *a* shows the current distri-

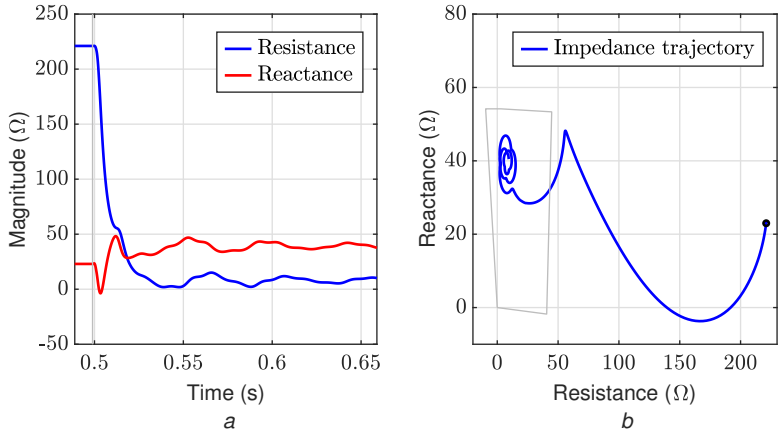


Figure 2.5: Impact of SSO on phasor based distance relay in a) resistance-reactance values with time b) impedance trajectory in R-X plane

bution for high fault current. With a higher fault current, the voltage across the capacitor becomes higher quickly. Therefore the MOV starts conducting current. As the fault current is high, the energy limit of the MOV is reached relatively quickly, within around 1.5 cycles, and the bypass CB closes to remove both the capacitor and MOV from the fault loop. In the next subplot *b*, the fault current is lower, and the bypass CB operates after around 3 cycles. However, with an even lower fault current in subplot *c*, the bypass CB does not operate even after 5 cycles after the fault. This behaviour creates uncertainty for the distance relay operation. It is challenging to estimate how much fault current passes through the series capacitor, and for how long, during a fault.

2.2 Line Protection used by Utilities

Some examples of protection methods used by various utilities in their series compensated lines are shown in Table 2.1 [17]. When distance protection is used, the zone 1 reach is reduced, and communication-aided schemes such as POTT, PUTT or DUTT are used. In other cases, differential relays are used, especially with higher levels of series compensation. It can be concluded that the schemes adopted for protection of series compensated lines almost always require some form of communication between two protected line terminals, or reduce the zone 1 reach. Neither of these options are ideal. Therefore, there is a need for a distance protection method that can work with only local measurements in series compensated lines without compromising reach or incurring the additional costs associated with communication aided protection.

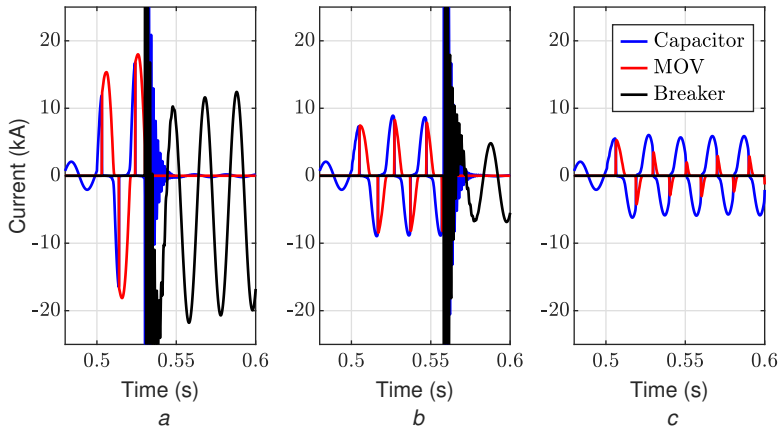


Figure 2.6: Capacitor bank protection operation for a) high b) medium c) low current fault

Table 2.1: Examples of compensated line protection (DP: distance protection)

Utility	Voltage	Level	Position	Solution
Eskom	400 kV	50% & 70%	End	Relay replacement and unit type protection [18]
National Grid	380 kV	50%	Mid	DP with memory voltage, zone 1 at 32.5% from ends [19]
CHESF	500 kV	70%	End	DP with POTT, DUTT, PUTT [20]
SIN	400 kV	24%–26%	End	DP with reduced zone 1, increase zone 2, POTT [21]
SIN	765 kV	44% & 51%	End	DP with reduced zone 1, increase zone 2, POTT [21]
BC Hydro	500 kV	-	Multiple lines	DP based on negative sequence impedance, time delays and coordination in auto-reclosing [22]
Hydro Québec	-	20%–44%	Multiple lines	Communication dependent main protection, lens shaped distance as backup [23]
Entergy	230 kV	-	End	DP [24]
Entergy	230 kV	70%	Mid	Current differential protection [24]
PG&E	500 kV	-	End	DP with reduced zone 1, memory voltage, POTT [25]
Idaho Power	230 kV	70%	End	Current differential protection [26]

Chapter 3

Literature Review on Improving Distance Protection

A comprehensive literature review is conducted to understand the proposed improvements for distance protection of series compensated lines. The literature search included literature from both academic research and relay manufacturers. The reviewed literature is limited to methods that can work with local measurements only. Both frequency and time domain methods are considered and are presented in sections 3.1 and 3.2, respectively. As phasor-based distance protection is widely used in transmission lines, most work has been done in this domain. Solutions from relay manufacturers for the protection of series compensated lines are also studied and presented in section 3.3. The comprehensive literature review helps the understanding of different avenues of proposed improvements and their possible shortcomings with higher levels of series compensation. The takeaway points from the literature review are presented in 3.4 for finding possible solutions for protecting series compensated lines. This chapter contains excerpts from publications 3 and 4.

3.1 Phasor Based Methods

Different methods for improving phasor based distance protection found in various literature are compiled below. The literature is divided into three broad categories namely capacitor voltage drop estimation, improving phasor estimation and adaptive distance protection, which are described below in brief [27].

Capacitor Voltage Drop Estimation

One of the challenges in distance protection of series compensated lines is calculating the voltage drop across the capacitor during faults, including the influence of the MOV. If this can be calculated correctly, then the phasor-based protection of the

SC compensated line can be improved. The models for capacitor banks and overvoltage protection can be divided into empirically or analytically developed models.

Examples of empirically developed models are presented in [28], [29]. A linearized equivalent model of the capacitor bank is presented in [28]. The MOV characteristic is shown in Equation 3.1. Here constants β and α are are calculated empirically [28].

$$I = \left(\frac{V}{\beta}\right)^{\alpha} \tag{3.1}$$

Voltage calculation based on this model is presented in [29]. The SC and MOV combination is represented by a resistance R_{c} and reactance X_{c} in series [28], [29]. The parameter values are calculated using Equation 3.2 [28].

$$\begin{aligned} R_{\mathrm{c}} &= X_{\mathrm{c0}}\left(0.0745 + 0.49e^{-0.243I_{\mathrm{pu}}} + 35e^{-5.0I_{\mathrm{pu}}}\right) \\ X_{\mathrm{c}} &= X_{\mathrm{c0}}\left(0.1010 - 0.005749I_{\mathrm{pu}} + 2.088e^{-0.8566I_{\mathrm{pu}}}\right) \end{aligned} \tag{3.2}$$

Here, the fault current peak I_{pu} expressed in per-unit of the rated load current is the only unknown [29]. Once the R_{c} and X_{c} are calculated, the voltage drop across them can also be estimated [29]. A similar approach is used in [30].

An analytically developed model is presented in [31]. The capacitor bank behaviour is expressed by Equation 3.3,

$$C\frac{\mathrm{d}v_x}{\mathrm{d}t} + i_{\mathrm{MOV}} - i = 0, \tag{3.3}$$

where C is the series capacitance, v_x is the voltage across the MOV, i_{MOV} is the current in the MOV, and i is the current in the line. The MOV current is approximated by Equation 3.4, in which I_{ref} and V_{ref} are reference quantities and q is a fitted exponent; this is essentially the same as Equation 3.1.

$$i_{\mathrm{MOV}} = I_{\mathrm{ref}}\left(\frac{v_x}{V_{\mathrm{ref}}}\right)^{q} \tag{3.4}$$

Equations 3.3 and 3.4 can be solved to get the voltage v_x [31]. This method has been used in different distance relay algorithms [32], [33].

In [34], the empirical method from [28] and the analytical method from [35] are compared. It was concluded that the analytical method represented the nonlinearity of the MOV better [34]. In another study [36], the same empirical method from [28] and analytical method from [35] were compared with the characteristic-based model found in PSCAD. It was concluded that the characteristic-based model in PSCAD gives the most typical values of asymmetrical fault current for SC compensated lines [36].

All the proposed methods in here are applied to improve phasor based distance protection. However, the capacitor voltage drop calculations can be used in time domain protection as well for the protection of series compensated lines.

Improving Phasor Estimation

Another avenue of research on distance protection in SC-compensated lines is improving phasor estimation from voltage and current values to calculate the fault impedance more accurately. A differential-equation based phasor estimation method for distance protection in lines with SC are presented in [37], [38]. A comparison between impedance estimation by differential equations and orthogonal components of voltage and current from Fourier transformation is presented in [33]. The differential equation method has a faster trip time with slightly lower dependability compared to the Fourier method [33]. Methods based on Fourier transform and differential equations were compared in [39] for impedance estimation in series compensated lines, leading to a recommendation of rectangular differentiation combined with the orthogonal component method.

In [40], five different phasor estimation techniques were compared in the context of SC line protection. It was concluded that the modified cosine algorithm [41] performs best, followed by DC-offset removal [42] and cascade filter algorithms [43]. Some additional methods for removing DC components in series compensated lines for better phasor estimation are presented in [44] and [45].

Adaptive Distance Protection

The idea of adaptive distance protection is to change or modify the relay parameters with changing system conditions to improve protection. Various forms of adaptive distance protection have been proposed for series compensated lines.

In [46], an adaptive solution is proposed with multiple relay characteristics for different fault characteristics. [47] presents a distance protection scheme with six zones. The protection method comprises phase-ground and phase-phase elements and has phase selection elements for each zone, and phase [47]. The directional element is based on phase current, positive sequence voltage, and memory voltage [47].

In [48] a method was proposed to adaptively switch off zone 1 and increase the zone 2 time delay in SC compensated lines. Delayed adaptive protection with reduced zone 1 setting is proposed in [49] for faults including SC. [50] proposed distance protection for adapting the zone boundary using the voltage drop across the SC and MOV during fault conditions.

