# An Investigation of the Impact of Distributed Flexible AC Transmission System (D-FACTS) Devices on Transmission Line Protection

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by

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## Authorization to Submit Dissertation

This dissertation of Hussain Beleed, submitted for the degree of Doctor of Philosophy with a Major in Electrical Engineering and titled "An Investigation of the Impact of Distributed Flexible AC Transmission System (D-FACTS) Devices on Transmission Line Protection," has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the College of Graduate Studies for approval.

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# Abstract

This thesis explores the effects of inductive Distributed Flexible AC Transmission System (D-FACTS) device implementations on the performance of different transmission line protection schemes. The reliability and sensitivity of the trip decision of the protection elements is crucial for delivering safe and reliable power to customers. Furthermore, accurate fault location information can help significantly reduce outage duration, operating costs, and the number of consumer complaints. Inductive D-FACTS devices offer a distributed solution for managing and relieving the congestion in transmission lines. However, their interaction with protection and fault location elements may potentially cause unnecessary tripping, relay misoperation, or misleading fault location information. The operation of these devices may also lead to unpredictable changes in transmission line impedance and fault current limitation due to their dynamic behavior before and during the disturbances. This work studies these negative aspects of D-FACTS devices and proposes solutions and alternatives to mitigate their impact.

An inductive D-FACTS model was developed in the ATP version of the Electromagnetic Transients Program (EMTP) and then the steady-state performance of these devices was validated against the existing D-FACTS model in PowerWorld using the IEEE 12 bus test system. Once the model was validated, a more practical system with D-FACTS implementation is simulated using ATP. Lastly, the generated fault event files are played back into commercial relays and a protective relay software model for evaluation.

This work examines the influence of two different implementations of inductive D-FACTS on the most common protection elements and schemes under different fault scenarios. The types of D-FACTS devices implementations studied were: dispersed (distributing the D-FACTS along the length of the line) and compressed (distributing them at specific distances on the line). Additionally, the impact of placing D-FACTS devices on adjacent lines was studied. Protection schemes studied in this thesis include distance elements (mho or quadri-

lateral elements), communication aided distance schemes (permissive overreaching transfer trip [POTT]), and fault location schemes. Furthermore, the influence of fault resistance and mutual coupling between parallel lines on relay response is studied in the presence of D-FACTS devices.

Dispersed or compressed D-FACTS implementation can cause underreaching of distance elements. This may lead to a delay in the tripping time or in fact, a failure to trip in a POTT scheme. The simulation results show that using dispersed D-FACTS implementation can reduce the error compared to the compressed implementation, and increase the ability of performing correction for these devices under some operating conditions.

This work also examined the effect of D-FACTS devices on distance elements' performance in presence of a fault resistance and mutual coupling between the parallel lines. The results illustrated how the direction of the power flow influences the fault resistance coverage of distance elements in the presence of D-FACTS devices. The D-FACTS may help to reduce the distance elements' underreach for forward faults and increase the underreach behavior for the reverse fault. The results show that mutual coupling influence on distance elements would be not impacted by addition of the D-FACTS devices.

Lastly, we investigated how implementing inductive D-FACTS devices on the adjacent line affects the dynamic behavior of mho distance elements and the calculated effective impedance tilt of quadrilateral distance elements' response. Inserting the D-FACTS behind the relay can help expand the mho circles for forward faults and contract them for reverse faults. As a result, fault resistance coverage can be improved. On the other hand, this may cause underreaching or overreaching of the quadrilateral distance elements' response when a fault resistance is present in a ground fault.

To deal with the challenges in the implementation of D-FACTS devices and minimize their influence on transmission line protection system performance, this thesis proposes mitigation for creating reliable protection and fault location schemes. The work concludes by offering recommendations for D-FACTS device implementation and protective relays' settings.

## Acknowledgements

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Last but not the least, I would like to thank my family and friends, for their unwavering belief in me throughout my personal and academic life. I would not be able to attain this position in my studies if not for their motivation and support.

## Dedication

*To the soul of my father Massoud Beleed and my mother Emilhna Salih for all their love, support, prayers, caring, and sacrifices for educating and preparing me for my future.*

*To Najwa Salih my dear wife for her encouragement and help that allowed me to obtain my advanced degree.*

*To Rafida, Rinad, Hana, and Zahra my daughters, and Haithm and Muhammad my sons for their patience and help while I worked on my research.*

*To my brothers and sisters.*

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## List of Abbreviations

| | |
|---|---|
| FACTS | Flexible AC Transmission Systems |
| STATCOM | Static Synchronous Compensator |
| SSSC | Static Synchronous Series Compensator |
| UPFC | Unified Power Flow Controller |
| D-FACTS | Distributed Flexible AC Transmission Systems |
| POTT | Permissive Overreaching Transfer Trip |
| SVC | Static Var Compensator |
| TSC | Thyristor Switched Capacitor |
| TCR | Thyristor Controlled Reactor |
| AC | Alternating Current |
| VSC | Voltage Sourced Converter |
| TSSC | Thyristor Switched Series Capacitor |
| TCSC | Thyristor Controlled Series Capacitor |
| NYPA | New York Power Authority |
| DC | Direct Current |
| DSSC | Distributed Static Series Compensator |
| STT | Single Turn Transformer |
| DSI | Distrbuted Series Impedance |
| DSR | Distrbuted Series Reactor |
| IGBT | Insulated Gate Bipolar Transistor |

| | |
|---|---|
| MTA | Maximum Torque Angle |
| DUTT | Direct Underreaching Transfer Trip |
| PUTT | Permissive Underreaching Transfer Trip |
| DCUB | Directional Comparison Unblocking |
| DCB | Directional Comparison Blocking |
| CT | Current Transformer |
| 87L | Line Current Diffrential Protection |
| MOV | Metal Oxide Varistor |
| ATP | Alternative Transients Program |
| VTR | Voltage Transformer Ratio |
| CTR | Current Transformer Ratio |
| COMTRADE | Common format for Transient Data Exchange for power systems |
| AMS | Adaptive Multichannel Source |
| SEL | Schweitzer Engineering Laboratories |
| SLGF | Single Line to Ground Fault |
| DLGF | Double Line to Ground Fault |
| LLF | Line to Line Fault |
| 3phF | Three Phase Fault |
| IEEE | Institute of Electrical and Electronics Engineers |
| R1 | Relay 1 |
| R2 | Relay 2 |

| | |
|---|---|
| DIF | Line Current Differential |

# CHAPTER 1

## Introduction

During the last decade, demand for electrical power has continued to increase at a significant rate. Furthermore, the concept of active consumers has changed how the grid operates. One of the major facilitators for this change is renewable energy resources which allow small customers to sell back excess power and fulfill their goal of preserving the environment. There has been an increase in large remote renewable installations. As a result, many renewable energy resources, such as wind and solar power, have been connected to the transmission system. These factors are adding more complexity to power systems, and because of this, new and capable technologies have been developed to control power flow variations. To meet the needs of solving power flow issues, power electronic devices are being more widely utilized in transmission and distribution systems. Some classes of these devices have seen use in powers system since the 1950s and 1960s [1].

In cases where fast acting devices are needed to control the power flow in transmission systems and improve transient stability of power systems, different types of Flexible AC transmission system (FACTS) devices have been proposed to solve the stability issues. These devices such as Static Synchronous Compensators (STATCOMs), Static Synchronous Series Compensators (SSSCs), and Unified Power Flow Controllers (UPFCs). At the same time, their somewhat low reliability and high capital costs limit their penetration into the power system [2],[3],[4],[5],[6]. Series Distributed Flexible AC Transmission Systems (D-FACTS) devices offer the possibility of overcoming these drawbacks by presenting a distributed solution at low cost and high reliability [7].

D-FACTS devices are power electronics based devices that offer the ability to manage congestion in a power system by controlling the power flow in certain transmission lines. They control the power flow by increasing the line impedance of an overloaded line to force the current to flow to lines with larger available capacity. D-FACTS devices are single phase devices. Each can clamp around one of the three phase conductors at the same site, and they can be distributed over the entire length of the transmission line in different configurations. They provide potential benefits to utilities, such as reducing the power flow through the overhead line, minimizing losses and operational costs, improving the system stability and controlling system voltage [8], [9], [10], [11]. Some electrical utilities have started to install these devices in their overhead lines [12].

In transmission systems, fault currents are interrupted by circuit breakers which are located at the ends of a transmission line to isolate the faulted lines. Circuit breakers receive tripping signals from protective relays (usually located inside the substation close to the circuit breaker) if a disturbance happens on the protected line [13]. This study focuses on the impact of D-FACTS devices on the protection elements and schemes that are commonly used in transmission systems. The most common elements and schemes are distance elements, permissive over-reaching transfer trip (POTT), and line current differential elements. The response of these elements may be impacted with the presence of D-FACTS devices in the transmission line.

The basic operation of a distance relay is to determine the effective impedance between a relay location and the fault point by using voltage and fault current measurements. The measured effective impedance should indicate the approximate location of the fault within the transmission line. Also, the distance element will send a trip signal to the circuit breaker if the effective impedance is smaller than the setting value. The basic operation principle of a POTT scheme is to use zone 2 distance elements' (the time delayed backup protection zone for distance elements) information from the relays at each end of the line such that if zone 2 is picked up by one relay, the relay will communicate to the relay at the other end of the line with this information. The remote relay will include it with the zone 2 local information (in a logical AND operation). If both relays are picked up in zone 2 for this fault, each one of them will send a trip signal to the circuit breaker for a high speed trip [14],[15],[16],[17],[18],[19]. In the presence of D-FACTS devices, these elements may not operate correctly.

To make these distance elements more secure and improve their sensitivity, different types of polarization have been used in the mho distance elements. There are three commonly applied types of polarization: self, cross, and memory polarization. Self polarized mho circles cannot change dynamically. By using the other two types, it is possible to change the behavior of mho circles to become dynamic and vary with time as a result of the fault. This dynamic behavior can improve the protection performance in most cases [20].

Typically, there is an impedance that is generated from the arc because of a fault between two conductors or between conductor and the tower, and from the ground path including any objects such as trees, buildings and animals during a ground fault. This resistance is called the fault resistance, and usually the fault resistance for ground faults has a much larger value than the fault resistance for phase faults. Inductive mutual coupling can occur between two or more parallel lines in single circuit lines or double circuit lines [20].

Quadrilateral distance elements have the ability to detect faults with larger values of fault resistance and cover a ground fault with a fault resistance close to the reach setting. Quadrilateral distance elements have a reactive reach setting, a resistance reach setting, and a directional element setting.

## 1.1 Problem Definition

Interactions between the operation of D-FACTS modules and transmission line protection elements due to the change in the effective line impedance parameters leads to a some concerns in protection performance. D-FACTS operation can lead to unpredictable changes in the impedance of the transmission line and possible limitation of fault current.

The presence of these devices may cause a failure to trip, unwanted trip, or misleading fault location information for some of the protection elements because of error in estimated distance due to the change in the transmission line impedance. Using different types of D-FACTS implementations, such as either compressed or dispersed implementation, can lead to different changes in measured values of the line impedance during faults. In such cases, it is hard to predict how many devices will be present in the fault path and how many devices will switch to bypass mode because of fault current.

The D-FACTS operation can lead to unpredictable changes in the dynamic behavior of mho distance elements. Also, the D-FACTS devices may impact the tilt angle compensation setting for quadrilateral distance elements. D-FACTS devices implementation in the adjacent line can lead to different changes in the expansion and contraction shape of the mho circles of cross and memory polarized distance elements. The changing in the expansion and contraction response of the mho elements and the inaccurate response of the quadrilateral distance elements may cause underreaching or overreaching of these distance elements.

In addition, the interactions between the operation of D-FACTS devices and transmission line protection elements may influence the fault resistance coverage (the ability of distance elements to respond correctly in the presence of fault resistance) of the mho ground distance elements. Also, this may impact the zero sequence mutual coupling due to the change in the effective line parameters and, as a result, may influence the protection performance.

The error in the measured impedance or the effective reach to the fault location may increase or decrease in the presence of D-FACTS. Either response is possible to see some cases where fault location elements overreach or underreach. This can lead to an error in the estimated distance to the fault (the fault location).

Performing an investigation on the impact of D-FACTS devices on the transmission line protection system is important to avoid problems such as unintentional outages, electrical equipment damage, low service reliability, and maintenance/operation costs.

## 1.2 Dissertation Contribution

The main objective of this study is to provide a good understanding of the effect of D-FACTS devices on line protection systems and then make recommendations for D-FACTS devices implementation and for protective relay settings in the context of D-FACTS devices.

- This study develops new models of D-FACTS devices to perform protection studies.

  - The D-FACTS models are developed in an electromagnetic transients program, and their performance is validated against an a built-in model in PowerWorld [21].
  - The D-FACTS models are implemented in the IEEE 12 bus dynamic test system [22].
  - The D-FACTS models are validated for performing simulation studies on the impact of these devices on transmission line protection systems.

- This study provides a good understanding of the D-FACT devices' effect on the performance of protection elements and schemes of the transmission lines.
  - This study addresses effects of D-FACTS devices on zone 1 and zone 2 distance elements, POTT schemes, and line current differential schemes for transmission lines. Effects are analyzed and investigated for hundreds of different fault cases.
  - This study addresses the effect of D-FACTS devices on the mutual coupling of double circuit lines and on how the protection systems of these lines may be impacted. This study also considers D-FACTS devices' impact on the protection system in the presence of a fault resistance.
  - Furthermore, this dissertation provides a demonstration of the effect of D-FACTS devices in the dynamic expansion and contraction of the mho circles of mho distance elements. Also, this thesis demonstrates the impact of D-FACTS implementation in the tilt angle of the quadrilateral distance elements and in turn, how that may impact the fault resistance coverage.

- The study also provides recommendations for D-FACTS devices implementation and for protective relays settings of the transmission lines with D-FACTS devices based on the results from the study tools.
  - This study shows the importance of performing a fault study before implementing

these devices.

- Corrections for the percent of D-FACTS devices potentially active in the line are needed in relay settings to overcome some of the challenges that are associated with using D-FACTS devices.
- Recommendations for D-FACTS implementations and protective relays setting are suggested in this study.

## 1.3 Thesis Roadmap

The development and analysis of the effect of D-FACTS devices on the performance of transmission line protection system is detailed in this dissertation in nine chapters. An introduction to this thesis, the problem definition, the dissertation contribution and study roadmap were presented in this chapter. Chapter 2 presents a general overview of power flow control devices, the basic concepts of D-FACTS devices, the basic transmission line protection schemes used in protective relays, and the general challenges for setting protective relays with conventional series compensations devices.

Chapter 3 explains the system and simulation design information, the protective relay settings, and the data collection and analysis process. The creation and validation of D-FACTS device models is presented in Chapter 4, which is a published paper that was presented at the 2017 North American Power Symposium (NAPS) [21]. Chapter 5 is a published paper that was presented at the 2019 North American Power Symposium (NAPS). It explains an investigation of the impact of D-FACTS devices' implementations on mho distance elements [23]. Chapter 6 is a published paper that was presented at 2019 North American Power Symposium (NAPS). The chapter presents an exploration of the D-FACTS influence on mho ground distance elements in presence of fault resistance and mutual coupling with parallel lines [24]. Chapter 7 is a published paper that was presented at the 2020 Innovative Smart Grid Technologies (ISGT) conference discussing the impact of D-FACTS on the dynamic behavior of mho and quadrilateral ground distance elements. [25].

Chapter 8 presents strategies for D-FACTS device implementations and practical recommendations for compensating for D-FACTS devices in protective relay settings. A summary of this work, conclusions and possible future work are presented in Chapter 9.

# CHAPTER 2

# Background

Electrical power is delivered to consumers from generation plants via transmission and distribution systems. The electrical power that flows through transmission and distribution lines is called power flow, which is the transported real and reactive power. The following is a review of some important related topics such as the power flow control devices, D-FACTS devices, and basic protection elements for protective relaying in the transmission system.

## 2.1 Power Flow Control Devices

The flow of power can be controlled by adjusting system parameters, such as the magnitude of the voltage, line impedance, and angle of delivery. Devices that can change these parameters of the system to control the flow of power are called power flow control devices, which include the commonly used conventional devices (capacitors, inductors, and phase angle regulators) and the less commonly used Flexible AC Transmission Systems (FACTS) devices. Depending on how the device is connected to the line, conventional devices and FACTS devices can be divided into shunt devices, series devices, or combined devices (both the shunt and series), as shown in Figure 2.1 [26].