3.2 Time Domain Distance Protection

Time domain distance protection for series compensated lines is dominated by methods using travelling waves. In one of the early works on the protection of series compensated lines using travelling waves presented in [51], the arrival time of transients in the relay bus is used to estimate the distance to fault. Voltage and current signals were used to determine faults in mid- and end-line series capacitors [51]. Later, a protection scheme based on current transients was presented [52].

A multi-channel filter is used to extract high-frequency signals from the current signal, comparison between different bands of the filter output is used to determine fault location. Two modal signals are created for analysis, as shown in Equation 3.5, from the phase currents I_a, I_b, and I_c [52]. A similar approach based on a multi-channel filter was presented in [53] for protection in transmission lines.

$$\begin{aligned} I_{m1} &= I_a - 2I_b + I_c \\ I_{m2} &= I_a - I_c \end{aligned} \tag{3.5}$$

A protection scheme consisting of two algorithms for the line with and without mutual coupling was presented in [54]. Both algorithms' signals from current and voltage transformers are first decoupled into modal components. Then they are decomposed using Discrete Wavelet Transform (DWT), and wavelet transform coefficients are obtained for further analysis. The time delay between different modes and their values are used to identify fault type, and location [54]. A similar communication-independent wavelet scheme method was proposed in [55] based on current transients only. As it was mentioned that current transformers are more effective in transferring high-frequency signals. First, the phase quantities are converted to modal components, wavelet modulus maxima are removed before fault detection, and fault location for issuing trip signal [55].

[56] presented a method for protection of series compensated lines by detecting distinct frequency bands in the transient fault current. Three phase current is combined to form one modal signal as shown in Equation 3.6. In contrast to [52], a single modal signal covers all faults. DWT is done on the modal signal, and fault detection and classification depend on the values of different wavelet coefficients [56].

$$I_m = I_a - 2I_b + 2I_c \tag{3.6}$$

Based on spectral energy analysis of different energy bands of transient phase voltages using wavelet transform is demonstrated in [57]. This method calculates the spectral energy of different bands of high frequencies from voltage signals. Then these are compared with a pre-set limit to detect a fault. Fault classification is done by comparison of spectral energies among different phases.

In a paper reviewing the use of different wavelets for series compensated line fault detection [58], the authors found Bior3.9 followed by the Meyer, Coiflet 5, Daubechies 10, and Symlets 8 wavelets to be most suitable.

The authors in [59] assessed the suitability of IEC 61850-2 LE sampled value in wavelet-based line protection, without communication between line ends. The proposed scheme is a hybrid of distance protection and transient-based protection: current values are decoded from sampled values for DWT, and both current and voltages are used in the distance protection [59]. The wavelet algorithm is based on previous work presented in [60]. The relay issues a trip signal only if both wavelet and impedance schemes detect the fault [59].

3.3 Relay Manufacturers' Solutions

Improvements in power system protection is strongly driven by relay manufacturers. Methods used by different relay manufacturers on the protection of distance protection are summarized below from [17].

Voltage inversion has been the most common problem in series compensated line protection. During inversion, the voltage phase angle changes abruptly. Therefore, the voltage phasor is always kept in the memory in line with SC. When a fault occurs, the pre-fault voltage phase from memory is used as a reference in relay operation. This method is called memory voltage polarization in general. The exact implementation of this varies from manufacturer to manufacturer. Many different relay manufacturers use memory voltage polarization to mitigate voltage inversion [61], [62], [63], [64], [65], [66], [67], [68].

The solution for mitigating current inversion is less commonly found in relay manufacturers' manuals. One manufacturer uses a multi-input comparator approach [62], with the distance element secured using multiple negative and zero sequence current conditions. Additionally, the memory voltage is checked before issuing a trip command [62]. As the relays might not operate during current inversion, it is recommended to use high-speed overcurrent protection for direct tripping [62].

SSO is tackled by using harmonic filters [69]. Adaptive relay characteristic is also used in the case of SSO [69], [62]. The tripping boundary in one relay is adjusted using the current magnitude in the capacitor bank [62]. The reach is reduced for high levels of compensation and low fault currents, but for high current faults the reach is kept at around 80% of the line [62].

3.4 Takeaway Points

Despite the research in improving phasor-based methods in distance protection presented in section 3.1 and 3.3, two main limiting factors hamper the protection of series compensated lines with them. Firstly, there is an inherent delay associated with using phasor-based methods; delays in relay operation will create uncertainties with capacitor bank over-voltage protection. Secondly, inversions and SSO are fundamental frequency phenomena; therefore, these will always impact any techniques that use the fundamental frequencies. Inversions become more problematic with higher levels of compensation. Therefore, suitable protection methods for SC-compensated lines should be fast and immune to inversion problems.

A good starting point is to start looking at time domain protection methods. Some techniques from phasor domain protection shown in 3.1, such as capacitor voltage estimation, can also be used in time domain protection. Time domain protection is usually faster and can break free of the limitations of the phasor calculations.

In time domain protection, most research has been done with travelling-wave-based solutions, as summarized in section 3.2. However, these methods have yet to be widely adopted in manufacturers' transmission line protection relays for distance protection. The main reason is their high requirement for measurement sampling rates, lower reliability and lack of general solution. The constraints discussed above motivate the investigation of other line protection methods that can be used in series compensated lines. A few other methods that can be useful in the distance protection of series compensated lines are discussed in the following chapter.

Chapter 4

New Distance Protection Methods

This chapter presents three protection methods that are assessed for the protection of series compensated lines with high compensation levels. For each method, a general background is given, and specific details are discussed about the application in the protection of series compensated lines. The chapter begins with describing generated test cases for assessing different methods. This chapter contains excerpts from publications 5, 6, 7 and 8.

4.1 Testing and Validation

Any relay algorithm must be tested extensively with many different test cases to understand its strengths and weaknesses. To this end, many different test cases were generated for testing. All the fault test cases were generated using PSCAD. The relay algorithms were developed and tested in Matlab. In all simulations, the frequency-dependent phase line model in PSCAD was used, as it gives results close to the actual behaviour of the line [70], [71]. The voltage levels in all cases are 500 kV, and the line is 200 km long. The PSCAD Python automation library was used to automate the creation of test cases with different systems and fault parameters. This helped in generating thousands of fault test cases. Examples of Python scripts for automating test case generation, along with PSCAD models and PSCAD output files, are available as open access data in [72], [73].

Table 4.1 shows an example of different variables tested. Two placements of the series capacitor are considered: line-terminal and mid-line. Two values of fault inception angle are used. Regardless of the fault's phase, the stated inception angle refers to a sinusoid in phase A. Therefore, six different fault inception angles are effectively tested for phase-to-ground faults. Three levels of compensation are used. Two SIR values are considered low because the research is aimed at long lines. The fault resistance level of 30 Ω is assumed sufficient in the considered voltage level [74]. Faults at different locations along the transmission line and reverse faults are considered (−5%). All fault types are considered, such as phase-A to ground (AG)

etc., with no-fault (NF) used as control.

Table 4.1: Test cases considered

Parameter	Value
Capacitor position	End and Middle
Phase A inception angle (°)	0, 90
Source impedance ratio (SIR)	0.20, 0.35
Compensation level (%)	50, 60, 70
Fault resistance (Ω)	0.10, 15, 30
Fault location (%)	−5, 5, 10, 20, 30, 40 50, 60, 70, 75, 80, 85, 90
Fault type	NF, AG, BG, CG, ABG, CAG BCG, ABCG, AB, CA, BC, ABC

4.2 Incremental Quantity Protection

Background

The incremental-quantity principle, also known as superimposed protection, is based on treating the voltage and current measured during a fault as the sums of their pre-fault and fault-induced values. The difference between pre-fault and fault quantities is called the 'fault-induced' value. Protection relays can calculate incremental voltage or current by taking the difference between the present instantaneous value and the corresponding point in an earlier period. A general expression for this can be written as in Equation 4.1, where $V(t)$ and $I(t)$ are instantaneous voltage and current, ΔV and ΔI are the incremental voltage and current, K is the fundamental frequency period, and n is the number of periods back in time that the pre-fault values are taken.

$$\begin{aligned} \Delta V &= V(t) - V(t - nK) \\ \Delta I &= I(t) - I(t - nK) \end{aligned} \tag{4.1}$$

The principle of estimating impedance based on the incremental voltage and current is based on a linear and time-invariant system. It works well for the traditional power system with synchronous machines as sources, in short timescales such as one period. However, with power electronic controlled sources, the situation can deviate significantly from these assumptions. This is a general weakness of algorithms based on superposition, such as incremental quantities and symmetric components [75]. Even synchronous generator sources impose a limit of some tens of milliseconds on the validity of incremental quantity methods [76], due to how long these sources remain stationary after a fault. Incremental-quantity based methods have been used in transmission line protection previously. Their use in

distance estimation is explained in [76], [77], [78], [79]. Their application in a series of compensated lines is presented in [80] and [81], and discussed briefly in the section below.

Application in SC lines

Incremental quantity protection works with instantaneous values of voltages and currents directly, without much processing or calculation. It can therefore be used to implement fast protection. All parts of a relay operation, such as fault detection, phase selection, directional discrimination and distance estimation, can be performed using incremental quantities.

In implementing incremental quantity-based distance protection in a series compensated line, it is necessary to estimate the voltage across the capacitor. Figure 4.1 shows a calculation of the capacitor voltage, that can run continuously on an input of sampled values of line current. The first sample of the capacitor voltage $V_c[1]$ is calculated in steady state conditions by multiplying the capacitive reactance X_c with the current value from a quarter cycle earlier $I[1 - 3/4T]$, where T is the number of samples in a period. Then the subsequent $V_c[i]$ values are calculated from the voltage of the previous sample $V_c[i-1]$ and the change in voltage $I[i-1]\,dt/C$ caused by the change in charge in the capacitor in one time-step dt. When a fault is detected, and the capacitor voltage crosses the MOV threshold V_{th}, the resistance-voltage characteristic of the MOV is used to calculate the distribution of the line current between the capacitor and MOV, so that the updates of the capacitor voltage can be based on the capacitor current alone.

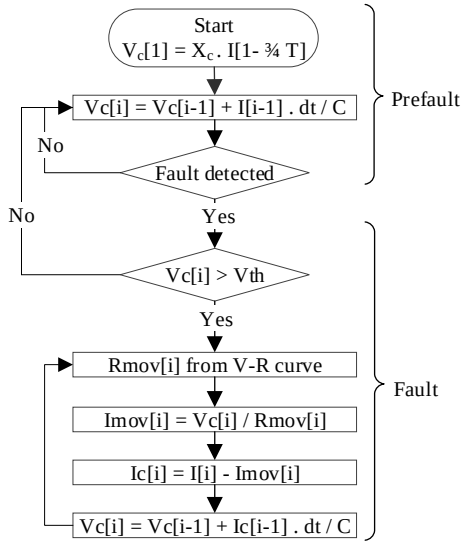


Figure 4.1: Capacitor voltage calculation process

The distance estimation is based on the assumption that voltage at the fault point becomes zero for a bolted fault. The pre-fault voltage and the change in voltage for faults at the end of zone 1 are equal in magnitude. The pre-fault voltage at the reach point can be calculated using the measured voltage in the line terminal and voltage drop along the line, in the time domain. This voltage is used as a reference. The change in voltage due to faults can be calculated by incremental voltage and currents and using appropriate fault loop impedance (based on fault type). In this method the distance calculations will under-reach in the presence of fault resistance.