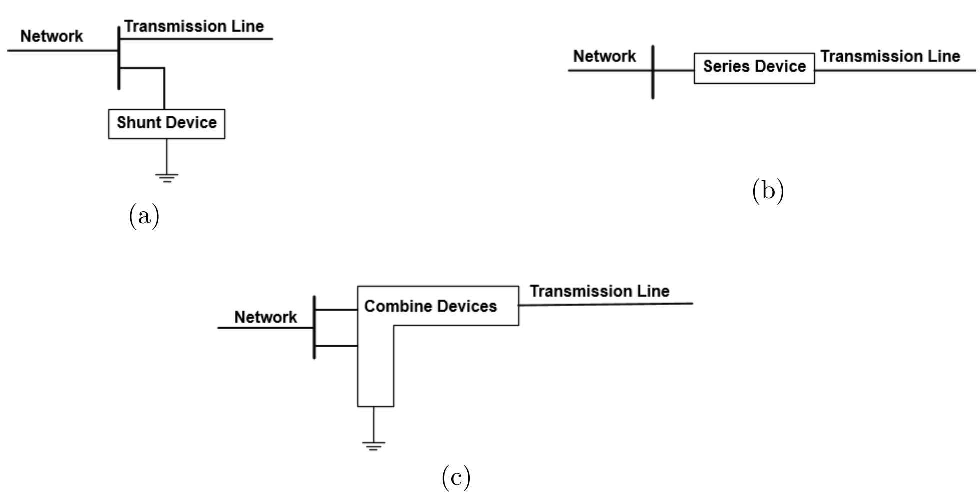



Figure 2.1: Schematic Diagram of (a) Shunt, (b) Series and (c) Combined Devices

### 2.1.1 Shunt Reactive Devices for Controlling Power Flow

A shunt device can be connected between the grid and neutral for the purposes of the following:

- To produce or absorb reactive power at the connection point so that the magnitude of the voltage can be controlled;
- To provide desired reactive power locally, thus reducing the undesirable flow of reactive power through transmission lines to reduce transmission system losses;
- To improve the quality of power, mainly during large variations in demand.

Shunt devices are categorized further into three types:

#### 2.1.1.1 Conventional Switched Shunt Inductor and Capacitor Devices

Figure 2.2 shows conventional shunt inductor and capacitor configurations.

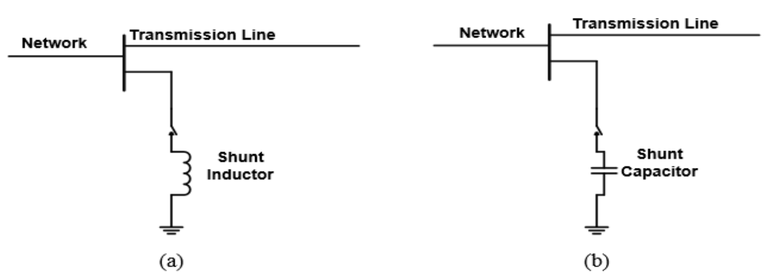



Figure 2.2: Shunt Inductor and Capacitor Configuration: (a) Inductor (b) Capacitor

#### 2.1.1.2 The Static Var Compensator (SVC)

A Static Var Compensator consists of networks of devices, such as thyristor switched capacitors (TSC), in combination with a thyristor controlled reactor (TCR). These devices use the thyristor to control the shunt reactive compensation by varying average current through the inductor or capacitor as can be seen in Figure 2.3. SVCs are commonly used in the transmission system. There were about 1300 devices around the world in 2018 [27].

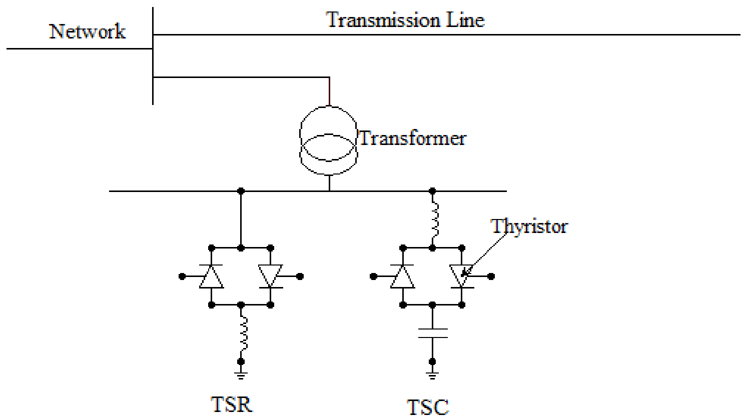



Figure 2.3: Configuration of Typical Static Var Compensator (SVC)

#### 2.1.1.3 Static Synchronous Compensator (STATCOM)

Figure 2.4 shows one configuration of a Static Synchronous Compensator (STATCOM). The STATCOM acts as a current-controlled voltage source and its control characteristics are similar to a synchronous condenser (synchronous generator with P=0) with much faster response, and is used to provide dynamic reactive shunt compensation. A STATCOM is a voltage source converter (VSC) based controller, which provides the ability to do fast dynamic compensation [28], [29]. Between 30 to 50 STATCOM devices were installed around the world in transmission systems in 2018 [27].

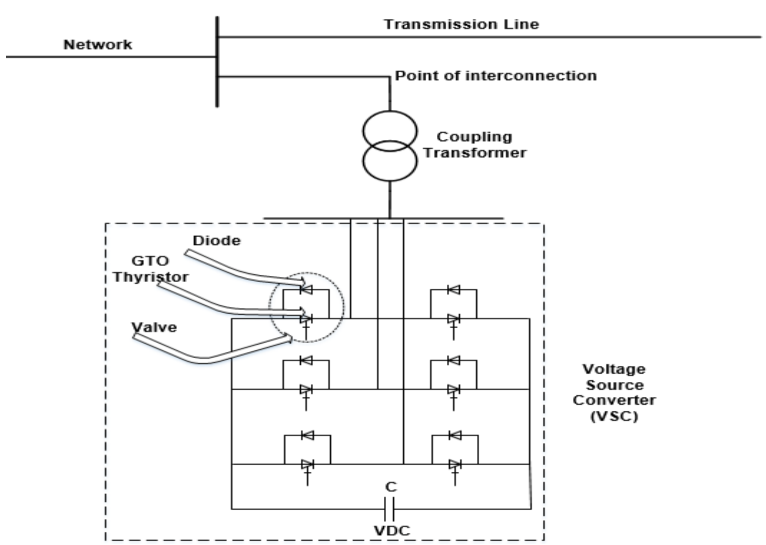



Figure 2.4: Configuration of a 2-level VSC Based Static Synchronous Compensator (STATCOM)

### 2.1.2 Series Devices for Controlling Power Flow

Series FACTS devices are connected in series with the transmission line. They affect the impedance of transmission lines and they can be used to:

- Modify (decrease or increase) the reactive impedance of the line to increase or decrease the inductive reactance;
- Reduce the inductive voltage drop by using a series capacitor to diminish the transmission line inductive impedance;
- Control and limit the current flowing in a transmission line to below the thermal limit and stability limit by injecting inductive series impedance [26].

Common series compensators comes in three configurations:

#### 2.1.2.1 Mechanical Switched Reactive Compensators

Figure 2.5 shows the arrangements of mechanical switched series mode devices: (a) capacitor and (b) an inductor. The use of mechanical switched reactors is rare in normal operating conditions.

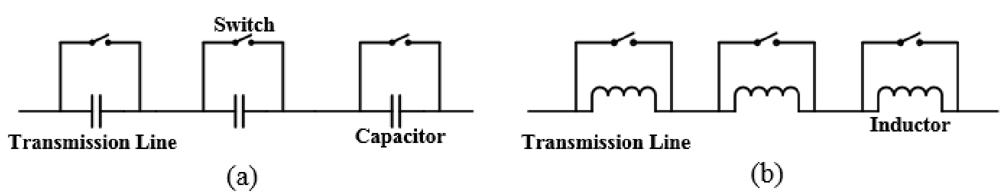



Figure 2.5: Arrangements of Mechanical Switched Series Mode Devices: (a) Capacitor and (b) Inductor

#### 2.1.2.2 Thyristor Series Compensators

##### 2.1.2.2.1 The Thyristor Switched Series Capacitor (TSSC)

For this particular type, there are two anti-parallel thyristors connected in parallel with the series capacitor to insert or bypass the capacitive compensation from a transmission line as shown in Figure 2.6. The TSSC provides fast dynamic series compensation [30], [31]. Some installations are used to protect the series capacitor in ac faults.

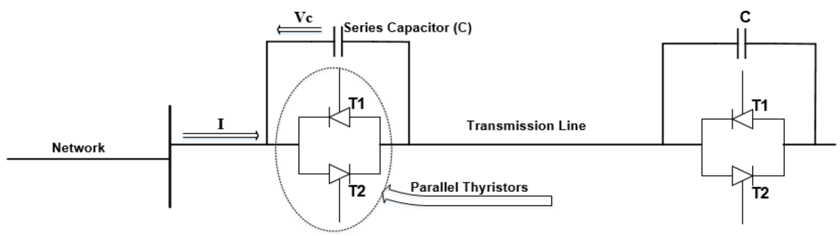



Figure 2.6: Arrangement of the Thyristor Switched Series Capacitor (TSSC)

#### 2.1.2.2.2 The Thyristor Controlled Series Capacitor (TCSC)

A series capacitor is driven in a controlled resonance by a thyristor controlled reactor to provide a range of variable capacitive or inductive reactance. The connection is shown in Figure 2.7. Around 20 TCSC devices were installed around the world in transmission system in 2017 [30], [32].

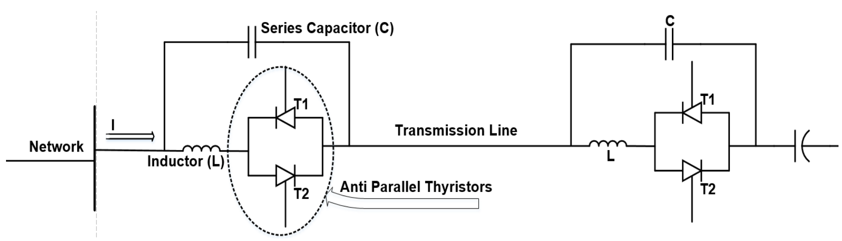



Figure 2.7: Arrangement of the Thyristor Controlled Series Capacitor (TCSC)

### 2.1.2.3 The Static Synchronous Series Compensator (SSSC)

The arrangement utilizes a voltage source converter (VSC) connected in series with the power line through a transformer, as shown in Figure 2.8.

The SSSC operates without an external energy supply. The series compensator output voltage either leads or lags the line current by 90 deg to inject reactive power into the transmission line. The goal is to increase or decrease the total reactive voltage drop across the transmission line. The first SSSC was installed in a transmission system at New York

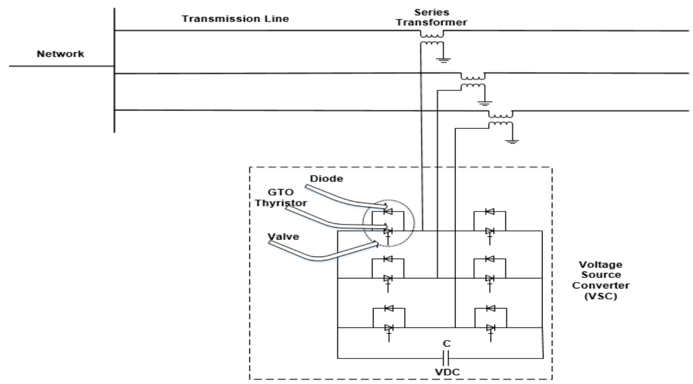



Figure 2.8: One Arrangement for Three Phase Static Synchronous Series Compensator

Power Authority (NYPA). This NYPA SSSC consists of two converters [33], [34]. It has the ability to temporarily inject real power by controlling the angle difference between the injection voltage and the line current [1], [35].

## 2.1.3 Combined Devices

Combined devices are interconnected shunt devices and series devices, connected to the transmission system for the purpose of providing control of power flow by modifying the angle difference, the impedance parameters of the transmission line, or, the voltage profile [26]. There are two common configurations.

### 2.1.3.1 Phase Shifting Transformer

A Phase Shifting Transformer, as shown in Figure 2.9, consists of a series transformer connected to a tap changer on the secondary of a shunt transformer. The basic principle of

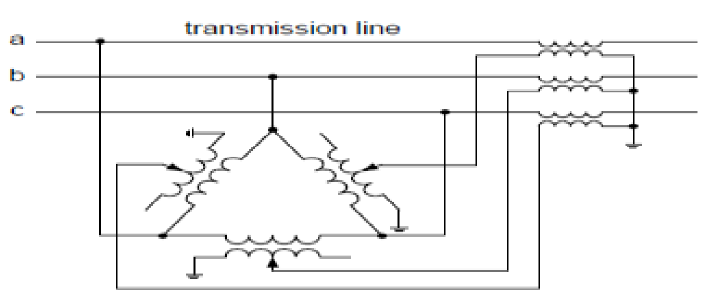



Figure 2.9: The Phase Shifting Transformer Configuration

phase shift transformer is injecting controllable series voltage [36], [37].

#### 2.1.3.2 Unified Power Flow Controller (UPFC)

A UPFC consists of a STATCOM and SSSC connected through a common DC link to control the power flow through a combination of SSSC and STATCOM output action, as shown in Figure 2.10 [28]. Similar to a phase shifting transformer, power can be circulated between the series and shunt converters. The STATCOM can also provide reactive power support, unlike the phase shifting transformer.

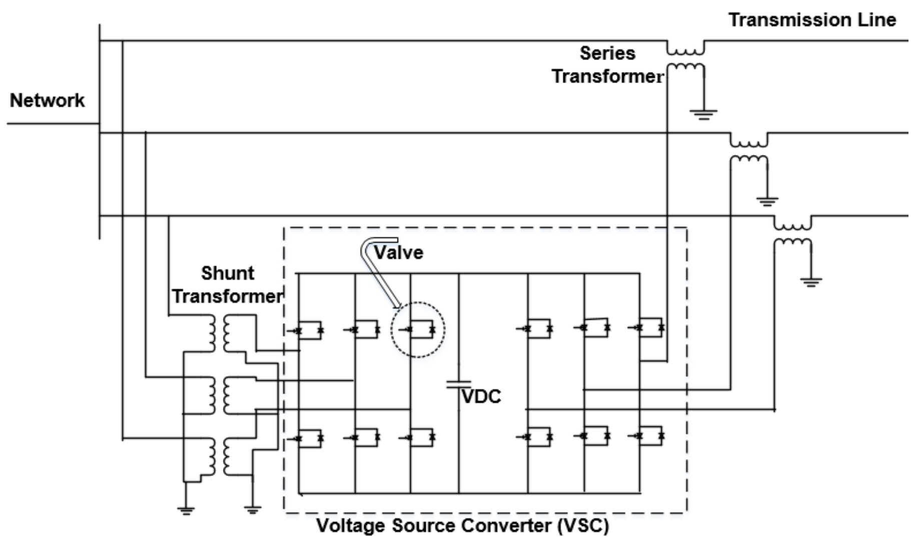



Figure 2.10: Arrangement of Unified Power Flow Controller (UPFC)

Large FACTS devices have faced major challenges in terms of cost and reliability, which has limited their spread in power systems. To provide more cost effective power flow control, newer types of power flow controllers are needed. Distributed flexible AC transmission system or D-FACTS as they are known, come from the concept of distributing the lumped FACTS devices into many smaller, low rated devices along the transmission line. Employing this D-FACTS strategy can potentially improve reliability and reduce system cost [38], [39].

## 2.2 The Distributed Flexible AC Transmission System (D-FACTS) Concept

The idea of D-FACTS was first proposed by Divan [38]. The D-FACTS concept was developed at Georgia Institute of Technology. Figure 2.11 illustrates that D-FACTS devices are clamped onto the transmission line conductors. D-FACTS devices can be distributed over the length of the transmission line. They are single phase devices with a single device clamp around each of the phase conductors at the same site. This can be repeated at specific locations along the transmission line. Since the failure of one of these devices has very limited effect on the whole application, the reliability is improved [38]. Development of D-FACTS can be divided into three types.