An illustration of using IQ-based distance protection for a series compensated line is shown in Figure 4.2 for bolted phase to ground faults 10 km, 60 km, 120 km and 180 km from the local bus in a 70% terminal series compensated line. The reference voltage is calculated for an 80% (160 km) reach of zone 1. In subplot *a*, the fault-induced and reference voltages are plotted. In subplot *b*, the running sum of the difference between the fault and reference voltage in each case is plotted along with a minimum threshold value. The cumulative voltage is seen to be higher than the threshold in the first three cases as these are inside the relay's zone 1 reach, and to be lower than the threshold for faults outside the zone 1 reach.

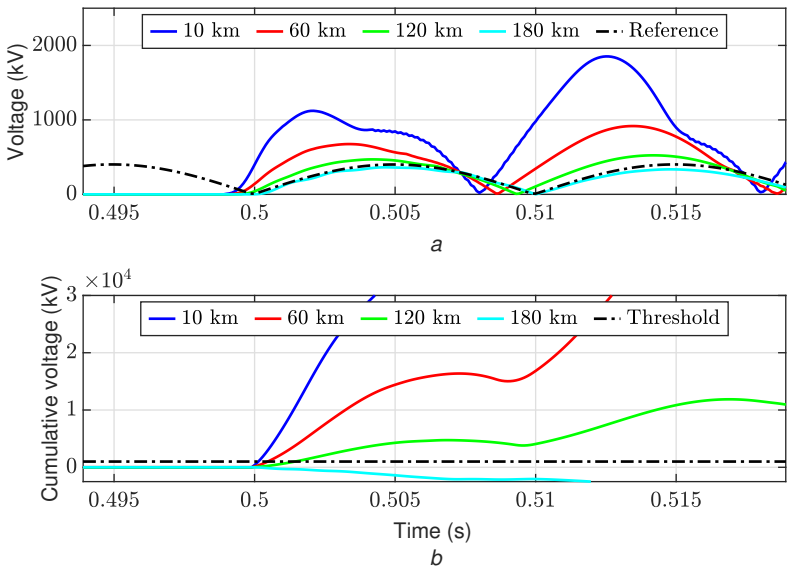


Figure 4.2: IQ-based distance estimation for 70% terminal SC a) incremental and reference voltages b) cumulative running sum between the difference between incremental and reference voltage

For capacitors in the line terminal, all points along the line come after the capacitor bank, so it can correctly be assumed that the fault current flows through

the capacitor bank. The capacitor voltages are calculated and subtracted from the measured voltage at the relay point, as a step towards calculating the fault distance. If the capacitor is in the middle of the line, the capacitor is not in the fault loop for faults before the capacitor. This may cause a significant error in distance calculation, when performing the fault distance calculation with subtraction of estimated capacitor voltage, for a fault that in fact does not include the capacitor. However, the performance is reasonably good, even though bolted faults before the capacitor are skewed to under-reaching. There are two reasons for this. First, the incremental voltage is higher as the capacitor is not included in the fault loop. Second, the higher incremental current means that the algorithm assumes activation of the MOV, so that the capacitor voltage is clamped at its maximum level and a significant current is assumed to bypass the capacitor through the MOV. As the reference voltage is calculated at zone 1 boundary (set at 80% of the line), distance calculations for faults after the mid-line capacitor operate without problems. The details of using incremental quantity protection in series compensated lines are presented in [80], [81].

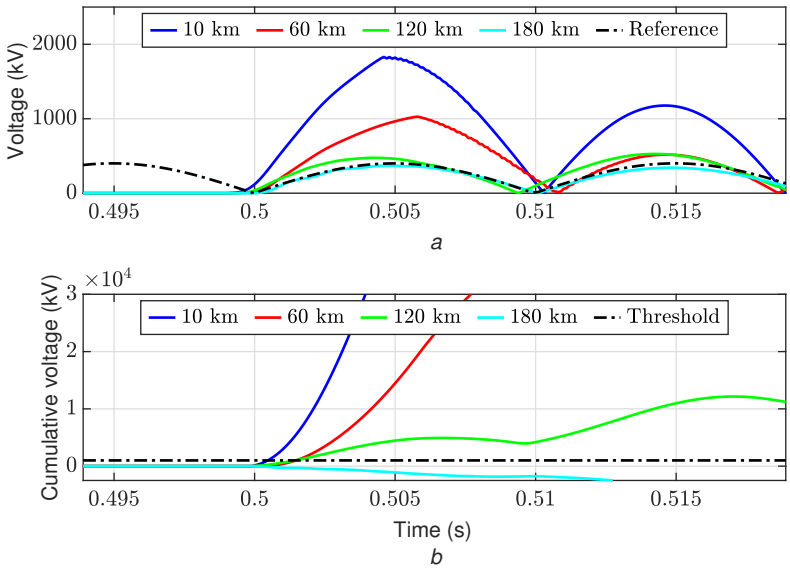


Figure 4.3: IQ-based distance estimation for 70% mid-line SC a) incremental and reference voltages b) cumulative running sum between the difference between incremental and reference voltage

IQ-based distance protection for a mid-line series compensation is shown in Figure 4.3. The results are shown for bolted faults 10 km, 60 km, 120 km and 180 km from the local bus in a 70% series compensated line. The fault induced voltage decreases with the increasing distance as expected, and the cumulative

voltage for the fault outside zone 1 correctly gets to a negative value. In Figures 4.2 and 4.3, there are differences between the shapes of the fault induced voltages for faults at 10 km and 60 km. When the SC is not in the fault loop (Figure 4.3), the highest fault induced voltage is immediately after the fault inception, whereas when the fault is in the fault loop (Figure 4.2), the highest fault induced voltage comes a bit later after the fault inception. This can be attributed to the behaviour of the fault current in the presence of SC in the fault loop. For mid-line compensation, when the fault happens before the capacitor, the current peak comes immediately after the fault, as seen from the fault induced voltage in subplot *a*.

4.3 Lissajous Curve Based Protection

Background

Lissajous or Bowditch curves are the trajectories of a point whose both components have sinusoidal motion. The components of a Lissajous curve can be expressed by Equation 4.2.

$$\begin{aligned} x(t) &= X \ \sin(\omega_x t + \alpha_x) \\ y(t) &= Y \ \sin(\omega_y t + \alpha_y) \end{aligned} \tag{4.2}$$

Here X, Y are amplitude coefficients, ω_x, ω_y are angular frequencies, and α_x, α_y are phase angles. Instantaneous voltage and current measurements in the relay terminal can be used to plot Lissajous curves. In steady state operation with $\omega_x = \omega_y$ the resulting Lissajous curves are elliptical and change their shape depending on the situation. From the ellipses, one can use the conic section general equation (CSGE) shown in Equation 4.3 to estimate the peak values of, and angle between, the voltage and current signals [82]. From these, the impedance can be estimated.

$$A\ x^2 + B\ xy + C\ y^2 + D\ x + E\ y + F = 0 \tag{4.3}$$

The shape of the ellipses would change between pre-fault and post-fault conditions. The fitted ellipses can be used to calculate impedance continuously. At inception of a fault there is clearly not a steady state; however, the fitting of an ellipse to a window of data from the transition between different conditions gives a compromise between the conditions, as with a DFT of a similar window.

Lissajous curves have been used to calculate impedance in other domains, and their application in power system protection is demonstrated in [82]. The potential for using them in series compensated lines is examined and summarized in the following section.

Application in SC lines

One of the significant problems in series compensated line protection is inversion. During inversion, the relay calculates an apparent capacitive reactance instead of an inductive one and hence faces the problem with fault direction and delay.

Figure 4.4 shows four Lissajous curves for forward bolted phase-ground faults at 10 km, 20 km, 40 km and 80 km from the local bus in a terminal series compensated line in subplots *a*, *b*, *c* and *d*. The arrows are placed in every 25 sample to show the direction of the trajectory. Before fault inception, the Lissajous curve is an ellipse with a small area with an anti-clockwise trajectory. From the local bus, for current flowing out (normal conditions and forward faults), the major axis of the ellipses are between quadrants 1 and 3. For reverse faults, the ellipse's major axis will shift between quadrants 2 and 4. After a fault, in subplots *a* and *b* for faults at 10 km and 20 km, the trajectory changes direction from an anti-clockwise to a clockwise direction. It is due to inversion and the apparent capacitive reactance of the line. In subplots *c* and *d* for faults at 40 km and 80 km, the trajectory direction remains the same as pre-fault.

If a complete cycle is used while using the CSGE to estimate the voltage and current parameters, the direction of the trajectory will not change the calculated reactance. The calculated reactance hence the estimated fault distance, will be positive despite inversion. The problem with Fourier transform-based calculations is that they will calculate a negative distance both during inversion and reverse faults. Nevertheless, using Lissajous curves, the calculated distance during inversion will be positive and negative during reverse faults.

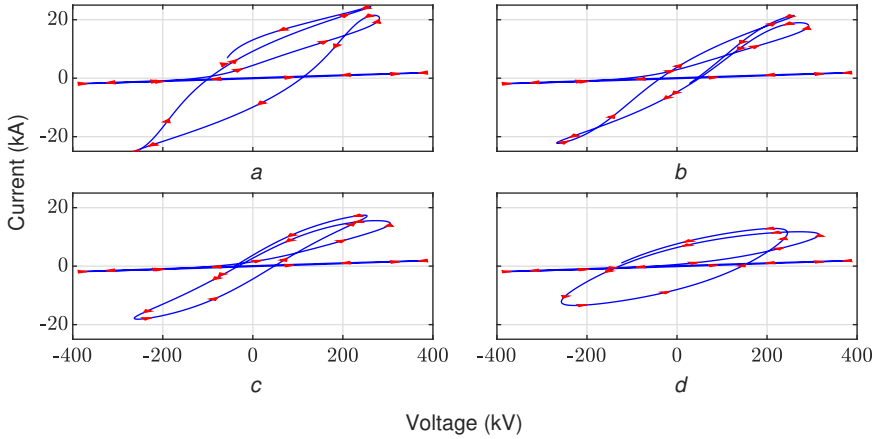


Figure 4.4: Lissajous curves for faults at different distances a) 10 km b) 20 km c) 40 km d) 80 km

Figure 4.5 shows the comparison between reactance calculation by DFT and CSGE for the Lissajous curves in Figure 4.4. A cycle-long sliding window calculates the impedance continuously from the Lissajous curves using CSGE. Therefore, valid impedance values are available only after 1 cycle post-fault.