Figure 2.11: Inductive D-FACTS Devices Installed on Transmission Line [12]

### 2.2.1 Distributed Static Series Compensator (DSSC)

The first developed was the DSSC, which applies the concept of a series static compensator (SSSC) with a 5kVA device rating. Figure 2.12 shows the simple circuit representation of the distributed static series compensator (DSSC).

The single-turn transformer (STT) is coupled magnetically with the transmission line. The transformer magnetically couples the power module to the line. The single phase trans-

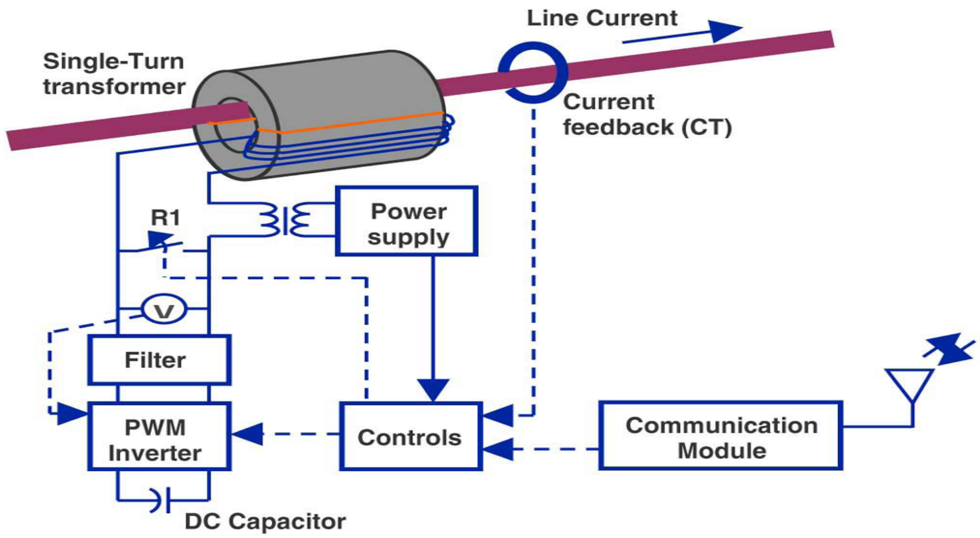


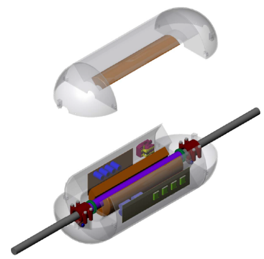

Figure 2.12: The Basic Circuit Representation of the DSSC [38]

former, it is possible to inject a desired voltage into the line. The required DC supply can be powered directly from the secondary of the STT to provide DC source for the inverter controller. Also, a current transformer is used in order to provide a feedback signal. Operating conditions can be changed according to a signal received using a wireless communication technique.

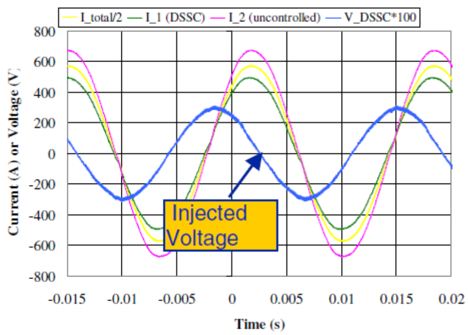
The bypass switch (R1) is closed when the line current is below a certain threshold. The phase conductor is used as the primary of the single turn transformer (STT) [40], [41].

An orthogonal voltage (leading or lagging the line current by 90 deg) can be injected into the line by the distributed static series compensator (DSSC) module to control the power flow. Figure 2.13 shows the concept of a distributed static series compensator (DSSC) module and the output waveform in case of leading and lagging voltage injection [7].

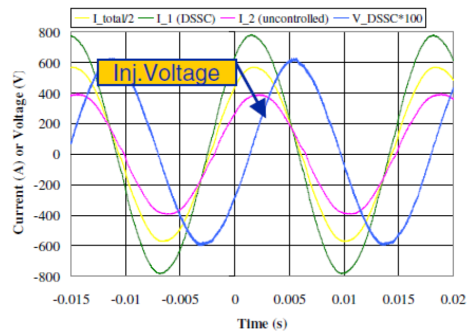
DSSC devices require a communication aid, which can increase the total cost and decrease the reliability. Therefore, a new concept of D-FACTS which is the Distributed Series Impedance (DSI) was proposed to obtain devices with low cost and higher reliability [38].



(a)




(b)




(c)

Figure 2.13: (a) Distributed Static Series Compensator (DSSC) Module with Output Waveforms for (b) Leading and (c) Lagging Voltage Injection
[7]

### 2.2.2 Distributed Series Impedance (DSI)

A Distributed Series Impedance has the ability to change the impedance of the transmission line in order to control the power flow. One of the DSI applications is to maximize the overall transmission system capacity by controlling the line current. In case of an overloaded line, the DSI inserts inductive reactance to prevent the current from reaching the thermal limit and forces the current to flow into less loaded lines. On the other hand, if the line is under loaded, the DSI can insert capacitive reactance to allow more current to flow in that line. Figure 2.14 shows the basic circuit of a Distributed Series Impedance device.

Figure 2.15 shows the injection of positive or negative series reactance into the line in steps, and each step represents one DSI device [7],[42]. The DSI is similar to the DSSC in that it requires a communication aid and therefore reliability and cost issues are still a challenge. To solve the communication issues, the Distributed Series Reactance (DSR) was

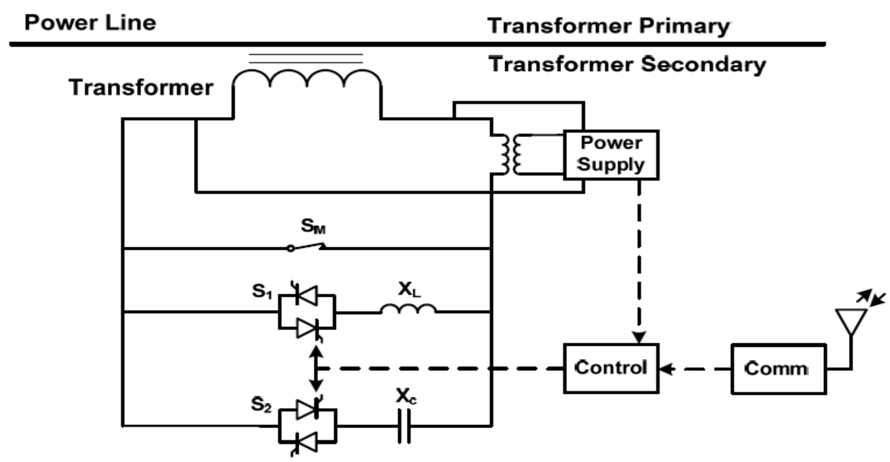



Figure 2.14: The Basic Circuit Representation of the (DSI) [42]

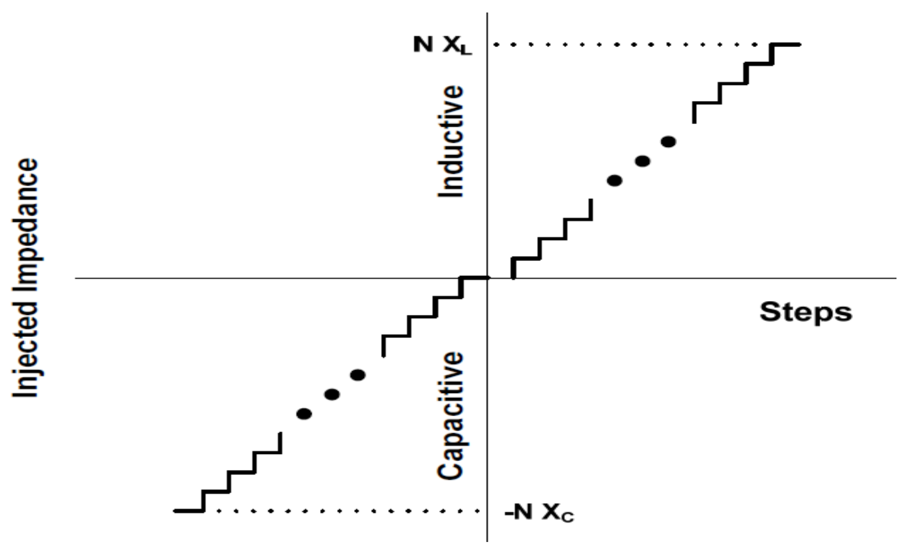



Figure 2.15: The Injection of Positive or Negative Series Reactance into the Line in Discrete Steps [7]

proposed based on the local measurements such as voltages and currents.

### 2.2.3 Distributed Series Reactance (DSR)

Figure 2.16 shows the basic circuit of a Distributed Series Reactor (DSR). The DSR can only inject a series inductive reactance. During the normal mode of operation, the switch $S_M$ is closed and the injected reactance is zero. The inserted reactance is equal to the magnetizing inductance of the STT when switch $S_M$ is open. The magnetizing inductance can be designed to match the desired value of series compensation. Thyristor switches are used for quick bypass for this device under high overcurrent conditions.

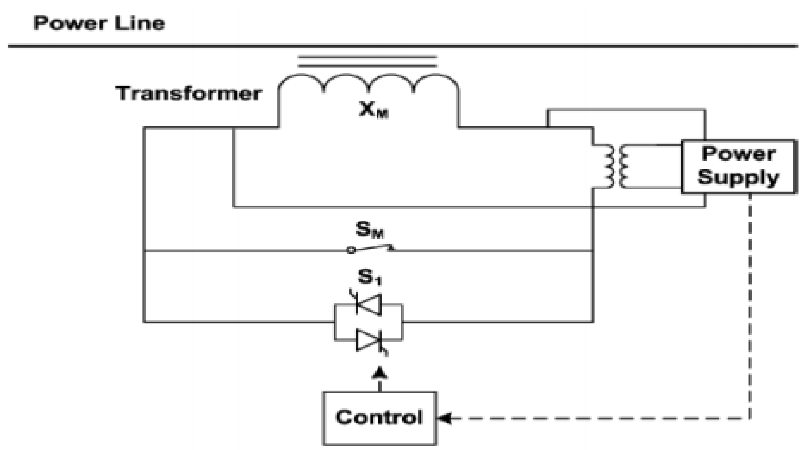



Figure 2.16: The Basic Circuit of Distributed Series Reactor (DSR) [7]

When the line current exceeds the threshold value, the DSR devices start to switch on to limit the flow of the power into this line [7], [43].

Figure 2.17 shows a summary of the categorization of power flow controller devices. This figure includes the more commonly used conventional devices (capacitor, inductor, and phase angle regulator) and the less commonly used Flexible AC transmission System devices (FACTS devices). The conventional compensations and FACTS devices are divided depending on how the devices are connected to the line (shunt devices, series devices, and combined devices), and their based controller.

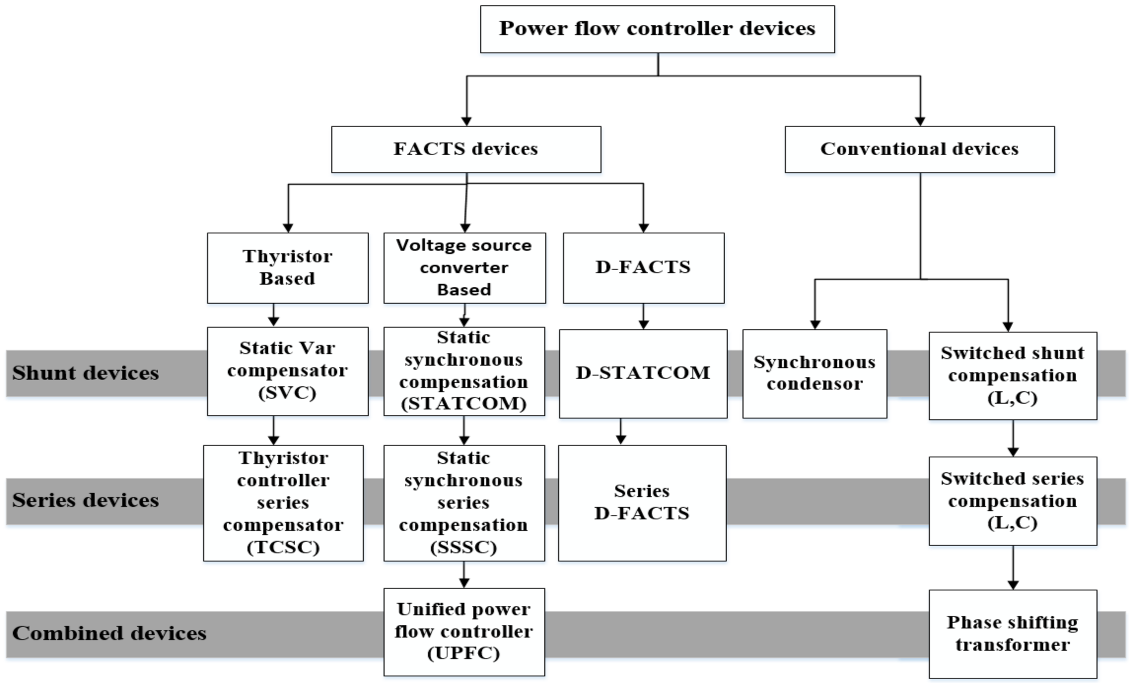



Figure 2.17: Summary of the Categorization of Power Flow Controller Devices

### 2.2.4 Implementation Approaches for D-FACTS

Some utilities have started implementing reactive D-FACTS devices on their network to control the power flow for both a long and a short term solution. One of the manufacturers calls the reactive D-FACTS devices "Guardians." Figure 2.18 illustrates how the reactive D-FACTS technology works when applied on a typical transmission system. This system includes a generation station which is far from the load center, and there are three transmission lines to deliver the electric power to the load center. One of the lines has lower current rating than the others. This limits the minimum power flow in the whole system when it is overloaded. Traditionally, the utility would reconductor the existing line or build a new line to solve this problem. These solutions are costly, time-consuming, and environmentally unfriendly. By using reactive D-FACTS devices, it is possible to prevent these issues by installing them on the overloaded line to push power away so it flows into the less utilized lines. These devices can be divided to two main groups: distributed D-FACTS (Guardians) and lumped D-FACTS [44].

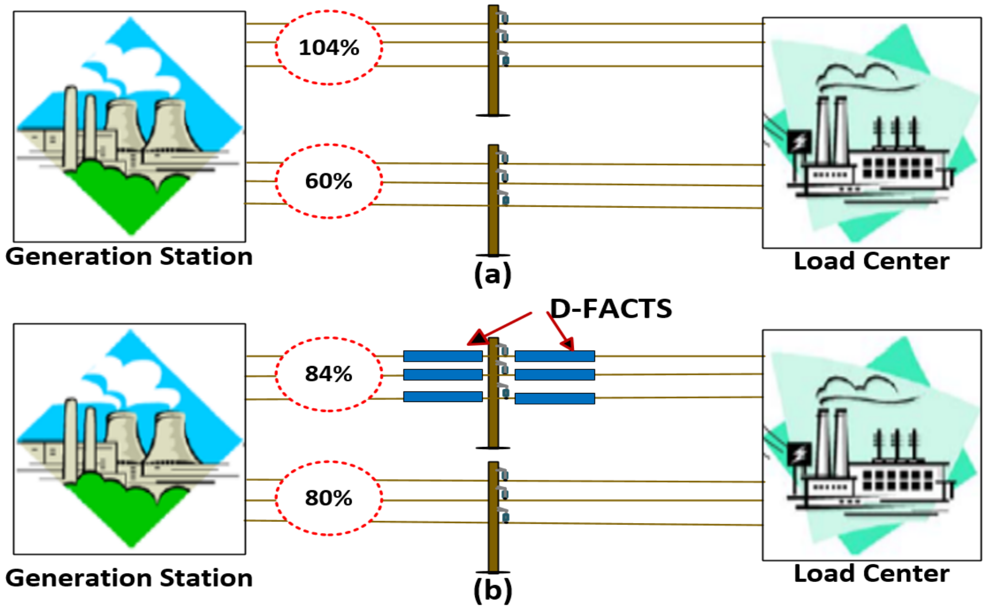



Figure 2.18: The Transmission System Power Flow (a) without D-FACTS Devices and (b) with D-FACTS Devices

#### 2.2.4.1 Distributed D-FACTS (Guardians)

The Guardians are mounted on each phase conductor to implement a distributed solution using the following two methods:

1. **Dispersed Implementation**: In this technology, the reactive D-FACTS devices are mounted on the phase conductors adjacent to the line towers. These devices should mount next to each tower along the length of the transmission line as shown in Figure 2.19 [45].