The faults in subplots *a* and *b* have inversions. This is reflected in the reactance calculated by the DFT, which is negative after the fault. However, the reactance

from CSGE is positive, as only the ellipse's shape, not the direction of traversal of the shape over time, is considered. The magnitude of the reactance is higher in subplot *a* than in *b* as it is the net value of the SC's capacitive (negative) reactance and the line's inductive reactance. The fault distance estimated from the reactance does not represent the actual fault distance. Nevertheless, the positive value helps to bypass the directional problem due to inversion. In subplots *c* and *d*, the calculated reactances are the same from both methods, as inversion is not present in those cases.

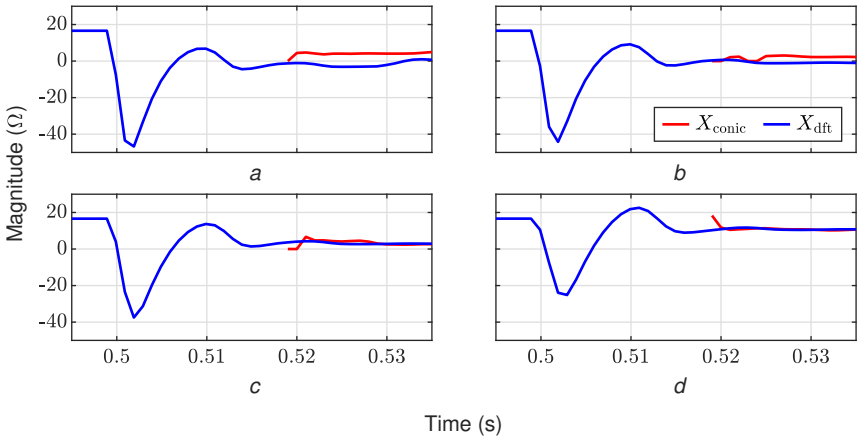


Figure 4.5: DFT and CSGE reactances for faults at different distances a) 10 km b) 20 km c) 40 km d) 80 km

Figure 4.6 shows the application of Lissajous curves and CSGE for distance estimation in series compensated lines. The fault cases show calculated reactances for bolted phase to ground faults at 10 km, 60 km, 120 km and 180 km from the local bus in a 70% terminal series compensated line. The reactance is seen to increase with more distant faults. However, the reactance values for 10 km and 60 km do not seem to be proportional with the distance. With this method the net reactance of the fault loop is measured. The net reactance is the sum of the negative (capacitive) reactance from the SC and the inductive reactance from the line. The 10 km fault has a higher net reactance due to a having a shorter line in the fault loop. The blip in the reactance value in the 10 km case is due to the parallel CB closing. A full-cycle sliding window was used in the calculation. Therefore, valid reactance values are available after a cycle after the fault.

Figure 4.7 show the distance calculations with CSGE method for bolted phase to ground faults 10 km, 60 km, 120 km and 180 km from the local bus in a 70% mid-line SC. The SC is located at 100 km from the local bus. Therefore, for faults at 10 km and 60 km the SC is not in fault loop, but it is in the fault loop for faults at 120 km and 180 km. The lower net reactance when the capacitor is in the fault

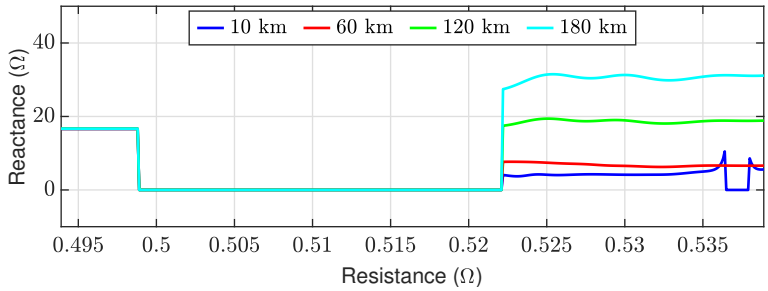


Figure 4.6: CSGE-based distance estimation for 70% terminal SC

loop is apparent in these two cases. In both Figures 4.6 and 4.7, the reactance for faults at 180 km is the same as both have the SC in the fault loop. This method has also been tested with faults in the reverse direction and it is possible to distinguish between forward faults with inversion and reverse faults with this method.

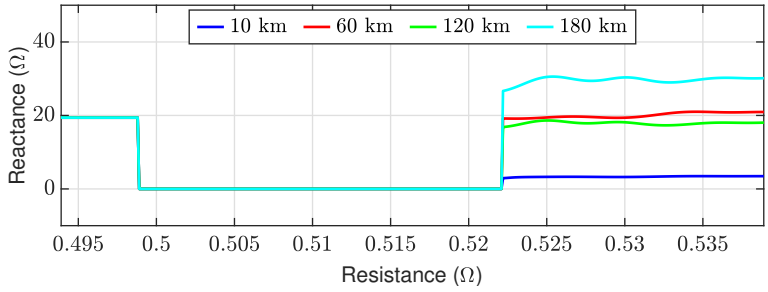


Figure 4.7: CSGE-based distance estimation for 70% mid-line SC

4.4 RL and RLC Line Model Based Protection

Background

The simplest form of modelling a transmission line is to represent the line with a series resistor and inductor. This model is called the RL model of the line. The RL line model in the context of the series compensated line is shown in Figure 4.8. A and B are two line terminals and C is the series capacitor. Bus A is the local bus. In sub-figure a, R_l and L_l are the line resistance and inductance, respectively. The sub-figure b shows the situations where a fault occurred at a distance m from the bus A. r_l and l_l are the line resistance and inductance parameters.

The voltage relationship at bus A is given by Equation 4.4 during faults with zero fault resistance $R_\mathrm{f} = 0$.

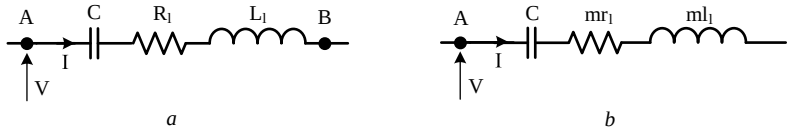


Figure 4.8: RL line model a) pre-fault b) during fault

$$V(t) = V_{\mathrm{c}}(t) + mr_{\mathrm{l}}\ I(t) + ml_{\mathrm{l}}\ \frac{dI(t)}{dt} \tag{4.4}$$

The RL model is further improved by adding two parallel capacitors at two ends of the RL line model. The model with the capacitor is noted as the RLC model of the line as shown in Figure 4.9.

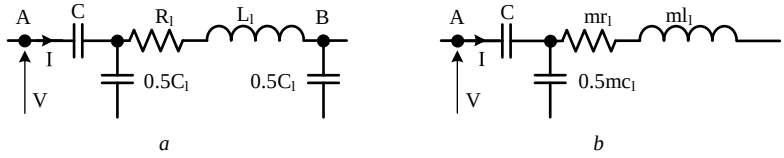


Figure 4.9: RLC line model a) pre-fault b) during fault

The relation between voltages at terminal A during faults for the RLC model is given by Equation 4.5 again with zero fault resistance $R_{\mathrm{f}} = 0$.

$$V(t) = V_{\mathrm{c}}(t) + mr_{\mathrm{l}}\ I(t) + ml_{\mathrm{l}}\ \frac{dI(t)}{dt} + mc_{\mathrm{l}}\ ml_{\mathrm{l}}\ \frac{d^2\ V(t)}{dt^2} + mc_{\mathrm{l}}\ mr_{\mathrm{l}}\ \frac{dV(t)}{dt} \tag{4.5}$$

The equations 4.4 and 4.5 can be further simplified by integrating them. Current and voltage samples during faults can be used to create a system of Equations in the form $Ax = b$ to solve for unknown quantities mr_l, ml_l and mc_l. The assumption is that the fault resistance R_f is zero. The capacitor voltage can be calculated according to the principle explained in section 4.2.

RL and RLC line models are often used in transmission line protection due to their simplicity, allowing faster calculation. For example, the classic phasor-based distance protection is based on the RL model assumption. These models can be used to implement fast-time domain protection [83], [84]. Their use in the protection of series compensated transmission lines is discussed and briefly explained the following section.

Application in SC lines

The Equations 4.4 and 4.5 are simplified and linearised with the assumption that the fault resistance R_f is zero. Although inducing some error, these equations work well

with realistic levels of R_f in high voltage transmission line faults. However, there is an additional problem in using this assumption in series compensated lines. The MOV is present in the fault loop in parallel with the capacitor. Therefore during faults, the MOV resistance also introduces errors in the parameter calculation. However, the non-linear character of the MOV helps here as the resistance presented by the MOV remains relatively low once the threshold voltage V_{th} of the MOV is reached. The MOV only conducts current once the capacitor voltage is higher than V_{th}. The resistance from the MOV does not introduce high levels of errors.

However, the introduction of the MOV resistance rules out using the resistive component mr_{l} quantity for estimating the fault distance as it is impossible to differentiate between line resistance, MOV resistance and any finite fault resistance in the fault loop. Additionally, the capacitive component mc_{l} is minute, and is therefore made unusable even by small inaccuracies in measurement or processing. The only valid value for distance calculation is the inductive component ml_{l}. It is larger than the resistive and capacitive parts and, therefore, immune to higher levels of error, and is not directly affected by the presence of MOV resistance in the fault loop. Therefore, the distance estimation is a series compensated line using RL and RLC models in the time domain should be done by the inductive component of the line model.

Although not directly valuable for distance estimation, the resistive component has another attribute that can be useful. It can be used to determine the presence of the SC in the fault loop for mid-line series compensation. For mid-line series compensation, if the fault happens before the capacitor, then the Equations 4.5 and 4.5 are not valid as they include the capacitor voltage in the calculation. When the estimated capacitor voltage is anyway included in the calculation for faults before the capacitor, it results in a negative resistance value in the term mr_{l}.

The resistance value is always positive if the capacitor is in the fault loop. This polarity change in the resistance can be used to determine the presence of the capacitor in the fault loop and then modify the relevant equations to include or exclude the capacitor voltage from calculations.