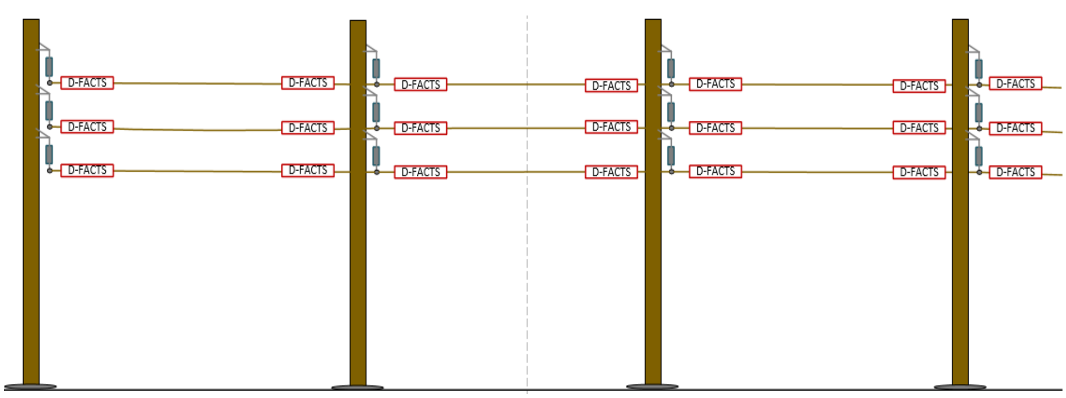



Figure 2.19: Dispersed Implementation of Distributed D-FACTS

2. **Compressed Implementation**: This technique provides choice for the utilities to select a favored position to install concentrated set of these devices to abstain from some issues such as tower wight loading, bundled conductors, or land sensitivity. In this technique, many more D-FACTS devices can be placed on a short length of line, but the utility may need to add new towers or/and reconduct a small part of transmission line without bundled conductor as shown in Figure 2.20.

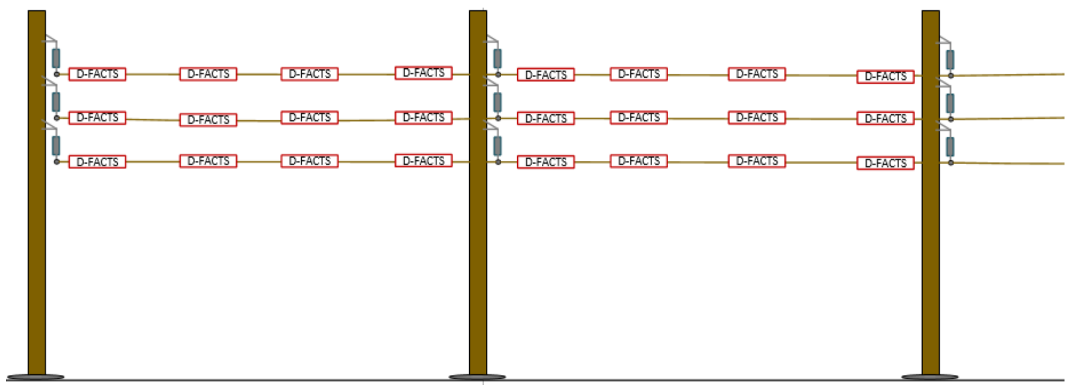



Figure 2.20: Compressed Implementation of Distributed D-FACTS

#### 2.2.4.2 Lumped D-FACTS

This type of implementation has the same technology of D-FACTS (PowerLine Guardians [45]) as described in the previous section, but each device has much larger capability (by factor of 20 to 60 times) to control the power flow. It can be used to solve the power flow issues of systems that require high percentage D-FACTS compensation. Lumped D-FACTS devices need to be installed on either a tower, a ground site, or a transferring station because of these D-FACTS devices' weight and size.

1. **Lumped on a Power Tower**: This technology may require the installation of a new tower in the transmission line for mounting the DFACTS devices. Typically, several of these towers can be present in the transmission line and each tower can host six to twenty devices.

2. **Lumped Installation on a Ground Site**: Another possibility is to implement this technology on a ground site or station somewhere along the transmission line. The advantage of this approach is that the station is easy to expand for future needs [44].

3. **Lumped Instillation at Transferring Station**: This is a mobile station which can be used for short-term solutions, for example, to allow the utility to perform maintenance or repairs on the system equipment. It is a new tool that can help the utility in getting a fast power flow solution. Like the other reactive D-FACTS, the mobile station is installed in the overloaded lines to force power to flow into less utilized lines [45].

## 2.3 Basic Transmission Protective Relays

In transmission lines, fault currents are interrupted by circuit breakers which are located at the ends of a transmission line to isolate the line in case a fault occurs. The circuit breakers receive the tripping signals from protective relays if a disturbance occurs on that line [13]. Protective relays are designed to detect faults and to send a tripping signal back to the circuit breaker for protecting the grid. The following subsections explain the function of distance, directional, and line current differential elements that are commonly used in transmission systems and may be impacted by D-FACTS.

### 2.3.1 Distance Elements

The principle role of the distance element is to determine the effective impedance between the relay location and the fault point and compare that to a set point. At the relay location in the power substation, there are current transformers (to measure current) and voltage transformers (to measure line to ground voltage). Measurements from these instrument transformers are received as inputs to the distance elements in the protective relay. Modern distance elements use multiple features (elements) including: directional supervision, overcurrent supervision and fault type selection. These three elements are often used to secure the protection system.

The effective impedance is calculated inside the relay based on the measured voltages and currents. The effective impedance will indicate the approximate location of the fault within the transmission line. The distance function will send a trip signal to the circuit breaker if the effective impedance is smaller than the reach setting. There are two common methods for implementing distance protection: the mho distance element, and quadrilateral distance element.

#### 2.3.1.1 Mho Distance Element

The protection area of the mho distance relay is divided into multiple zones as shown in Figure 2.21. Zones 1 and 2 are used as primary protection, and zones 2 and 4 can serve as backup protection for the adjacent lines [46].

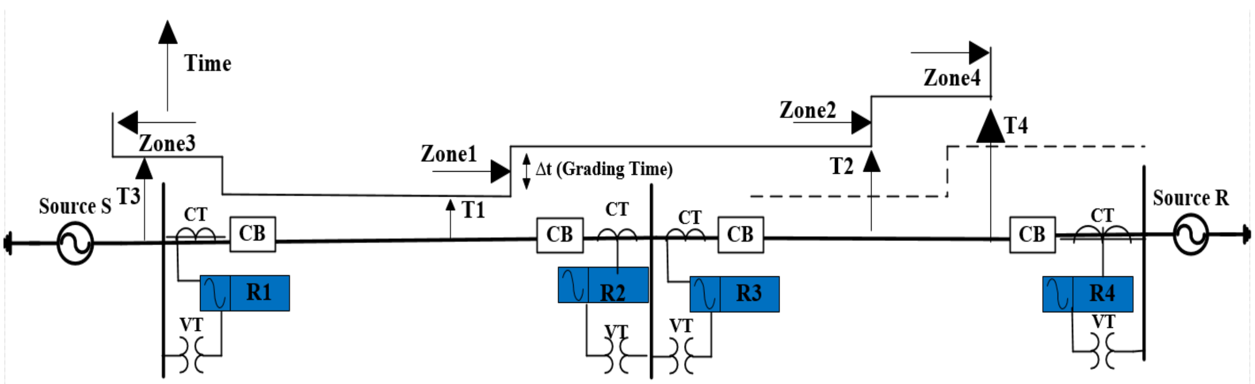



Figure 2.21: Illustration of the Protection Zones Along the Transmission Line

Modern distance relays can include additional zones: for example, three forward protection zones and a fourth one that serves as a reverse zone to add security to some communication aided schemes. The settings of the forward zones: zone 1, zone 2, zone 4 and the reverse zone (zone 3) are typically 80%, 120%, 160%, and 40% of line impedance, respectively. Figure 2.22 shows mho circles for self-polarized elements with four zones.

The distance elements' calculations inside the relay include ground elements and phase

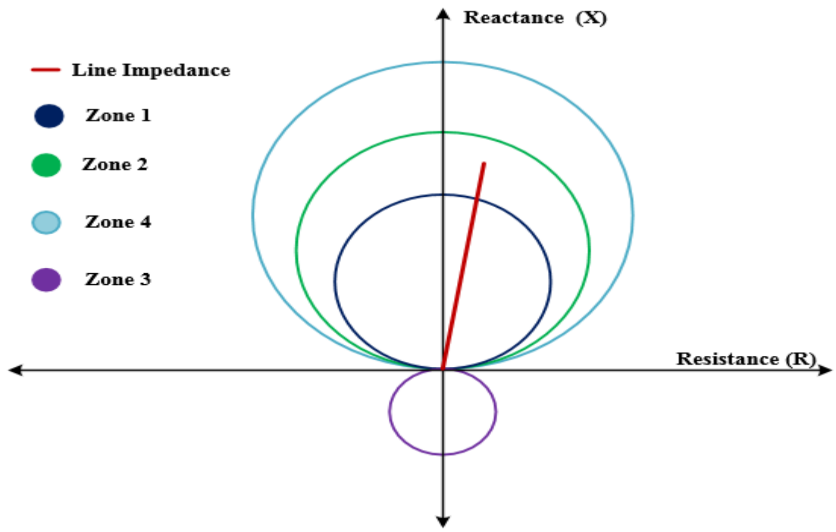



Figure 2.22: The Mho Circles for Self-Polarized Elements with Four Zones

elements. The ground distance elements are: $Z_{AG}$ (phase A to ground element), $Z_{BG}$ (phase B to ground element), and $Z_{CG}$ (phase C to ground element) as shown in (2.1), (2.2) and (2.3).

$$Z_{AG} = \frac{V_{AG}}{I_A + k_0 3 I_{A0}} \tag{2.1}$$

$$Z_{BG} = \frac{V_{BG}}{I_B + k_0 3 I_{B0}} \tag{2.2}$$

$$Z_{CG} = \frac{V_{CG}}{I_C + k_0 3 I_{C0}} \tag{2.3}$$

The coefficient ($k_0$) is a zero sequence compensation factor and can be calculated using equation (2.4).

$$k_0 = \frac{Z_{L0} - Z_{L1}}{3 * Z_{L1}} \tag{2.4}$$

The variables $Z_{L0}$ and $Z_{L1}$ are the zero sequence impedance and the positive sequence impedance of the line, respectively.

The phase elements are: $Z_{AB}$ (phase A to phase B element), $Z_{BC}$ (phase B to phase C element), and $Z_{CA}$ (phase C to phase A element) as shown in equations (2.5), (2.6), and (2.7).

$$Z_{AB} = \frac{V_{AG} - V_{BG}}{I_A - I_B} \tag{2.5}$$

$$Z_{BC} = \frac{V_{BG} - V_{CG}}{I_B - I_C} \tag{2.6}$$

$$Z_{CA} = \frac{V_{CG} - V_{AG}}{I_C - I_A} \tag{2.7}$$

The variables $V_{AG}$, $V_{BG}$, and $V_{CG}$ are the phase A to ground voltage, phase B to ground voltage, and phase C to ground voltage, respectively. $I_A$, $I_B$, and $I_C$ are the phase A, B and C currents, respectively. $I_{A0}$, $I_{B0}$, and $I_{C0}$ are the phase A referenced zero sequence current, phase B referenced zero sequence current, and phase C referenced zero sequence current, respectively.

As shown Figure 2.22, there are mho circles for different protection zone settings. The mho function will compare the ground and phase elements effective impedance calculation results to the mho circles as they vary with time. During normal operation, the calculated effective impedance will be far outside the mho circle boundaries, but when a fault occurs, the effective (calculated) impedance of the faulted phase will move towards the mho circle. As soon as this effective impedance falls inside the mho circle and stays inside it for a certain period of time, the distance function will generate a trip command or the timers of the time-delay distance elements start. If it stays outside the mho circle, it will not generate a trip command.

In most cases, if the calculated impedance due to a disturbance falls inside zone 1 circle, the relay will send a trip signal to the circuit breaker immediately. If the measured impedance falls in zone 2, after a set time delay the relay will initiate a trip signal if the fault is still present. The delay is included to allow the next relay downstream the line to respond first if the fault is in an adjacent line. For zone 4, the relay will initiate a trip signal with a longer delay time to allow the other distance elements on other lines (zone 1 and zone 2) to respond first [20].

To make these distance elements more secure and improve the sensitivity, different types of polarizing references have been used in the distance function. There are three commonly used types of polarization: self polarization, cross polarization, and memory polarization. The mho circles cannot be changed dynamically when self polarization is used. By using the other two types, the mho circles can be changed dynamically and vary with time in response to the fault.

The distance function uses a polarizing reference value to compare it to an operating point. The operating point is the difference of the voltage drop between the relay and the reach setting point ($r * Z_{L1} * I_R$) defined by the voltage at the relay location ($V_R$). The term representing the operating point in (2.8) is the line drop compensated voltage, which shows the voltage value between the fault location and the reach setting point [20].

$$V_{op} = rI_RZ_{L1} - V_R, \tag{2.8}$$

The operating voltage is denoted by $V_{op}$, $r * Z_{L1}$ is the reach setting in the relay, $I_R$ is the measured relay current, and $V_R$ is the measured relay voltage. The mho circles of the self, memory, and cross polarizing references for a forward fault (in front of the relay) are illustrated in Figure 2.23 with blue, brown, and green circles, respectively. Figure 2.24 illustrates mho circles of the self, memory, and cross polarizing references for a reverse fault (behind the relay) with blue, brown, and green circles, respectively.

The $Z_p$ term is the equivalent source impedance (the impedance behind the relay), and the magnitude and angle of this term influences the expansion shape of the mho circle of the memory polarized distance element for a forward fault as can be seen in Figure 2.23. Also, this term influences the contraction shape of the mho circle of the cross and memory polarized distance elements for a reverse fault can be seen in Figure 2.24 [20].

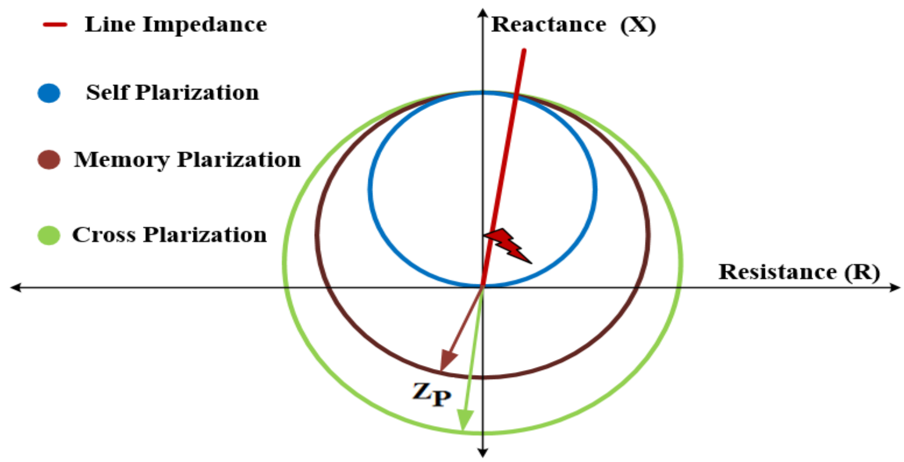



Figure 2.23: The Mho Circles Showing Dynamic Behavior with Self, Memory, and Cross Polarized References for a Forward Fault

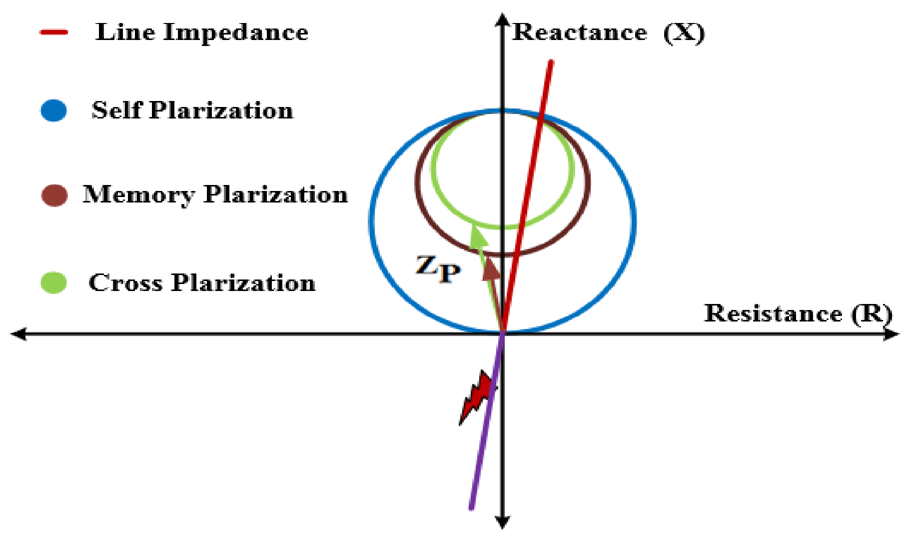



Figure 2.24: The Mho Circles Showing Dynamic Behavior with Self, Memory, and Cross Polarized References for a Reverse Fault

For self polarization, the polarizing reference term $V_{pol}$ is the voltage at the relay location used by the elements that are active. The calculation is simple, but the catch is that if a low impedance fault occurs close to the relay location, the reference will have a magnitude of zero (the reference will be lost). For example, if the phase A to ground voltage $V_{AG}$ is used as a reference for the $Z_{AG}$ element for a close SLG fault, $V_{AG}$ will be equal to zero, and because of that, it is hard for the relay to tell if it is a forward or reverse fault. The self polarizing mho circle does not vary, as shown in Figure 2.23 and Figure 2.24.

For the cross polarized case, the polarizing reference term $V_{pol}$ for each element will be based on other phases that are not involved with the mean fault type. Each distance element would use the voltages of the other unfaulted phases as a reference. For example, for the $Z_{AG}$ element, the relay would use $V_{BG}$ and $V_{CG}$ as a reference such that ($V_{pol} = V_{BG} - V_{CG}$) or ($V_{pol} = V_{BG} + V_{CG}$). For the $Z_{AB}$ element, the relay would use $V_{CG}$ as a reference. This approach still has trouble with close-in three-phase faults, which are rare, but it can improve the reliability for unbalanced faults. The cross polarizing mho circle shape can vary with the time in response to a fault as shown in Figure 2.23 and Figure 2.24.

In modern distance relays, memory polarization is the most commonly used scheme. The microprocessor relay takes the measured phase voltages and saves them in a buffer to use them as a polarizing reference term when the fault occurs. Either the phase voltages or the positive sequence voltages can be used as a momory reference. The positive sequence memory voltage will be used as a reference for the distance element in this work. The memory polarized mho circle can vary with the time in response to a fault as shown in Figure 2.23 and Figure 2.24.

The effective (calculated) impedance at the relay location can be impacted by the power system structure and the operating conditions prior to fault occurrence. For example, the measured impedance can be greatly affected by the fault resistance, which is a resistance that is generated from the fault arc, and may occur due to the presence of objects such as trees, buildings and animals in the ground fault path. The error in the measured impedance can be high or low depending on how the value of the fault resistance interacts with the power flow conditions and local and remote source impedances [47].

Using cross or memory polarizing reference can help in gaining more fault resistance coverage especially for a fault close to the relay as illustrated in Figure 2.25.

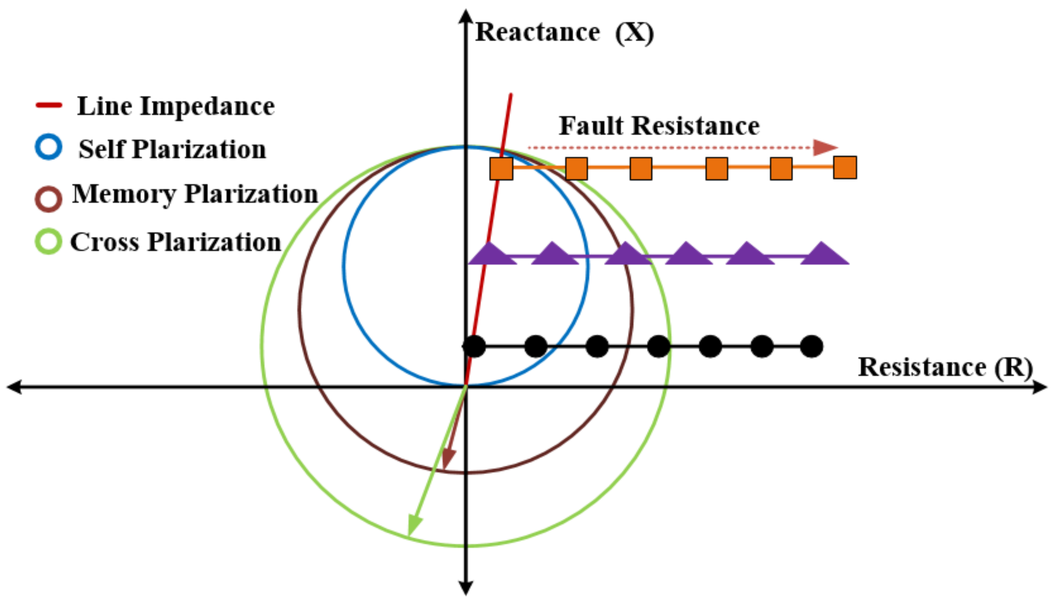



Figure 2.25: The Fault Resistance Coverage for Forward Faults with Self, Cross, Memory Polarizing References

For a SLG fault at phase A, the $Z_p$ term can be calculated from (2.9) where K is a constant and the value of this constant is based on the type of polarizing reference. K should make $V_{AG} - KV_{pol}$ equal to zero in normal balanced steady-state operation.

$$Z_p = \frac{V_{AG} - KV_{pol}}{I_A - k_0 3I_0} \tag{2.9}$$

For a forward fault, the $Z_p$ term will extend back. The $Z_p$ term will extend toward the line for a reverse fault which makes the mho circle contract. This behavior can reduce the chances of having mis-operation due to unfaulted phases responding to the fault.

#### 2.3.1.2 Quadrilateral Distance Elements

The quadrilateral distance element has the ability to handle bigger values of fault resistances, and cover faults with large resistances close to the reach setting. The quadrilateral distance element typically has a reactive reach setting, a resistance reach setting, and directional element setting as shown in Figure 2.26. The horizontal line in the figure is the reactive

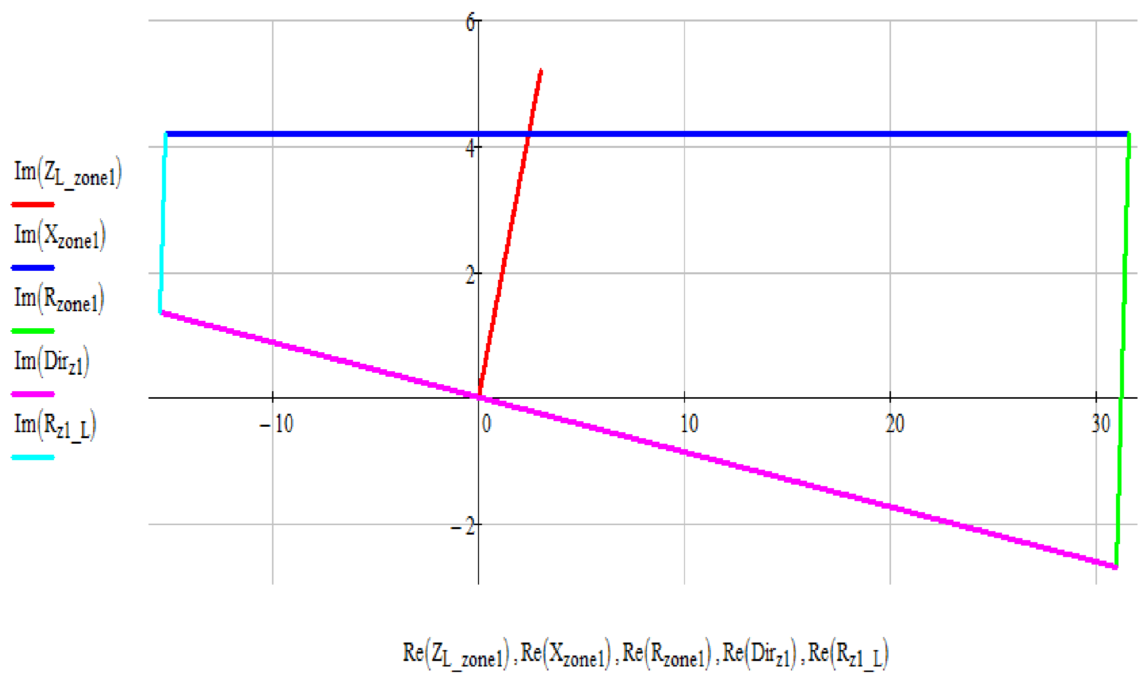



Figure 2.26: The Reactance, Resistance, and Directional Element Settings for a Quadrilateral Distance Element

reach setting, and its value is entered in the relay setting. The vertical lines are the resistive reach settings, and they are parallel with the line impedance vector (has the same angle of line impedance). The bottom line is the directional element setting. It should be orthogonal to the line impedance vector. In order for this element to trip, the real and the imaginary part of the effective impedance should fail between the reactive and resistive reach setting and be determined as forward fault by the directional elements.

One of the challenges with the quadrilateral element is load current. For a high load current with a near unity power factor, the effective impedance will appear in the impedance plane looking like a fault with high fault resistance. The second challenge is calculating the effective impedance for resistive faults. The effective impedance calculation for most common schemes will have a tilt that makes the effective impedance with fault resistance move up or down based on the power flow levels, the fault location, and the angle of the effective local and remote source impedance. Based on [17], it is possible to overcome these issues by making corrections for correcting for the tilt angle when calculating the effective reactance ($X_{eff}$) and removing the load current effects when calculating the effective resistance ($R_{eff}$) as illustrated in equations (2.10) and (2.11) for phase A to ground element.

$$X_{effAG} = \frac{Im[V_{AG}[\overline{3I_0\angle\theta_T}]]}{Im[(1\angle\theta_{Z1})[I_A + K_0 3I_0][\overline{3I_0\angle\theta_T}]]} \tag{2.10}$$

$$R_{effAG} = \frac{Im[V_{AG}[\overline{(1\angle\theta_{Z1})[I_A + k_0 3I_0]}]]}{Im[\frac{3}{2}(I_2 + I_0)[\overline{(1\angle\theta_{Z1})[I_A + k_0 3I_0]}]]} \tag{2.11}$$

The angle of the positive sequence impedance is $\theta_{Z1}$, $k_0$, as mentioned in equation (2.4). The magnitude and the angle of the tilt ($Mag_T\angle\theta_T$) can be calculated by dividing the total zero sequence fault current ($I_{0F}$) by the zero sequence current that is seen by the relay ($I_{0R}$) as shown in (2.12). This is calculated for one fault location, usually using either the reactive reach setting or the remote bus relative to the relay.

$$Mag_T\angle\theta_T = \frac{I_{0F}}{I_{0R}} \tag{2.12}$$

If the system is homogeneous, $\theta_T$ will be zero and the effective impedance response with fault resistance will be perfectly flat (horizontal). If the system is not homogeneous (the angle of the source impedance is not the same angle of the line impedance), $\theta_T$ will have some tilt in the effective impedance response, and in that case, it is important to use the tilt term for tilt correction in equation (2.15) when calculating the effective reactance. The tilt in the effective impedance may go up or down in the case of nonhomegenous system for a given fault location as the fault resistance increases. Without doing the tilt correction, the distance element may under-reach for some faults, and also it may overreach in some cases as shown in Figure 2.27 [20].

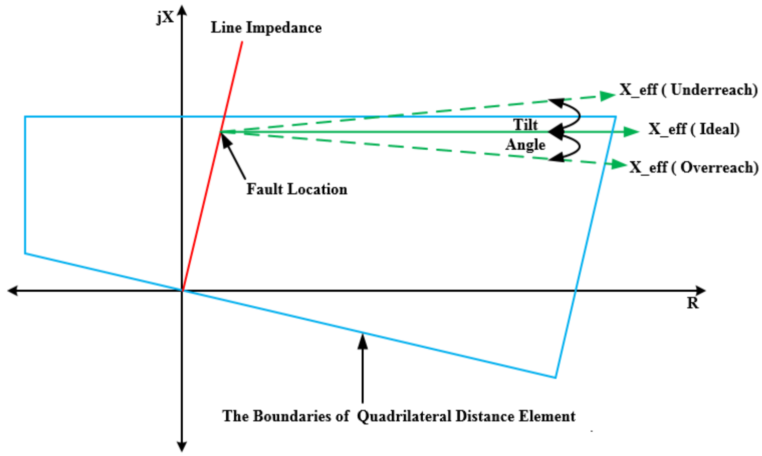



Figure 2.27: Quadrilateral Distance Element Response with Fault Resistance Under Different Power Flow Conditions

### 2.3.2 The Directional Element

The directional element in the relay can be a phase directional element, a positive sequence directional element, a negative sequence directional element, or a zero sequence directional element, and some relays use a combination of all three with logic to select between them. The main job for the directional element is to supervise a distance element or overcurrent element (it operates for a forward fault and holds for reverse fault) [48]. In the case of a power system with two voltage sources and parallel lines as shown in Figure 2.28, When a line-to-line fault happens in line 2, it is possible to see the fault current flow toward the fault from two directions. It can then cause an unwanted operation of relay 2 [49].

In this case, relay 2 can trip for this fault even though the fault is behind that relay if there is not directional element. Transmission systems are likely to have multiple sources of fault current; therefore, directional sensing has a significant impact.

In a modern protective distance relay, overcurrent elements are sometimes used to indicate

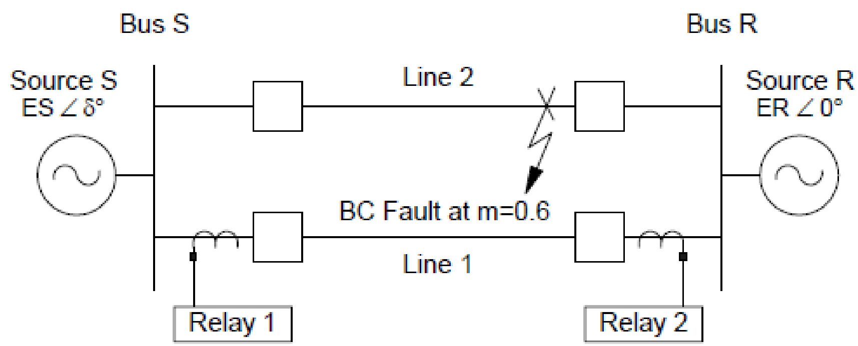



Figure 2.28: Power System with Two Voltage Sources and Double Circuit Line Configuration [49]

that there is a fault if the current exceeds a minimum value. A trip signal will be generated if the fault current exceeds a certain threshold (the distance element picks up), and the fault is in forward direction. The directional elements make the distance elements more secure and reliable in the microprocessor relay. Directional elements use a calculated torque or a calculated effective impedance from phase or sequence of voltages and currents at the relay point to identify the direction of the fault [49].

The measured negative sequence voltages and currents at the distance relay location can be used to calculate negative sequence torque or an effective negative impedance to create directional elements to supervise the distance elements for unbalanced faults. Figure 2.29 shows the simple negative sequence equivalent circuit to illustrate the negative sequence directional element for : (a) forward fault (b) reverse fault.

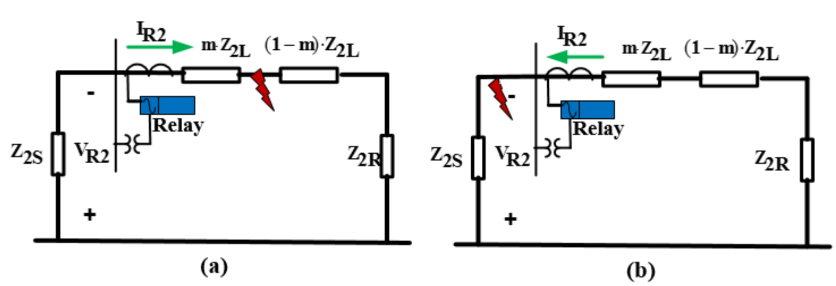



Figure 2.29: Simple Negative Sequence Circuit for (a) Forward Fault (b) Reverse Fault

For forward faults, the measured negative sequence current has a positive polarity, and the measured negative sequence voltage is negative (opposite to the reference negative sequence voltage measurement). On the other hand, for reverse faults, the measured negative sequence current is negative, and the measured negative voltage is negative (opposite to the reference polarity of the negative sequence voltage). Because of the negative polarity of the measured voltage, the negative sequence directional element will produce a negative torque for a forward fault and a positive torque for a reverse fault. Also the effective negative sequence impedance is used in some vendors' relays to determine the direction of the fault by using (2.13) to calculate the effective negative sequence impedance [20]. Equation (2.13) gives a positive or negative value approximating the impedance.

$$Z_2 = \frac{-Re[V_2(\overline{I_2 \angle \theta_{Z1ANG}})]}{|I_2|^2} \tag{2.13}$$

The measured zero sequence voltages and currents at the distance relay location can also be used to supervise the distance elements. The zero sequence impedance directional elements function similar to the negative sequence impedance directional elements described above [20].