Figure 4.10 shows values of resistances for two different fault inception angles in two subplots. The fault is a bolted phase to ground fault with faults before and after the capacitor. The resistance is negative for faults before the capacitor, and positive for faults after the capacitor.

A demonstration of using RL and RLC line models in distance estimation in series compensated lines is shown in Figure 4.11 for bolted phase to ground faults 10 km, 60 km, 120 km and 180 km from the local bus in a 70% terminal series compensated line. As expected, the distances are accurate for faults closer to the local bus. The performance of these simple models starts to deviate for faults further away from the measurement point. A quarter-cycle-long sliding window is used to calculate distances. The valid distance calculations are available only after the delay caused by the sliding window and other signal processing.

Figure 4.12 shows the distance calculations from RL and RLC models for bolted phase to ground faults at 10 km, 60 km, 120 km and 180 km from the local bus with

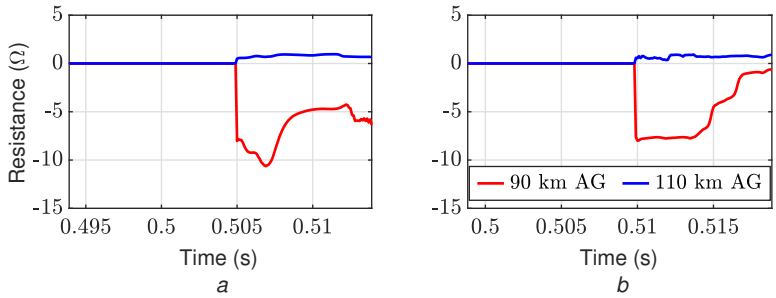


Figure 4.10: Resistance for faults before and after the capacitor for a) 0° b) a) 90° fault inception angle

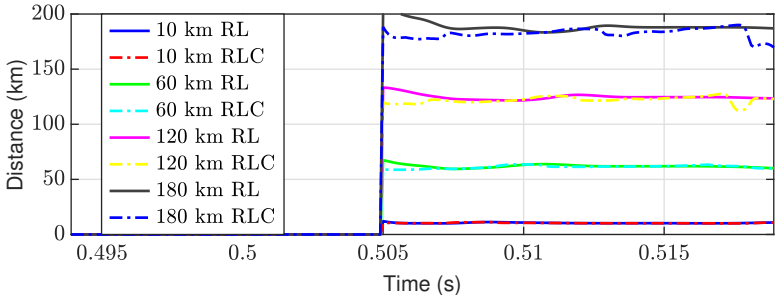


Figure 4.11: RL and RLC model-based distance estimation for 70% terminal SC

a 70% mid-line SC. For faults before the capacitor at 10 km, 60 km, the additional delay for self correcting to exclude the capacitor from the fault loop can be seen. For faults further away, the performance of these models starts to falter as shown before. It can be concluded that these methods work best with shorter lines.

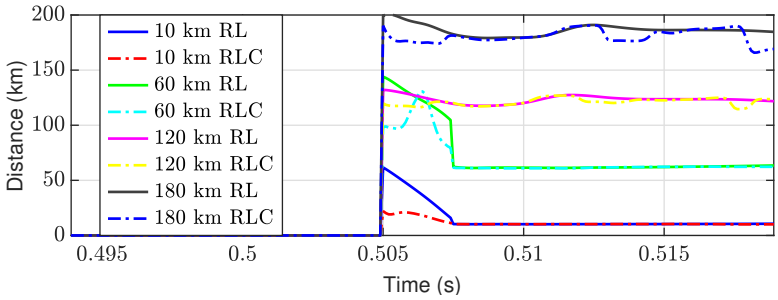


Figure 4.12: RL and RLC model-based distance estimation for 70% mid-line SC

Chapter 5

Comparing Different Distance Protections Methods

The three methods described in the previous section will be compared to understand their suitability in different situations. IQ, RL and RLC model-based solutions are fast time-domain methods that avoid inversion and oscillation problems. Their performance deteriorates with increasing fault resistance. They also can avoid problems associated with capacitor bank operation due to operating times lower than a cycle. The CSGE-based method is slower when fitting whole cycles. It can avoid inversion problems, but other than this, it behaves similarly to DFT-based methods.

The performance of the new methods in cases where traditional distance protection fails is presented in the following sections. Additionally, situations, where these new methods falter are also discussed. It is assumed that other parts of a typical protection system, such as fault detection, phase selection and directional discrimination, have operated correctly before the fault distance algorithm starts working. Only the zone 1 operation of the distance elements is considered. The sampling frequency and signal processing are identical for all methods. Measured current and voltage signals are passed through a low-pass filter with cut-off frequency 500 Hz for 10 kHz sampling rate. In all figures below, the subplots *a, b, c* indicate the results from IQ, CSGE and RL/RLC methods, respectively. The horizontal black line in the time axis indicates the fault inception time in all cases. The results in the sections below are adopted and summarized from 9.

5.1 Current and Voltage Inversion

Current and voltage inversion are major problems for protection of series-compensated lines by phasor-based distance relays. In Figure 5.1, calculations for the three methods are shown for a phase to ground bolted fault 10 km from the local bus for a 70% terminal series compensated line. All three subplots show the results for 1.5

cycles after the fault. This fault causes inversion for phasor-based distance protection. However, all three assessed methods perform well in countering inversion. The IQ-based method shows a much higher fault voltage compared to the reference. The impedance trajectory is inside the operating zone for the case of CSGE-based protection. Finally, the RL and RLC method also gives good results.

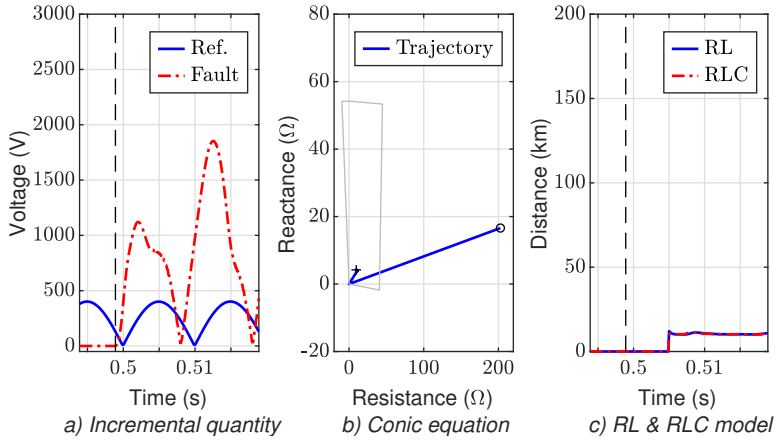


Figure 5.1: Impact of inversion condition using a) incremental quantity b) CSGE and Lissajous curves c) RL and RLC line model

5.2 Sub-synchronous Oscillation

Sub-synchronous oscillation is most common when the capacitor stays in the fault loop. For higher compensation levels, the worst cases of SSO happen for faults in other line segments, beyond the protected line. Figure 5.2 shows calculations for the three methods for a bolted phase to ground fault 180 km from the local bus for a 50% terminal series compensated line. The results are plotted for 5 cycles after the fault for subplot *b* and 1.5 cycles in subplots *a* and *b*. During oscillation, the calculated impedance takes a long time to settle in phasor-based distance relays. The same behaviour is seen in the CSGE-based method. The trajectory is plotted for a longer time to demonstrate the problem. However, with the IQ-based method, the fault-induced voltage is lower than the reference voltage, as the reference voltage is calculated at 160 km. The results from the RL and RLC methods show some oscillatory behaviour, because the fault is far away from the measuring point.

5.3 Capacitor Bank Protection

The operation of the capacitor bank overvoltage protection creates uncertainty with the distance protection of series compensation lines. One way to bypass this

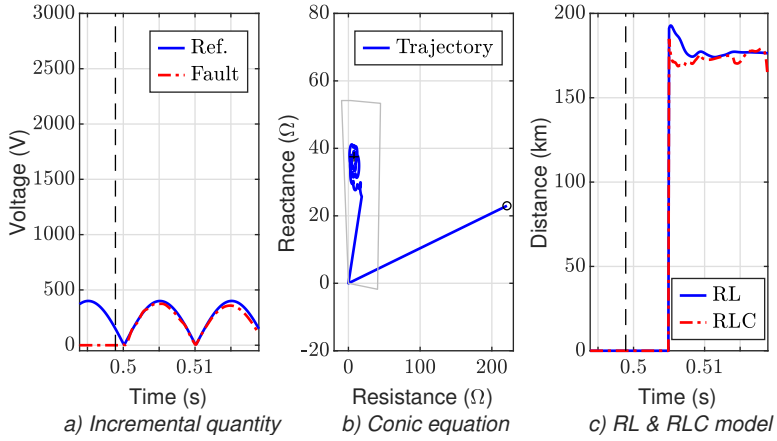


Figure 5.2: Impact of SSO using a) incremental quantity b) CSGE and Lissajous curves c) RL and RLC line model

problem for distance protection is to make a decision so quickly that the bypass CB cannot yet have been operated. Time-domain methods such as IQ and RL/RLC model-based methods can be quick enough to be immune to the uncertainty caused by the activation of the bypass CB.

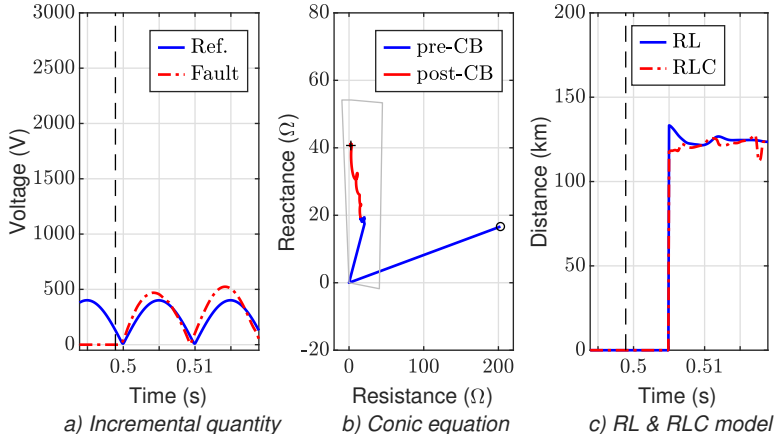


Figure 5.3: Impact of capacitor bank operation using a) incremental quantity b) CSGE and Lissajous curves c) RL and RLC line model

In Figure 5.3, calculations for the three methods are shown for a bolted phase to ground fault 120 km from the local bus for a 70% terminal series compensated line. Subplots *a* and *c* show the results for the time-domain methods for 1.5 cycles after

the fault. The CSGE-based method is slower than the other two methods and can face uncertainties due to bypass CB operation. Its impedance trajectory is plotted in subplot *b* for 8 cycles after the fault while the bypass breaker operates after around 3 cycles after the fault. The CSGE-based method reaches steady values and can operate within 1.5 cycles post fault, and as inversions do not impact it, there would not be further delays for its operation. The CSGE-based method would face uncertainties with bypass CB operation only for very high current faults close to the local bus where the CB operates within 1.5 cycles.