### 2.3.3 Communication Aided Distance Elements

Communication between relays at both ends can be used to provide high-speed line protection with distance elements. Distance elements are typically set to cover about 80% of the length of the line from each end in zone 1, which means about 20% of the line on each end is covered in a time delayed zone (called zone 2), as seen from each end. By using communication aided protection, it is possible to cover 100% of the line without any set time delay. The response of the two relays at the ends of the line can be improved because they can exchange information with each other through communication channels. This can decrease the duration the fault is present and speed up the reclose time, which can improve the systems stability [13]. Also, using the communication aided protection can improve the fault resistance coverage because of using zone 2 information. The communication schemes can be classified into two main groups: transfer trip schemes and blocking/unblocking schemes.

#### 2.3.3.1 Transfer Tripping Schemes

In Transfer Tripping schemes, a trip command is sent to the other end of the line through communication channels, and then the far end relay receives this signal and acts according to trip logic specific to the scheme type.

- Direct scheme: if the relay at the sending end picks up and trips based on local information, it will send the same trip command to the remote end to trip directly with no need for checks based on that relays' measurement.

- Permissive scheme: if the relay at the sending end sends a local command to the remote end relay, it will respond to this command if it meets some sort of locally measured conditions to increase security [20]. The same logic process applies to the sending end [20].

  Commonly applied transfer tripping schemes can be classified as follows.

  1. **Direct Underreaching Transfer Trip (DUTT) Scheme**: Figure 2.30 shows the logic circuit for the DUTT scheme. This scheme is simple and has high speed

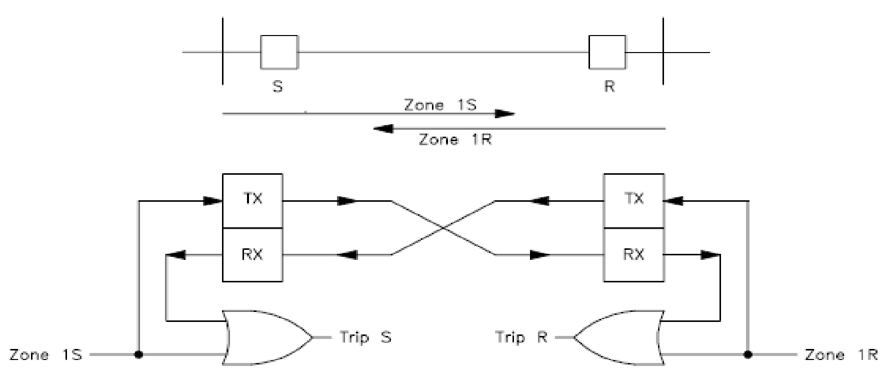



Figure 2.30: Logic Circuit for a DUTT Scheme
[19]

response to clear the fault because it uses zone 1 type information at either end, and the tripping signal will be sent directly to the other end. It does have potential for false trips.

2. **Permissive Underreaching Transfer Trip (PUTT) Scheme**: Figure 2.31 shows the logic circuit of a PUTT scheme. The basic concept for one implemen-

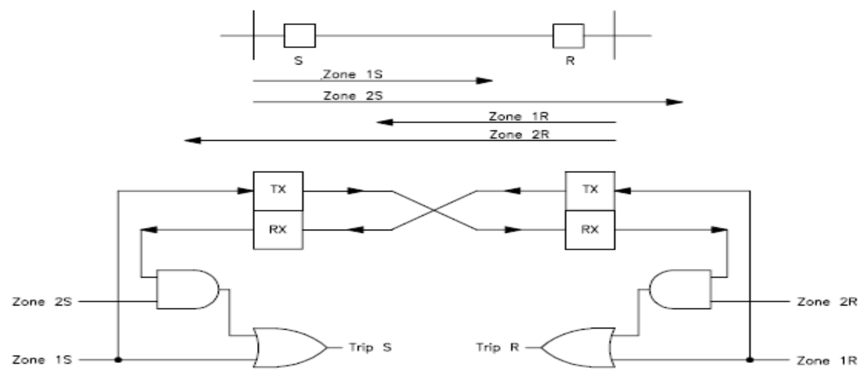



Figure 2.31: Logic Circuit for a PUTT Scheme
[19]

tation of the PUTT scheme is that if zone 1 of either end and zone 2 of the other end picks up through the communication channel, both breakers will trip. The local relay uses logic output information from the other to initiate a trip signal if its zone 1 element hasn't picked up and its zone 2 element has picked up.

3. **Permissive Overreaching Transfer Trip (POTT) Scheme**: Figure 2.32 shows the logic circuit of a POTT scheme. The POTT scheme uses the zone 2 type, such that if zone 2 elements pick up at one end, the relay will communicate to the relay at the other end with this information, and that relay will trip immediately if its zone 2 element has also picked up in zone 2. If both relays are picked up for this fault, both of them will initiate a trip signal with high speed delayed only by the channel delay [20]. An advantage of the POTT scheme is that it has a larger fault resistance coverage than a DUTT scheme because of use of zone 2 mho distance element with larger fault resistance coverage. For application with parallel lines, a reverse zone 3 for each relay can be added to the POTT scheme for more security [20].

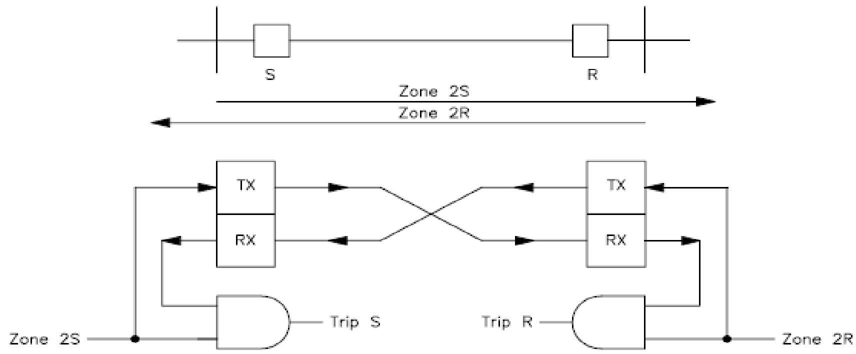



Figure 2.32: Logic Circuit for a POTT Scheme
[19]

#### 2.3.3.2 Blocking and Unblocking Schemes

In blocking and unblocking schemes, the command signal from the relay at the other end acts to block or to unblock a tripping decision for local relays. The commonly applied blocking and unblocking schemes can be classified into three types as described below.

1. **Directional Comparison Unblocking (DCUB) Scheme**: This scheme was developed for schemes using power line carrier communication, where a fault on a line can cause a loss of communication. There are two separate communication channels: the first one carries trip signals, and the second one carries a guard signal, as shown in Figure 2.33. The first communication channel with the trip signals works the same as

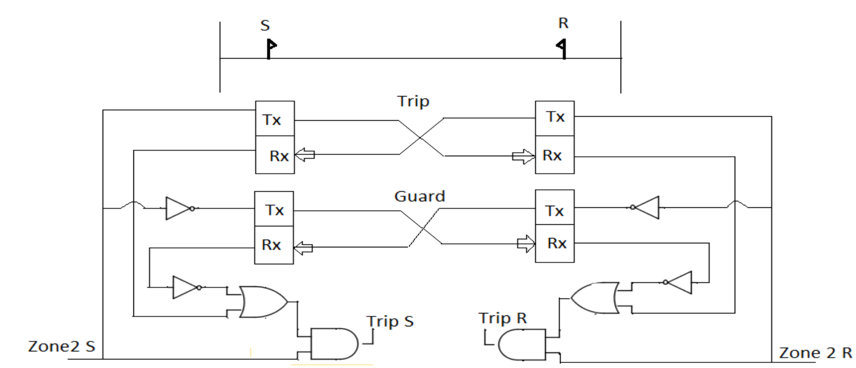



Figure 2.33: Logic Circuit for a DCUB Scheme

the POTT scheme. The second communication channel, the guard signal, will produce a logic 1 output in case of communication loss, such that the relay will treat the loss of guard as equivalent to trip signal from the other end [19].

2. **Directional Comparison Blocking (DCB) Scheme**: Figure 2.34 shows the logic circuit for a DCB scheme. The DCB scheme depends on communicating signals to block a trip at the relay at other end of the line. The relay has a reverse zone 3 element where the reach is set longer than the zone 2 reach of the remote end relay. The same condition applies to the remote end element. The logic status of each zone 3 element is communicated to the other end. The zone 3 element is used to block tripping for a reverse fault [20]. The local zone 2 element will not initiate a high speed trip if the it receives a signal from the remote end saying the fault is behind the relay as indicated by the zone 3 pick up.

   The DCB and POTT schemes are the most commonly applied communication aided distance schemes.

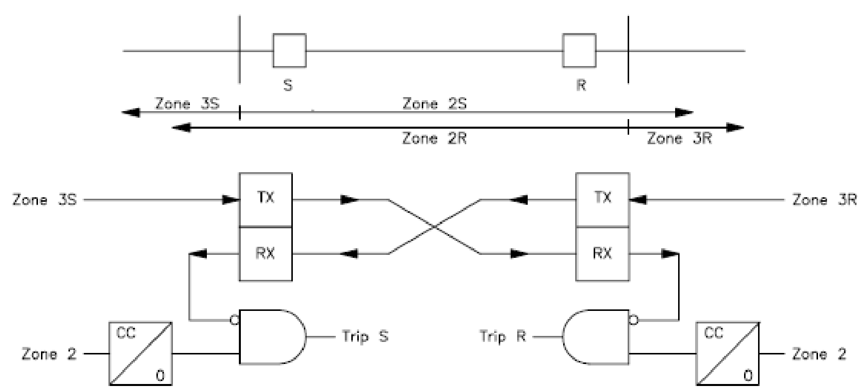



Figure 2.34: Logic Circuit for a DCB Scheme
[19]

### 2.3.4 Line Current Differential Protection

Modern line current differential schemes used in transmission line protection require relatively high bandwidth communication channels between the line ends to exchange a data to provide high speed response to clear the fault within the line. In a line current differential protection scheme, the local measured current information is transmitted through communication channels to the other relay at the other end to use this information to determine location of the fault (internal or external fault). The data are time aligned between the relays.

The first relay application of a differential type scheme was the phase comparison scheme, which was simple and needed less communication bandwidth. The communication channels sent the directional information of the phase currents. The basic idea of this scheme was that the measured currents at each end go through zero crossing detectors and then share this information between the relays at the line terminals to compare this information and determine if the fault was internal or external [50].

The most commonly used options to implement true line differential protection with microprocessor relays are: current restrained differential schemes and current ratio schemes.

#### 2.3.4.1 Current Restrained Differential Scheme

For full digital communication, each relay transmits phasor currents ($I_A$, $I_B$, and $I_C$) as magnitude and angle for each phase, and then each relay time synchronizes the data and calculates the operating and restraint quantities. For a two-terminal line, the operating quantity $I_{op}$ is equal to the magnitude of the phasor sum of the currents (the sending end current $I_S$ and the remote end current $I_R$ for each phase) as shown in (2.14).

$$I_{OT} = |\overline{I_S} + \overline{I_R}| \tag{2.14}$$

One option for the restraint quantity is to use the sum of the magnitudes of the currents (sending and remote end currents) as seen in (2.15). The operating current is compered to a restraint current for the trip decision.

$$I_{RT} = |I_S| + |I_R| \tag{2.15}$$

A characteristic slope can be set relating the operating quantity to the restraint quantity, scaled by a ratio, along with a minimum operating quantity. The minimum operating current, $I_{opmin}$ is set above the charging current, and the slope of the characteristic compensates for CT error and CT saturation. Figure 2.35 shows the characteristic slope of a current restrained differential scheme [51].

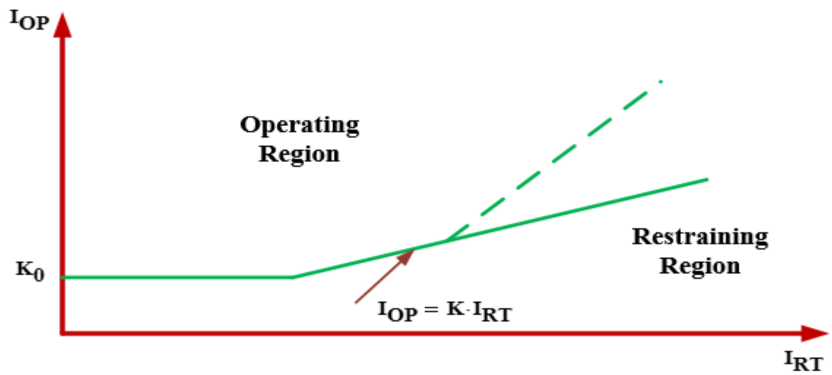



Figure 2.35: The Characteristic Slope of a Current Restrained Differential Scheme

#### 2.3.4.2 Current Ratio ($\alpha$-plane) Based Scheme

The alpha-plane scheme can be applied by using phasor calculations of the ratio between the sending end current and the remote end current to get $\alpha$ as a phasor quantity as shown in (2.16).

$$\alpha = \frac{I_{Remote}}{I_{Source}} \tag{2.16}$$

Figure 2.36 shows the characteristic of $\alpha$-plane scheme used in the SEL-311L, SEL-387L and SEL-411L relays. An internal fault will fall in the trip region, which is the right side of the $\alpha$-plane. The outer radius of the trip region is determined by setting 87LR. Load current or external fault will fall in the restraint region which is the left side of the $\alpha$-plane. The left side of the $\alpha$-plane contains $1 \angle 180^o$ point. The angular length of the restraint region is determined by setting 87LANG (based on maximum alpha-plane angle for an external fault) [51]. This scheme is better than the current restrained scheme because it has a more precise operating region. Also it can operate correctly for extreme cases like current inversion phenomenon, which will be described in Section 2.4.3.

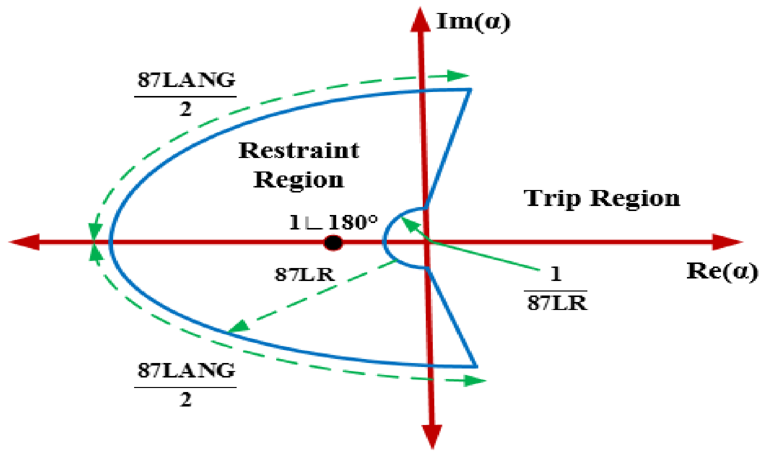



Figure 2.36: Alpha Plane Line Current Differential Element Characteristic

## 2.4 Challenges for Setting Protective Relay with Conventional Series Line Compensation

In power systems, series compensation can be used for different purposes such as [52]:

- Increasing power transfer capability (capacitive compensation)
- Improving transient stability (capacitive compensation)
- Reducing transmission losses (capacitive or inductive compensation)
- Routing the power flow (inductive or capacitive compensation)

The most commonly used series compensation solution for increasing power transfer and improving system stability in series capacitor compensation. Many papers have demonstrated the impact of a series capacitor on the transmission line protection system and recommended solutions [53], [54], [55]. Later in this dissertation, response of D-FACTS devices to disturbances will be examined, along with how the behavior of these devices differ from conventional series compensation.