5.4 Fault Resistance

Figure 5.4 the results from all methods are presented for a phase to ground fault with three levels of fault resistance 40 km from the local bus in a 70% terminal series compensated line. The results are plotted for 1.5 cycles after the fault in all subplots. The IQ and RL/RLC model-based protection solutions face problems with fault resistances, as the equations in these methods are developed under the assumption of zero fault resistance. With the IQ-based method, the decrease of the fault voltage is seen with increasing fault resistance in subplot *a*. Therefore, higher resistance faults will cause under-reach with the IQ-based method. The CSGE and Lissajous curve-based method behaves typically of phasor-based distance protection. In subplot *b*, with the increasing resistance, the impedance trajectories shift on the X-axis. The RL and RLC-based methods also demonstrate errors with higher fault resistance. The fault resistance was assumed to be zero to simplify and linearise the equations of these methods. With increasing fault resistance, they show under-reach and somewhat oscillatory behaviour as seen in subplot *c*.

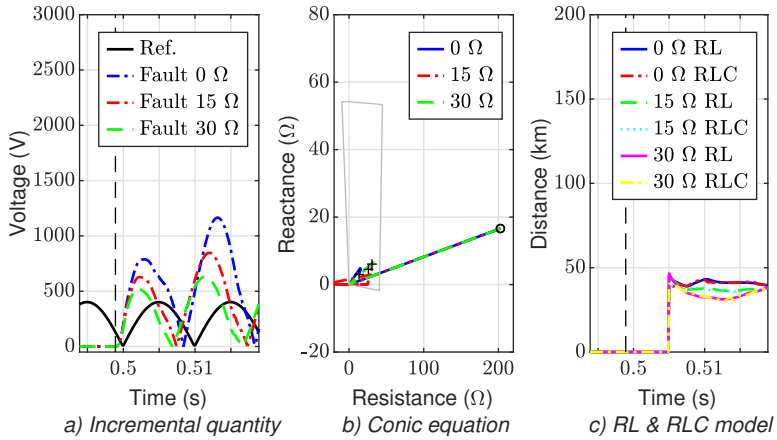


Figure 5.4: Impact of fault resistance using a) incremental quantity b) CSGE and Lissajous curves c) RL and RLC line model

5.5 Capacitor Position

For capacitors in the middle of the line, if the fault is after the capacitor, the fault current flows through the capacitor and the algorithms work as usual. If the fault is before the capacitor, then the behaviour of the methods changes. Figure 5.5 shows the results from all methods for a bolted phase to ground fault 90 km from the local bus for 70% mid-line series compensation. The results are plotted for 1.5 cycles after the fault in all subplots. For IQ based method, there is some under-reach, but for bolted faults and with moderate fault resistances, it works well within the first half cycle after the fault as shown in subplot *a*. In subplot *b*, the CSGE method does not use the capacitor voltage, and therefore has no problem when the fault loop does not include the capacitor. As discussed earlier, the RL and RLC methods can be used to determine the presence of the capacitor in the fault loop. This is evident in the subplot *c*, where, after the initial delay, the algorithm self-corrects using the resistance value to remove the capacitor from the fault loop and measure the correct distance.

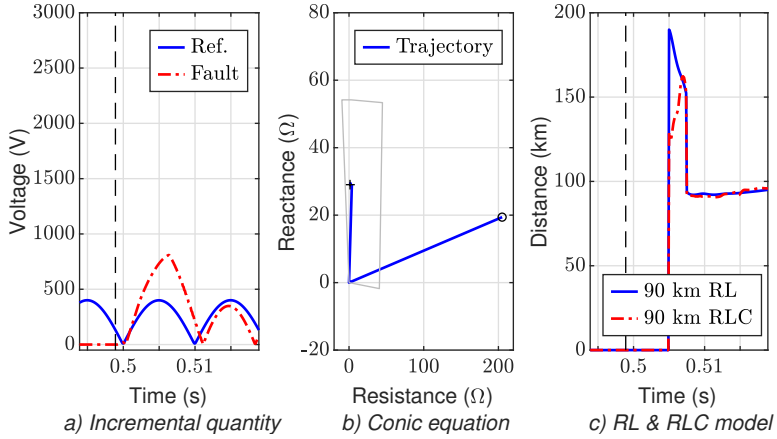


Figure 5.5: Impact of mid-line series compensation using a) incremental quantity b) CSGE and Lissajous curves c) RL and RLC line model

5.6 Summary

A summary of the different methods compared in the previous sections is presented in the table 5.1 below. The performance of the protections is divided into three broad categories. Green indicates good performance, yellow indicates some challenges, and red indicates unacceptable performance. As demonstrated in chapter 2, DFT-based distance protection does not work properly during inversion and SSO, and has delayed operation due to capacitor bank over-voltage protection. Therefore,

the table lists those conditions and additionally a few more categories for comparison. During inversion, all methods work well. Oscillation causes similar problems for CSGE-based protection as for DFT-based phasor protection. Incremental quantity protection experiences reduced reach with higher resistance. CSGE-based protection performs well with fault resistances. RL/RLC models also perform worse with increasing fault resistance. The MOV and CB in capacitor bank protection can lead to further delays in phasor-based protection, while CSGE-based protection can perform better as it can operate faster by avoiding inversions. Time domain methods do not have any issues with MOV and CB operation as they work in a shorter time frame. In mid-line series compensation, the RL/RLC model can be used to determine the presence of the series capacitor in the fault loop. The other methods can not determine that, but they work reasonably well anyway with regard to making an in-zone versus out-of-zone decision. The inversion is lower for faults after the capacitor, as at least half of the line is always in the fault loop. In terms of operating speed, the IQ based method is the fastest, followed by RL/RLC and CSGE-based methods. All of these methods can be used to distinguish between forward and reverse faults. Finally, with faults further away from the local bus, the IQ and CSGE methods work well but the methods based on RL and RLC models start to show more errors in distance estimation.

Table 5.1: Summary of comparison

	IQ	CSGE	RL,RLC
Inversion			
SSO			
Fault resistance			
MOV & CB			
Mid-line SC			
Speed			
Reverse fault			
Fault distance			

Chapter 6

Conclusion and Future Work

6.1 Conclusions

Protection of series compensated transmission without communication between the terminals of the protected line has been a challenge for the last few decades. This thesis attempts to improve the state of art protection of series compensated lines to ameliorate the protection challenges of lines with higher levels of compensation, which may allow more flexibility for the electric power grid.

The thesis identifies four objectives in studying distance protection of series compensated lines with high levels of series compensation. The objectives are to evaluate traditional phasor-based distance protection (O1), review different methods for improving distance protection (O2), evaluate different line distance protection methods suitable for SC line protection (O3) and finally to compare their performances (O4). The scope is limited to protection methods operating with only local measurements.

The first objective (O1) of the thesis has been addressed in publications 1 and 2. It has been demonstrated that traditional distance protection does not perform well with high levels of series compensation as voltage and current inversion problems increase with increasing compensation levels. However, the protected line becomes less prone to SSO issues with higher compensation levels.

An overview of literature from both academic and industrial research is presented in publications 3 and 4 to cover the second objective (O2) to identify possible ways to improve series compensated line protection. Today, series compensated lines are protected either with communication-aided methods or by reducing the functionality of distance protection, e.g. reducing the reach. Frequency domain behaviour and phasor calculation delays limit the research on improving phasor-based distance protection. Time domain protection research has been focused mainly on travelling wave-based methods that relay manufacturers have yet to adopt widely.

Three different line protection methods based on IQ, CSGE and RL/RLC line models are presented in publications 5, 6, 7 and 8 to understand their suitability in

the protection of series compensated lines for fulfilling objective three (O3). The implementation aspects of these protection methods in series compensated lines are also discussed. All of these show promise in distance protection of series compensated lines mitigating problems of inversion and SSO. The performance of these methods is evaluated together to asses their relative advantages and disadvantages for addressing objective four (O4) and shown in publication 9. IQ and RL/RLC methods are fast but face inaccuracies with high fault resistances. The CSGE-based method avoids inversion in the presence of SC but behaves similarly to DFT-based methods in other cases.

Further system-level studies are required before recommending these single-ended protection methods for being used as the primary protection in transmission lines with high levels of series compensation. However, they show optimistic results for being employed as backup protection instead of traditional distance protection, which drastically loses reliability with higher compensation levels.

6.2 Future work

Due to time constraints and to keep the focus of the work, some possibilities have been bypassed during this work. Some of those could be pursued for further continuation of this work. For example, while studying the impact of high levels of series compensation, the basic implementation of phasor-based distance protection was done. It may be interesting to quantify the improvement with methods such as memory voltage polarization in high levels of series compensation.

Compensation levels up to 70% were tested in this thesis while assessing new distance protection methods. The performance of the methods with even higher levels of compensation and overcompensation can be conducted.

The voltage and current measurements used in testing have been assumed to be ideal: the impact of non-ideal measurement devices and errors can be investigated. Additionally, the performance of the methods at various sampling frequencies can be assessed.

The power system is connected to more renewable energy sources, and transmission and distribution systems require more flexibility in operation. In that regard, the performance of the proposed methods in the presence of power electronic controlled sources needs to be investigated. Moreover, series compensation is being applied to sub-transmission and distribution voltage levels. It would be interesting to study protection methods for series-compensated lines at lower voltage levels where there are shorter lines with less strict protection requirements but more complicated grounding methods.

References

[1] International Energy Agency. Key World Energy Statistics 2021. Technical report, International Energy Agency, 2021.

[2] Yan Li, Changhong Zhao, Huaiguang Jiang, Yingchen Zhang, and Eduard Muljadi. Chapter one - Introduction. In Huaiguang Jiang, Yingchen Zhang, and Eduard Muljadi, editors, *New Technologies for Power System Operation and Analysis*, pages 1–21. Academic Press, 2021. ISBN 978-0-12-820168-8. doi:10.1016/B978-0-12-820168-8.00001-8.

[3] S. Sivanagaraju and S. Satyanarayana. *Electric Power Transmission and Distribution*. Pearson, 1st edition edition, 2008.

[4] Nirupma Sharma, Aparna Acharya, Irene Jacob, Sumanth Yamujala, Vikas Gupta, and Rohit Bhakar. Major Blackouts of the Decade: Underlying Causes, Recommendations and Arising Challenges. In *International Conference on Power Systems (ICPS)*, pages 1–6, Kharagpur, India, 2021. IEEE. doi:10.1109/ICPS52420.2021.9670166. ISSN: 2691-0233.

[5] André dos Santos, M. T. Correia de Barros, and P. F. Correia. Transmission line protection systems with aided communication channels—Part I: Performance analysis methodology. *Electric Power Systems Research*, 127:332–338, October 2015. ISSN 0378-7796. doi:10.1016/j.epsr.2015.05.028.

[6] Jeff Rooker. Misoperations. Technical report, Southwest Power Pool (US), 2012.

[7] North American Electric Reliability Corporation (NERC). Analysis of System Protection Misoperations. Technical report, North American Electric Reliability Corporation (NERC), 2015.

[8] R. Grünbaum, P. Halvarsson, and P. Jones. Series compensation for increased power transmission capacity. In *International Conference on Power Electronics, Machines and Drives*, pages 1–6, Brighton, UK, 2010. IET. doi:10.1049/cp.2010.0037.

[9] C. Hor, J. Finn, G. Thumm, and S. Mortimer. Introducing series compensation in the UK transmission network. In *International Conference on AC and DC Power Transmission*, pages 1–5, London, UK, 2010. IET. doi:10.1049/cp.2010.0967.

[10] D. Korot, P. Marken, and L. Bock. The next fifty years of series capacitors — And the last eighty-six. In *IEEE PES T&D Conference and Exposition*, pages 1–5, Chicago, Illinois, USA, 2014.

[11] United Nations. Transforming Our World: The 2030 Agenda for Sustainable Development, 2015. URL `https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf`.

[12] Jeffrey Wischkaemper and Sukumar Brahma. Machine learning and power system protection [viewpoint]. *IEEE Electrification Magazine*, 9(1):108–112, 2021. doi:10.1109/MELE.2020.3047031.

[13] CIGRE Working Group C4/B5.41. Challenges with series compensation applications in power systems when overcompensating lines. Technical report, CIGRE, Paris, France, 2021.

[14] M. T. Hoq, J. Wang, and N. Taylor. The Impact of Current Inversion on Line Protection in High Voltage Transmission Lines with Series Compensation. In *The Conference on Energy, Power Systems and Power- and Industrial Electronics*, Narvik, Norway, 2019. doi:10.1109/NORPIE55843.2019.9967828.

[15] M. T. Hoq, J. Wang, and N. Taylor. Impact of High Levels of Series Compensation on Line Distance Protection. In *International Conference on Developments in Power System Protection (DPSP 2020)*, Liverpool, UK, 2020. IET. doi:10.1049/cp.2020.0037.

[16] John Miller, Marc Brunet-Watson, and Jed Leighfield. Review of Series Compensation for Transmission Lines. Technical report, PSC North America, 2014.

[17] M. T. Hoq and N. Taylor. Distance Protection of Series Capacitor Compensated Lines: Practical Considerations, Industrial Status and Development. *Electricity*, 2(2):168–186, 2021. doi:10.3390/electricity2020011.

[18] Graeme Topham and Edmund Stokes-Waller. Steady-State Protection Study for the Application of Series Capacitors in the Empangeni 400 kV Network. In *Annual Western Protective Relay Conference*, page 23, Washington, USA, 2004.

[19] CIGRE Working Group B5.10. Protection, control and monitoring of series compensated networks. Technical report, CIGRE, Paris, France, 2010. OCLC: 762766298.

[20] A. P. De Oliveira and P. Da Silveira. Evaluation of Distance Protection Performance applied on Series Compensated Transmission Lines using Real Time Digital Simulation. In *IEEE/PES Transmission & Distribution Conference and Exposition: Latin America*, pages 1–6, Caracas, Venezuela, 2006. IEEE. ISBN 978-1-4244-0287-8. doi:10.1109/TDCLA.2006.311637.

[21] Rogelio Castro and Hector Pineda. Protection System Considerations for 400 kV Series Compensated Transmission Lines of the Central Western Network in Venezuela. In *IEEE/PES Transmission & Distribution Conference and Exposition: Latin America*, pages 1–5, Caracas, Venezuela, 2006. IEEE. ISBN 978-1-4244-0287-8. doi:10.1109/TDCLA.2006.311662.

[22] F. Plumptre, M. Nagpal, X. Chen, and M. Thompson. Protection of EHV transmission lines with series compensation: BC Hydro's lessons learned. In *Annual Conference for Protective Relay Engineers*, pages 288–303, College Station, Texas, USA, 2009. doi:10.1109/CPRE.2009.4982520.

[23] Simon Chano. Transmission Line Protection – Doing it Right. *PAC World*, 03, 2008. URL `https://www.pacw.org/fileadmin/doc/WinterIssue08/cover_story_winter08.pdf`.

[24] N. K. Saia. The importance of site selection for series compensation. In *Annual Conference for Protective Relay Engineers*, pages 201–210, College Station, TX, USA, 2005. IEEE. ISBN 978-0-7803-8896-3. doi:10.1109/CPRE.2005.1430434.

[25] D. Erwin, M. Anderson, R. Pineda, D. A. Tziouvaras, and R. Turner. Pacific Gas and Electric 500 kV series-compensated transmission line relay replacement: Design requirements and RTDS® testing. In *Annual Conference for Protective Relay Engineers*, pages 191–202, College Station, Texas, USA, 2011. doi:10.1109/CPRE.2011.6035620.

[26] Eric Bakie, Curtis Westhoff, Normann Fischer, and Jordan Bell. Voltage and current inversion challenges when protecting series-compensated lines — A case study. In *Annual Conference for Protective Relay Engineers*, pages 1–14, College Station, TX, USA, 2016. IEEE. ISBN 978-1-5090-1532-0. doi:10.1109/CPRE.2016.7914925.

[27] M. T. Hoq, J. Wang, and N. Taylor. Review of recent developments in distance protection of series capacitor compensated lines. *Electric Power Systems Research*, 190:106831, 2021. doi:10.1016/j.epsr.2020.106831.

[28] D. L. Goldsworthy. A Linearized Model for Mov-Protected Series Capacitors. *IEEE Transactions on Power Systems*, 2(4):953–957, 1987. ISSN 0885-8950. doi:10.1109/TPWRS.1987.4335284.

[29] F. Ghassemi, J. Goodarzi, and A. T. Johns. Method to improve digital distance relay impedance measurement when used in series compensated lines protected by a metal oxide varistor. *IEE Proceedings - Generation Transmission and Distribution*, 145(4):403–408, 1998. ISSN 1350-2360. doi:10.1049/ip-gtd:19982002.

[30] Z. Y. Xu, Z. P. Su, J. H. Zhang, A. Wen, and Q. X. Yang. An Interphase Distance Relaying Algorithm for Series-Compensated Transmission Lines. *IEEE Transactions on Power Delivery*, 29(2):834–841, 2014. ISSN 0885-8977. doi:10.1109/TPWRD.2013.2281067.

[31] M. M. Saha, B. Kasztenny, E. Rosolowski, and J. Izykowski. First zone algorithm for protection of series compensated lines. *IEEE Transactions on Power Delivery*, 16(2):200–207, 2001. ISSN 0885-8977. doi:10.1109/61.915483.

[32] E. Rosolowski, J. Izykowski, P. Pierz, M. Fulczyk, P. Balcerek, and M. M. Saha. High voltage series-compensated transmission line - evaluation of new distance protection. In *International Conference on High Voltage Engineering and Application*, pages 513–516, Orleans, Louisiana, USA, 2010. doi:10.1109/ICHVE.2010.5640715.

[33] E. Rosolowski, J. Izykowski, P. Pierz, M. M. Saha, P. Balcerek, and M. Fulczyk. Optimization of distance protection algorithm for series-compensated transmission line. In *IEEE PowerTech*, pages 1–7, Trondheim, Norway, 2011. doi:10.1109/PTC.2011.6019172.

[34] A. Damnjanovic, D. Dayton, and G. Ferguson. Assessment Modeling of Series Capacitors Protected by Metal Oxide Varistors in Power System Studies. In *IEEE Power Engineering Society General Meeting*, pages 1–5, Tampa, Florida, USA, 2007. doi:10.1109/PES.2007.385452.

[35] Aleksandar Damnjanovic and Rastko Zivanovic. Analytical model for series capacitor protected by metal oxide varistor. In *Southern African Universities Power Engineering Conference*, Potchefstroom, South Africa, 1999.

[36] U. J. Shenoy, P. Sandeep, and S. Srivastava. Impact of MOV models on asymmetrical fault current calculations in fixed series compensated lines. In *IEEE PES Asia-Pacific Power and Energy Engineering Conference*, pages 1–6, Bangalore,India, 2017. doi:10.1109/APPEEC.2017.8308910.

[37] Eugeniusz Rosolowski, Bogdan Kasztenny, Jan Izykowski, and Murari Mohan Saha. Comparative analysis of impedance algorithms for series compensated lines. In *The Power System Protection Conference*, Bled, Slovenia, 1996.

[38] E. Rosolowski, J. Izykowski, B. Kaszenny, and M. M. Saha. Differential equation based impedance measurement for series-compensated lines. In *IEEE PowerTech*, pages 205–, Budapest, Hungary, 1999. doi:10.1109/PTC.1999.826637.

[39] Murari Mohan Saha, Eugeniusz Rosolowski, Jan Izykowski, and Piotr Pierz. Evaluation of relaying impedance algorithms for series-compensated line. *Electric Power Systems Research*, 138:106–112, 2016. ISSN 0378-7796. doi:10.1016/j.epsr.2016.03.046.

[40] A. C. C. Q. A. Figueiredo, W. L. A. Neves, and D. Fernandes. Evaluation of phasor estimation methods for transmission lines with capacitive series compensation. In *Simposio Brasileiro de Sistemas Eletricos*, pages 1–6, Rio de Janeiro, Brazil, 2018. doi:10.1109/SBSE.2018.8395859.

[41] David G. Hart, Damir Novosel, and Robert A. Smith. Modified cosine filters, 2000. URL `https://patents.google.com/patent/US6154687A/en`. US Patent US6154687A, granted in 2000.

[42] Yong Guo, Mladen Kezunovic, and Deshu Chen. Simplified algorithms for removal of the effect of exponentially decaying DC-offset on the Fourier algorithm. *IEEE Transactions on Power Delivery*, 18(3):711–717, 2003. ISSN 0885-8977. doi:10.1109/TPWRD.2003.813894.

[43] Alana K. X. S. Campos, Washington L. A. Neves, and Damásio Fernandes. A new phasor estimation method for digital protective relays. *Electric Power Systems Research*, 142:227–236, 2017. ISSN 0378-7796. doi:10.1016/j.epsr.2016.10.001.