The use of series capacitor compensation in a transmission system may lead to certain issues for the protection system [53]. Variation in the series compensation causes variation in the effective line parameters and this can affect the settings needed for a conventional protective relay scheme. Changes in series compensation can change the estimated impedance seen by the distance elements and in some cases, capacitive series compensation impacts directional supervision elements because of voltage inversion or current inversion [54], [55].

### 2.4.1 Change in Apparent Impedance

The variation in the measured impedance due to the change in the level of series compensation can cause mal-operation and unwanted tripping by causing underreach or overreach for distance relays which are set based a single level of compensation. To illustrate this situation, Figure 2.37 shows simple transmission line with midpoint series capacitor compensation.

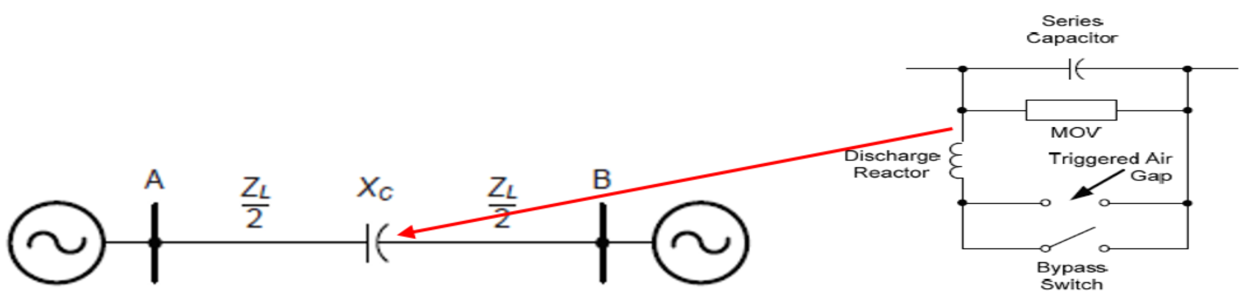



Figure 2.37: Simple Transmission Line with Midpoint Series Capacitor Compensation [56]

The self-protection system for the series capacitor compensation consists of a metal oxide varistor (MOV) to protect the series capacitor from overvoltage. The installation also includes a bypass switch to bypass the series capacitor when the energy ratting of the MOV exceeds a certain threshold. The gap is fired first since it has faster response and then the bypass breaker is triggered at the same time.

The self-protection system for the series capacitor compensation works well for large fault currents, and it will operate at bypass mode to protect the series capacitor from high voltage. For a case where the fault current is low due to remote faults or cases where the fault resistance is high, the series capacitor continues to be part of the line because the voltage across the metal oxide varistor (MOV) is below the bypass threshold. The distance elements at bus A will face an error in the measured impedance. The presence of series capacitor can cause overreaching of distance elements. Figure 2.38 shows the effect on the effective impedance for faults beyond the protection zones with the capacitor inserted and with it bypassed.

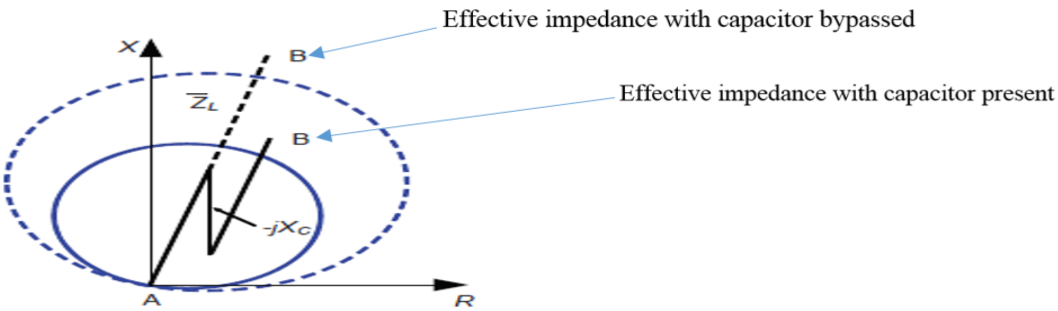



Figure 2.38: Variation in the Protection Zones Due to the Presence of a Series Capacitor on Line AB

[56]

Distance elements on series compensated lines are set based on the amount of series compensation, often with short zone 1 reach settings. Communication-aided schemes are very import in these cases.

### 2.4.2 Voltage Inversion with Series Capacitor

In the presence of series compensation, voltage inversion phenomenon can occur if the net impedance from the relay location to the fault position is a net capacitive reactance. This is more likely to happen if the series capacitor location is at either end of the line rather than at the midpoint. With the source impedance included, the net impedance in the fault current path is usually still an inductive reactance. The current that be seen by the relay is given in equation (2.17) with resistance neglected.

$$I_R = \frac{V_S}{j(X_S + mX_L - X_C)} \tag{2.17}$$

Figure 2.39 shows two sources, which are connected through a compensated transmission line, with the phasor diagram of this line at the bottom.

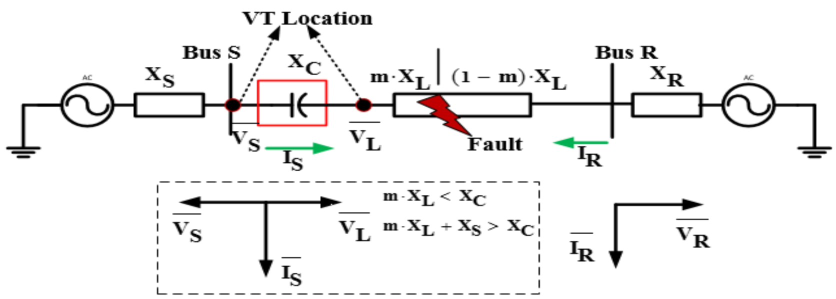



Figure 2.39: Voltage Inversion Condition in the Presence of Series Capacitor Compensation Along with the Phasor Diagram of Voltages and Currents at Bus S and Bus R for a Forward Fault

For a forward fault, if the capacitive reactance ($X_C$) is bigger than the inductive reactance ($mX_L$) from the relay to the fault point, the voltage in the bus side of the capacitor will be negative and the voltage on the line side of the capacitor will be positive. In this case, as long as the voltage transformer is located on the line side, the directional supervision element will respond correctly for a forward fault. But it could respond incorrectly for a close-in fault in the reverse zone because of the voltage inversion. On the other hand, if the voltage transformer is located on the bus side of the capacitor, the directional elements may respond incorrectly for a close-in forward fault and correctly for the fault in the reverse zone which is in the adjacent line. As a result, voltage inversion conditions can cause problems for the directional supervision element [56], [57]. Modern protection relays often use memory polarization which provides security against the voltage inversion.

### 2.4.3 Current Inversion with Series Capacitor

Current inversion can occur in the unlikely case that the net impedance from the voltage source to the fault location has an effective capacitive reactance (the imaginary part of the source impedance plus the imaginary part of the line impedance to the fault point is less than the capacitive reactance) as shown in equation (2.18).

$$X_S + mX_L < X_C \tag{2.18}$$

Figure 2.40 shows the current inversion condition in the presence of series capacitor compensation with phase diagram of voltages and currents at bus S and bus R.

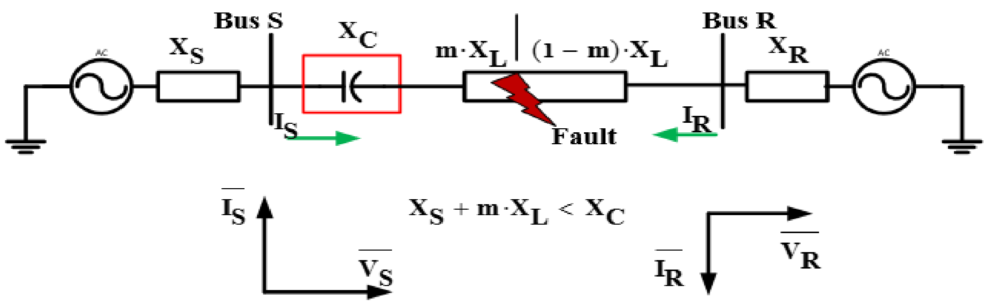



Figure 2.40: Current Inversion Condition in Presence of Series Capacitor Compensation Along with the Phasor Diagram of Voltages and Currents at Bus S and Bus R

The fault current path has a net capacitive effect that makes line side voltage transformer see an opposite polarity for the forward fault, and the CT current will lead the bus side voltage by 90°. The bus voltage will have the correct positive polarity for forward fault but the line side voltage will have negative polarity and it has a small magnitude compered to the bus side voltage. The fault current will be in an opposite direction of the load flow.

The bus side voltage transformer will incorrectly see the forward fault as reverse a fault. On the other hand, the line side voltage transformer will see the inverted voltage (negative voltage), but when it combines with the inverted current, the directional element will see the correct relationship and identify the fault as a forward fault [57]. Current inversion is very rare since stiff systems do not generally need series capacitors. Current inversion will have a very short duration before the MOV and the self-protection for the series capacitor will conduct.

## 2.5 Summary

This chapter provides background information related to the major topics of this research. These topics include the power flow controller devices, distributed flexible AC transmission system devices (D-FACTS), and basic protection functions of transmission protective schemes. Also this chapter shows the general challenges for setting protective relays for conventional series compensation, especially with series capacitors.

The most commonly used protection elements in transmission systems that may be impacted by D-FACTS implementation are distance elements, directional elements, POTT schemes, and line current differential elements. The essential task of the distance elements is to determine the actual impedance between the relay location and the fault point. Based on the measured voltages and the currents, the actual impedance is calculated inside the relay to be able to determine the approximate fault location.

The series capacitor compensation is the most popular solution to increase the power transfer and improve system stability. Practically, the use of this type of series compensation in transmission system may lead to certain issues for transmission line protection system such as change in the apparent impedance or inaccurate operation of directional supervisor elements because of voltage inversion or current inversion.

# CHAPTER 3

# Study System Configurations

## 3.1 Study System

Figure 3.1 shows a schematic diagram of the example 230 kV system that will be the basis of this study. This system is used in this dissertation to perform a comprehensive study on the impact of D-FACTS devices on common transmission line protection systems. It consists of six buses, six transmission lines, and two sources. All are at 230kV [58]. The tower configurations for the transmission lines is implemented as described in [22].

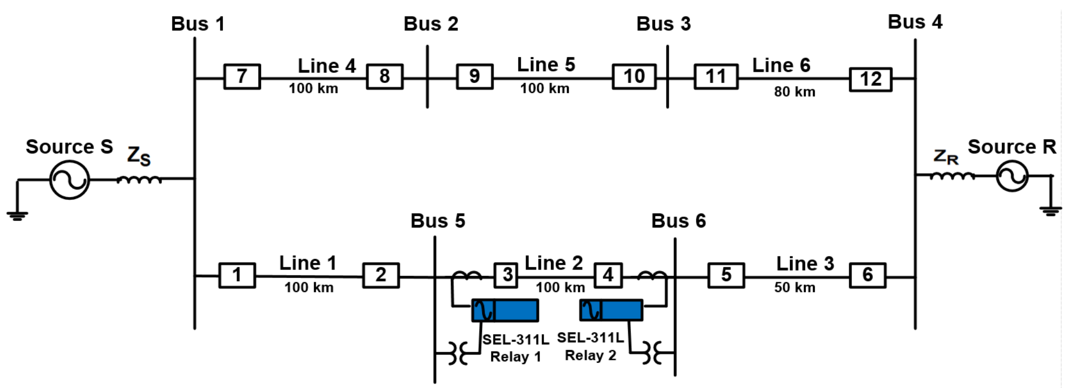



Figure 3.1: Single-Line Diagram of 230 kV Six-Bus System

The system elements are modeled in ATP as follows. The sending source and the receiving source are modeled as voltage sources behind source impedances [58]. Next, each transmission line is modeled as a constant parameter distributed line using Bergeron's model. The geometrical and structural parameters for the transmission lines are as shown in Tables A.1, A.2, and A.3 in Appendix A and Figure 3.2. All lines in this system share the same geometrical and structural parameters, except their lengths, which are different [59], as shown in Table 3.1. The system data that will be used for setting the protective relays for transmission line 2 are summarized in Table 3.2.

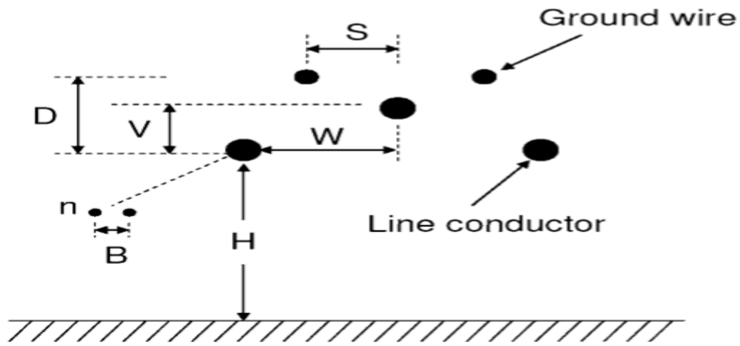



Figure 3.2: Tower Structure for the Transmission Lines Used in the System [59]

Table 3.1: Line Lengths for Study System

| ***Line number*** | ***Length (km)*** |
|---|---|
| Line 1 | 100 |
| Line 2 | 100 |
| Line 3 | 50 |
| Line 4 | 100 |
| Line 5 | 100 |
| Line 6 | 80 |

Table 3.2: Lists of the 230KV System Parameters

| ***Parameter*** | ***Value*** |
|---|---|
| Nominal system line-to-line voltage | 230 KV |
| Nominal relay secondary current | 5 A secondary |
| Nominal frequency | 60 Hz |
| Line 2 length | 100 miles |
| Line 2 positive sequence impedance $Z_{1L}$ | $77.98\angle 82.7° \ \Omega$ |
| Line 2 zero sequence impedance $Z_{0L}$ | $180.98\angle 69.817° \ \Omega$ |
| Source S positive sequence impedance $Z_{1S}$ | $17.95\angle 87.67° \ \Omega$ |
| Source S zero sequence impedance $Z_{0S}$ | $14.99\angle 80.86° \ \Omega$ |
| Source R positive sequence impedance $Z_{1R}$ | $3.80\angle 87.69° \ \Omega$ |
| Source R zero sequence impedance $Z_{0R}$ | $6.02\angle 80.9° \ \Omega$ |
| Line 2 PTR (potential transformer ratio) | 230 kV:115 V=2000 |
| Line 2 CTR (current transformer ratio) | 500:5=100 |
| Phase rotation | ABC |

## 3.2 Relay Settings for Line 2

In this study, SEL-311L relays are used to protect line 2. As shown in Table 3.2, the CTRs ratio of line 2 are 100, and the PTRs ratio of this line are 2000, therefore conversion factor (K) calculated from equation (3.1) is.

$$K = \frac{CTR}{PTR} = \frac{100}{2000} = 0.05 \tag{3.1}$$

The line impedance ($Z_L$) referred to the secondary side of the CTs and PTs can be calculated using equation (3.2).

$$Z_{L(secondary)} = K * Z_{L(primary)} \tag{3.2}$$

The zero sequence current compensation factor ($k_0$) is calculated using equation (3.3).

$$k_0 = \frac{Z_{L0} - Z_{L1}}{3 * Z_{L1}} \tag{3.3}$$

Based on the configuration process described in [60], the SEL-311L settings are summarized in Table B.1 in Appendix B.

## 3.3 The Data Collection Process

Different percentages of compensation using inductive D-FACTS devices are used to reduce the load on line 2 in Figure 3.1 and push the power to flow into the parallel lines. The data collection process of this work can be illustrated by the following steps as shown in Figure 3.3.