[44] M. Pazoki. A New DC-Offset Removal Method for Distance-Relaying Application Using Intrinsic Time-Scale Decomposition. *IEEE Transactions on Power Delivery*, 33(2):971–980, 2018. ISSN 0885-8977. doi:10.1109/TPWRD.2017.2728188.

[45] Ujjaval J. Patel, Nilesh G. Chothani, and Praghnesh J. Bhatt. Adaptive quadrilateral distance relaying scheme for fault impedance compensation. *Electrical, Control and Communication Engineering*, 14(1):58–70, 2018. doi:10.2478/ecce-2018-0007.

[46] S. G. Srivani and K. Panduranga Vittal. Adaptive distance relaying scheme in series compensated transmission lines. In *Joint International Conference on Power Electronics, Drives and Energy Systems & Power India*, pages 1–7, New Delhi, India, 2010. doi:10.1109/PEDES.2010.5712452.

[47] M. M. Saha, T. Einarsson, and S. Lidström. A new adaptive high speed distance protection scheme for power transmission lines. In *International Conference on Developments in Power System Protection (DPSP 2016)*, pages 1–6, Edinburgh, UK, 2016. doi:10.1049/cp.2016.0088.

[48] X. G. Magagula, D. V. Nicolae, and A. A. Yusuff. The performance of distance protection relay on series compensated line under fault conditions. In *IEEE AFRICON*, pages 1–6, Addis Ababa. Ethiopia, 2015. doi:10.1109/AFRCON.2015.7332035.

[49] S. Paladhi and A. K. Pradhan. Adaptive Zone-1 Setting Following Structural and Operational Changes in Power System. *IEEE Transactions on Power Delivery*, 33(2):560–569, 2018. ISSN 0885-8977. doi:10.1109/TPWRD.2017.2728682.

[50] P. Mazniewski and J. Izykowski. ATP-EMTP investigation of adaptive distance protection for transmissions lines with series compensation. In *Modern Electric Power Systems*, pages 1–6, Wroclaw, Poland, 2010. URL `https://ieeexplore.ieee.org/document/6007269`.

[51] D. W. P. Thomas and C. Christopoulos. Ultra-high speed protection of series compensated lines. *IEEE Transactions on Power Delivery*, 7(1):139–145, 1992. ISSN 0885-8977. doi:10.1109/61.108900.

[52] Z. Q. Bo. A new non-communication protection technique for transmission lines. *IEEE Transactions on Power Delivery*, 13(4):1073–1078, 1998. ISSN 0885-8977. doi:10.1109/61.714458.

[53] Z. Chen, Z. Q. Bo, F. Jiang, and G. Weller. A fault generated high frequency current transients based protection scheme for series compensated lines. In *IEEE Power Engineering Society Winter Meeting*, volume 3, pages 1838–1843 vol.3, Minneapolis, Minnesota, USA, 2000. doi:10.1109/PESW.2000.847631.

[54] A. Abur and F. H Magnago. Use of time delays between modal components in wavelet based fault location. *International Journal of Electrical Power & Energy Systems*, 22(6):397–403, 2000. ISSN 0142-0615. doi:10.1016/S0142-0615(00)00010-7.

[55] Zijun Huang, Yunping Chen, and Qingwu Gong. A protection and fault location scheme for EHV line with series capacitor based on travelling waves and wavelet analysis. In *International Conference on Power System Technology*, volume 1, pages 290–294 vol.1, Kunming, China, 2002. doi:10.1109/ICPST.2002.1053551.

[56] A. I. Megahed, A. M. Moussa, and A. E. Bayoumy. Usage of wavelet transform in the protection of series-compensated transmission lines. *IEEE Transactions on Power Delivery*, 21(3):1213–1221, 2006. ISSN 0885-8977. doi:10.1109/TPWRD.2006.876981.

[57] C. Aguilera, E. Orduna, and G. Ratta. Fault detection, classification and faulted phase selection approach based on high-frequency voltage signals applied to a series-compensated line. *IEE Proceedings - Generation Transmission and Distribution*, 153(4):469–475, 2006. ISSN 1350-2360. doi:10.1049/ip-gtd:20045157.

[58] Nitin U Gawali and R P Hasabe. A Comparison of Different Mother Wavelet for Fault Detection & Classification of Series Compensated Transmission Line. *IJIRST*, 1(9):7, 2015.

[59] S. Kariyawasam, A. D. Rajapakse, and N. Perera. Investigation of Using IEC 61850-Sampled Values for Implementing a Transient-Based Protection Scheme for Series-Compensated Transmission Lines. *IEEE Transactions on Power Delivery*, 33(1):93–101, 2018. ISSN 0885-8977. doi:10.1109/TPWRD.2017.2693395.

[60] Bogdan Kasztenny, Armando Guzmán, Normann Fischer, Mangapathirao V Mynam, and Douglas Taylor. Practical Setting Considerations for Protective Relays That Use Incremental Quantities and Traveling Waves. In *Annual Western Protective Relay Conference*, page 26, Washington, USA, 2016.

[61] ABB. REL670 2.1 IEC Application manual Line distance protection, 2016.

[62] GE Digital Energy. D60 Line Distance Protection System Manual, 2013.

[63] RFL Electronics Inc. Gard 800 Distance Relay Instruction Manual, 2010.

[64] Schneider Electric. MiCOM P441/P442 & P444 Numerical Distance Protection Technical Guide, 2012.

[65] Schweitzer Engineering Laboratories, Inc. SEL-421 Relay Protection and Automation System Instruction Manual, 2011.

[66] Siemens. SIPROTEC 4 Distance Protection 7SA522 Manual, 2016.

[67] Sifang. CSC-103 Line Protection IED Technical Application Manual, 2016.

[68] ZIV Grid Automation. 8ZLS-J Distance Protection Instructions Manual, 2012.

[69] ERL Phase Power Technologies Ltd. L-PRO 4500 Transmission Line Protection Relay User Manual, 2018.

[70] Pairoj Kajoijilertsakul, Santi Asawasripongtorn, Peerayot Sanposh, Jittiwut Suwatthikul, and Hideaki Fujita. Modeling and Simulation of 500 kV Transmission Network for Numerical Fault Calculation, Detection, Using PSCAD/EMTDC. In *Asia-Pacific Power and Energy Engineering Conference*, pages 1–4, Wuhan, China, 2011. doi:10.1109/APPEEC.2011.5749105. ISSN: 2157-4847.

[71] Xiaojun Chen, Wenjie Zheng, Shu Huang, and Hui Chen. The relationship between operating maintenance and lightning overvoltage in distribution networks based on PSCAD/EMTDC. In *International Forum on Energy, Environment Science and Materials*, pages 984–988, Shenzhen, China, 2015. Atlantis Press. ISBN 978-94-6252-117-9. doi:10.2991/ifeesm-15.2015.181. ISSN: 2352-5401.

[72] Md Tanbhir Hoq. Fault test cases for series compensated transmission line with capacitor at line terminal, 2021. URL `https://zenodo.org/record/5113208`. Type: dataset, Zenodo, doi: 10.5281/zenodo.5113208.

[73] M. T. Hoq. Fault test cases for series compensated transmission line with capacitor at mid line, 2021. URL https://zenodo.org/record/5643563. Type: dataset, Zenodo, doi: 10.5281/zenodo.5643563.

[74] Virgilio De Andrade and Elmer Sorrentino. Typical expected values of the fault resistance in power systems. In *IEEE/PES Transmission and Distribution Conference and Exposition: Latin America*, pages 602–609, Sao Paulo, Brazil, 2010. IEEE. ISBN 978-1-4577-0488-8. doi:10.1109/TDC-LA.2010.5762944.

[75] Daniil Danylov. Evaluation of Symmetrical Components Theory in Power Systems with Renewable Sources. Master's thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2021. URL http://urn.kb.se/resolve?urn=urn%3Anbn%3Ase%3Akth%3Adiva-303506.

[76] Edmund O. Schweitzer, Bogdan Kasztenny, Armando Guzman, Veselin Skendzic, and Mangapathirao V. Mynam. Speed of line protection – can we break free of phasor limitations? In *Annual Conference for Protective Relay Engineers*, pages 448–461, College Station, TX, USA, 2015. IEEE. ISBN 978-1-4799-8722-1. doi:10.1109/CPRE.2015.7102184.

[77] E. Schweitzer, B. Kasztenny, and M. Mynam. Performance of time-domain line protection elements on real-world faults. In *Annual Conference for Protective Relay Engineers*, pages 1–17, College Station, TX, USA, 2016. IEEE. ISBN 978-1-5090-1532-0. doi:10.1109/CPRE.2016.7914904.

[78] C. Dzienis, M. Kereit, J. Blumschein, and M. Claus. An Experimental Analysis of High-Speed-Distance Protection. In *Modern Electric Power Systems*, page 8, Wroclaw, Poland, 2010. URL https://ieeexplore.ieee.org/document/6007181.

[79] C. Dzienis, M. Kereit, and J. Blumschein. Analysis of High-Speed-Distance protection. In *International Conference on Advanced Power System Automation and Protection*, pages 1330–1336, Beijing, China, 2011. IEEE. doi:10.1109/APAP.2011.6180585.

[80] Md Tanbhir Hoq, Jianping Wang, and Nathaniel Taylor. An Incremental Quantity Based Distance Protection with Capacitor Voltage Estimation for Series Compensated Transmission Lines. *IEEE Access*, pages 1–1, 2021. ISSN 2169-3536. doi:10.1109/ACCESS.2021.3134558.

[81] Md Tanbhir Hoq, Jianping Wang, and Nathaniel Taylor. An Incremental Quantity Based Protection with Capacitor Voltage Estimation for Mid-Line Series Compensation. In *International Conference on Developments in Power System Protection (DPSP 2022)*, Newcastle, UK, 2022. IET. doi:10.1049/icp.2022.0955.

[82] Priscila de Lima Vianna and Giovanni Manassero Junior. Time-domain distance protection of transmission lines based on the conic section general equation. *Electric Power Systems Research*, 205:107740, 2022. ISSN 03787796. doi:10.1016/j.epsr.2021.107740.

[83] Neriton Hoxha and Jean-Claude Maun. Ultra-fast distance protection algorithm in time-domain based on a Gamma model of line. In *Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion*, pages 1–5, Dubrobnik, Croatia, 2018. doi:10.1049/cp.2018.1839.

[84] Neriton Hoxha. *Ultra fast line protection relay algorithm based on gamma model of line*. PhD thesis, Université Libre de Bruxelles, Brussels, Belgium, 2020.