The steps can be summarized as follows:

- Simulating the study system in ATP

1. Running the simulation in ATP for each case after building the model of the

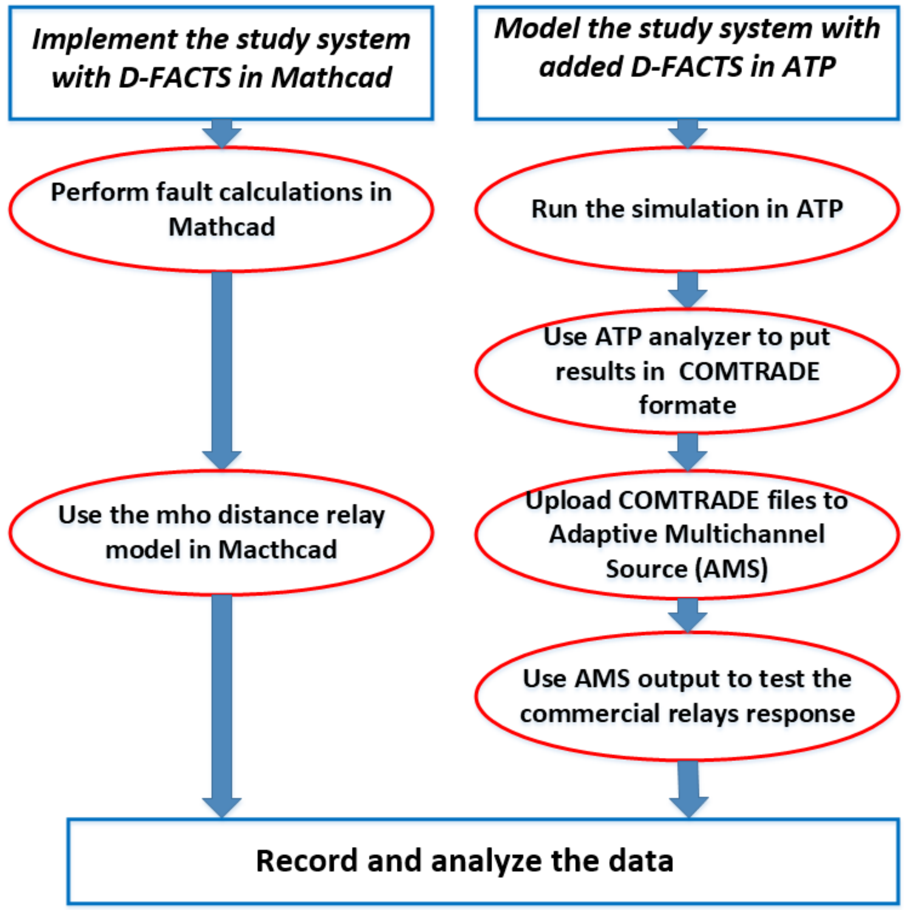



Figure 3.3: Data Collection and Analysis Process Steps

study system with D-FACTS devices added in order to perform fault analysis. Faults are applied in 10% distance increments on line 2 to cover zone 1 and zone 2 reach settings from both ends of the line, with different percentages of series compensation using D-FACTS devices.

2. Use ATP analyzer to convert the ATP simulation output data to the IEEE C37.111.1991 COMTRADE format [61]. ATP analyzer was written to help protection engineers conduct a protection analysis to test protective relays (the response of settings).

3. Using the SEL-5401 system test software to upload the COMTRADE format files from ATP simulation and converting them to an appropriate format for use in the SEL-AMS (Adaptive Multichannel Source) [61].

4. Using the SEL-AMS to playback the simulation results into the SEL-311L relays to study the resilience of the protection system response [61].
5. Record and analyze the results of the resilience evaluation give a better visualization of the performance evaluation results of the protection schemes.

- Implementing the study system with D-FACTS in $MathCAD^{®}$ software for phasor domain analysis.

1. Performing a fault study (fault calculation) for the study system with different percentages of D-FACTS compensation.
2. Evaluate the response of the protection elements of line 2 using a Mho distance relay model in $MathCAD^{®}$.

# CHAPTER 4

# Modeling and Validation of D-FACTS Devices

This chapter contains a paper that was published in the Proceedings of the 2017 North American Power Symposium [21]. The copyright permission is shown in Appendix K.

## 4.1 Introduction

Electric power is delivered to consumers from geographically dispersed generation plants through transmission and distribution systems. The electrical power that flows via the transmission and distribution lines includes real and reactive power. During the last decade, the demand in electrical power continued to increase in most cases. Many renewable energy resources such as wind and solar power have been connected to the transmission system. The traditional flow of electrical power from generation plants directly to the customers does not exist anymore. These factors are adding more complexity to power systems and due to that, new capable technologies have been developed to solve the power flow challenges [26]. In cases where fast acting devices are needed to dynamically control the power flow in the transmission systems and improve the stability of the power system, different types of Flexible AC transmission system (FACTS) devices, such as Static Synchronous Compensation (STATCOMs), Static Synchronous Series Compensation (SSSC), and the Unified Power Flow Controller UPFC, have been proposed and implemented to solve dynamic issues. At the same time, the perception of somewhat low reliability and the high capital costs for FACTS devices limits their penetration into the power system. Series connected Distributed Flexible AC Transmission System (D-FACTS) devices offer the possibility of addressing some of these concerns by presenting a distributed solution for congestion management in the power system at low cost and better reliability. This can help to avoid the cost, delay and environmental issues of building a new transmission lines [38].

The D-FACTS concept was first proposed in [38] . D-FACTS devices are power electronics based devices and offer the ability to manage the congestion in the power system by controlling the power flow for existing transmission lines. This can be done by increasing the line impedance of an overloaded line to force the current to flow to the lines with larger available capacity. D-FACTS devices provide potential benefits to the power system such as reducing the power flow through the overhead line, minimizing losses and operation cost, improve the system stability and control system voltage. In addition, according to [12], some electrical utilities have been started to install these devices in their overhead lines. The D-FACTS devices clamp on the transmission line and they are single phase devices, as shown in Figure 4.1, where the D-FACTS devices distributed over the length of the transmission line [12]. Relatively small devices can be placed on multiple locations in a given line.

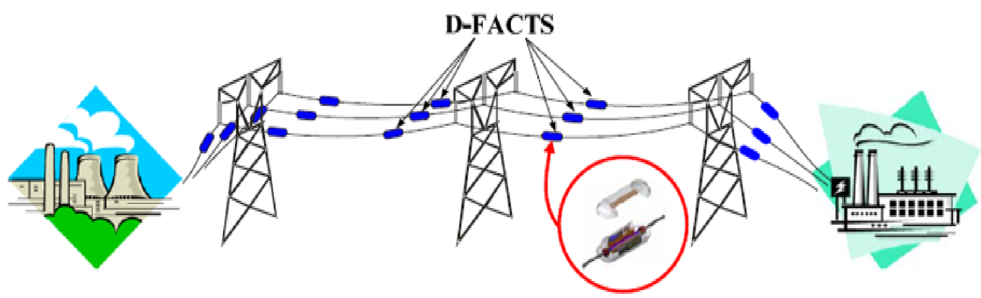



Figure 4.1: Installing the D-FACTS Devices on Transmission Line

Figure 4.2 shows the basic circuit of a single phase inductive D-FACTS device and known as a Distributed Series Reactor (DSR) [38] .The set of DSRs on a line can insert a variable series inductive reactance in the line. In normal operation, the switch $S_M$ is closed and the inserted reactance is zero. When the switch $S_M$ is open the inserted reactance is equal to the magnetizing inductance. The magnetizing inductance can be designed to match the desired value of series compensation, but in practice is set to standard values to allow mass production of modules. The thyristor switches in Figure 4.2 are used for a quick bypass for this device under disturbances [43].

When line current exceeds the threshold in a line, the DSR devices start to switch on to force the current to flow into the alternate paths [43]. Other types of D-FACTS devices can be used in a capacitive or an inductive mode.

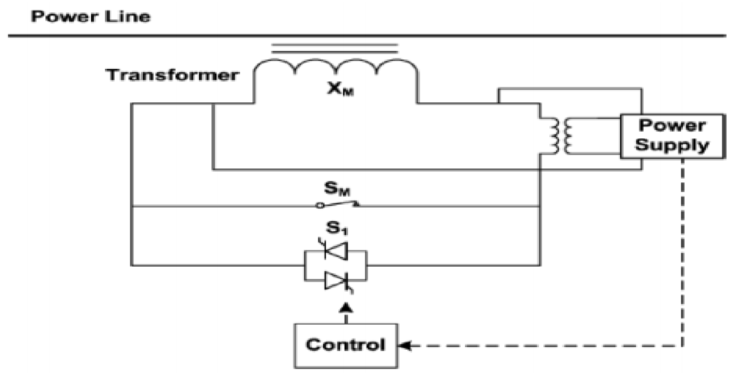



Figure 4.2: Reproduced From [2], Shows the Basic Circuit of Distributed Series Reactor (DSR)

Power systems are simulated using a variety of simulation tools, each geared toward different applications. By using various software tools to compare the results of the power flow simulation for the power system model, it is possible to judge if this model is accurate or not for validation and further study. The validation of the power system model is very important in order to get a reliable model because each simulation tool has a different configuration and its own strengths and weaknesses [62]. The transient simulation program models developed in this chapter will later be used in this dissertation for protection studies and system dynamic response studies.

Through use of the IEEE12 bus test system, this work builds a simulation model in two simulation tools: PowerWorld simulator and Alternative Transients Program (ATP), to compare the power flow results for this system before and after the addition of D-FACTS devices. The work demonstrates a comparison of the magnitudes and angles of bus voltages and real and reactive power flows in this system.

The IEEE 12 bus system information (study system) is described as well as its modeling in both tools. The work studies the power flow results of these two models to validate and compare the ATP model against the PowerWorld model in three cases: without D-FACTS devices, adding inductive devices, and adding capacitive devices to manage congestion to verify the accuracy of the ATP model for later studies.

Section 4.2 describes the D-FACTS modelling, then Section 4.3 describes the IEEE 12 bus test system. Section 4.4 presents the results from the case studies and the impact of these cases in some scenarios of losing lines. Section 4.5 has conclusions.

## 4.2 D-FACTS Device Models

### 4.2.1 PowerWorld Model

There is an existing D-FACTS device model in PowerWorld which can be used on an inductive or a capacitive mode for congestion management. In the PowerWorld model, the D-FACTS devices can be added on transmission line as a lumped device (representing all these devices at a given iteration). The inserting series impedance can be controlled based on the line current. The number of devices varies to achieve the set point goal within limits on the maximum number of devices. This single model is associated with a line and is set through a D-FACTS dialog window, where the user determines some characteristics such as an inductance or a capacitance value for each single phase module, the maximum number of modules, and the maximum $I_{lim}$ and minimum $I_0$ operating current thresholds as shown in Figure 4.3 [63].

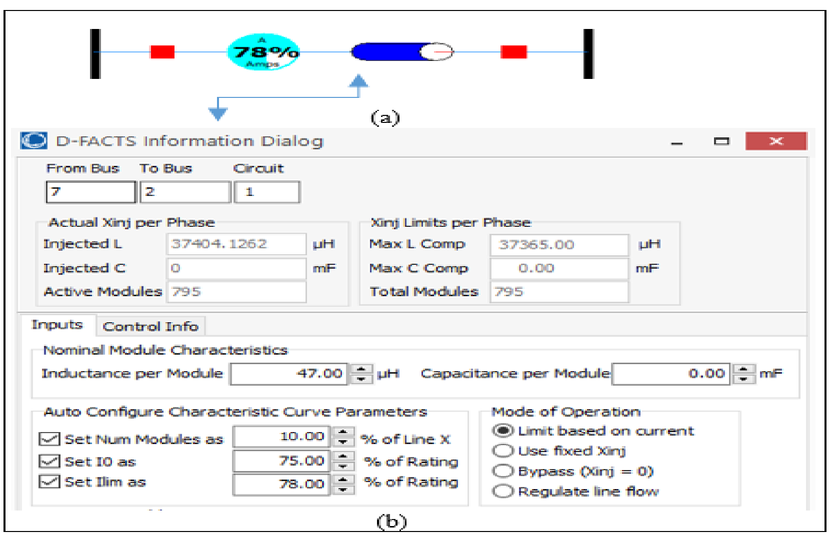



Figure 4.3: Powerworld D-FACTS Model: (a) The Single D-FACTS Module (b) D-FACTS Information Dialog

[63]

### 4.2.2 D-FACTS Model in ATP

The D-FACTS devices are modeled in ATP to represent the behavior of the existing modules. The inductive D-FACTS devices are modeled as a reactor with a control circuit, as shown in Figure 4.4.

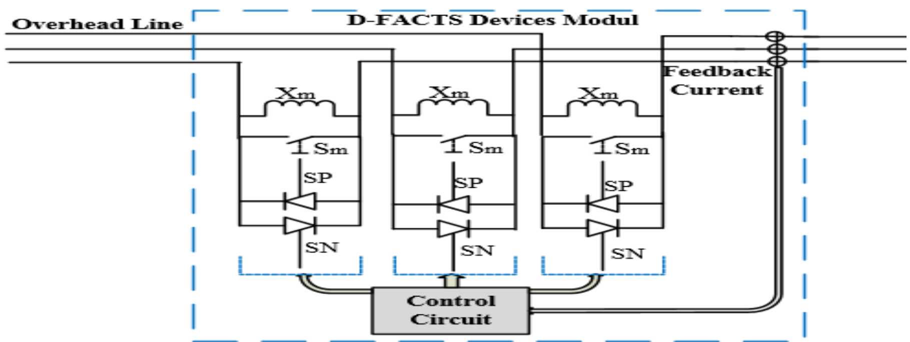



Figure 4.4: Three Phase D-FACTS Devices Module in ATP

The design of the control circuit is done based on the published operating principles of these devices [38], [64], which is to control the power flow in the line by inserting positive or negative reactance (for devices with that capability) based on the line current. If the line current is less than the setting value of the minimum operating current (normal operation), the switch Sm remains on to bypass the series reactor. On the other hand, if the line current exceeds the setting of the minimum operating current, the control circuit will open switch $S_m$ to insert the reactor as a part of the line circuit path. Figure 4.5 shows the current in line 1-6 with five D-FACTS models in Figure 4.4 versus the output reactance of these models. The inductance of each phase is chosen to match the values used in the PowerWorld module, which is the desired value of the series compensation. Also, this model has ability to bypass and protect itself under disturbances if the line current exceeds an over current setting threshold, and this is done by controlling the thyristor switches SP and SN.

The capative D-FACTS devices are modeled in ATP by making the model in Figure 4.4 inserting a capacitive reactance into transmission line.

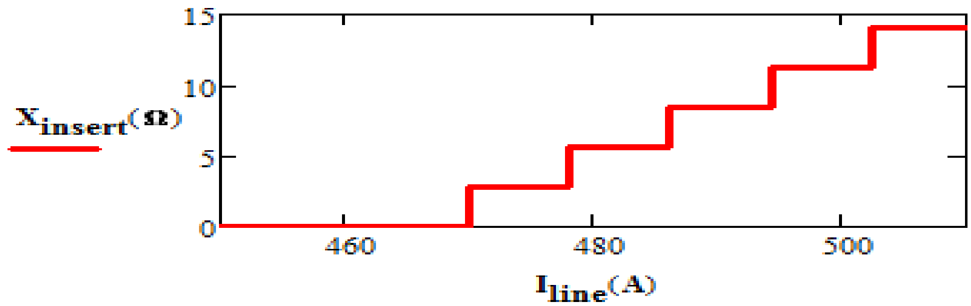



Figure 4.5: Operation Profile of a Line With 5 D-FACTS Modules in ATP

## 4.3 Study System

### 4.3.1 The IEEE 12 Bus System

Figure 4.6 shows the schematic diagram of the IEEE12 bus power system. This power system contains twelve buses, seven transmission lines, five loads, three capacitive shunt compensation elements, three hydroelectric synchronous generators, and an infinite bus, which represents the main network. There are three voltage levels in this system: 22 kV, 230 kV and 345 kV [22]. More detail about the IEEE 12 bus power system data are illustrated in the Appendix A (Tables A.1, A.2, A.3) as well as in [59]. Previous power flow studies for this system show that overloading of line 1-6 can occur under some circumstances such as losing line 4-5 or losing generation [59].

### 4.3.2 Model Implementation in PowerWorld and in ATP

The system elements are modeled in PowerWorld and ATP as follows: first the generators (G2, G3 and G4) are modeled in both software tools as hydraulic turbine synchronous machines, which are controlled by IEEE type AC4A excitation systems [65] and turbine governor systems (HYGOV Model)[66]. The G1 generator is modeled in the main network by connecting it as a slack bus in the power flow model. Next, each transmission line is modeled as a lumped parameters RLC pi equivalent circuit. Third, each transformer is modeled as two windings with leakage reactance. Finally, each load and shunt compensation is modeled as constant real and reactive power for PowerWorld and as corresponding parallel RLC circuits for ATP.

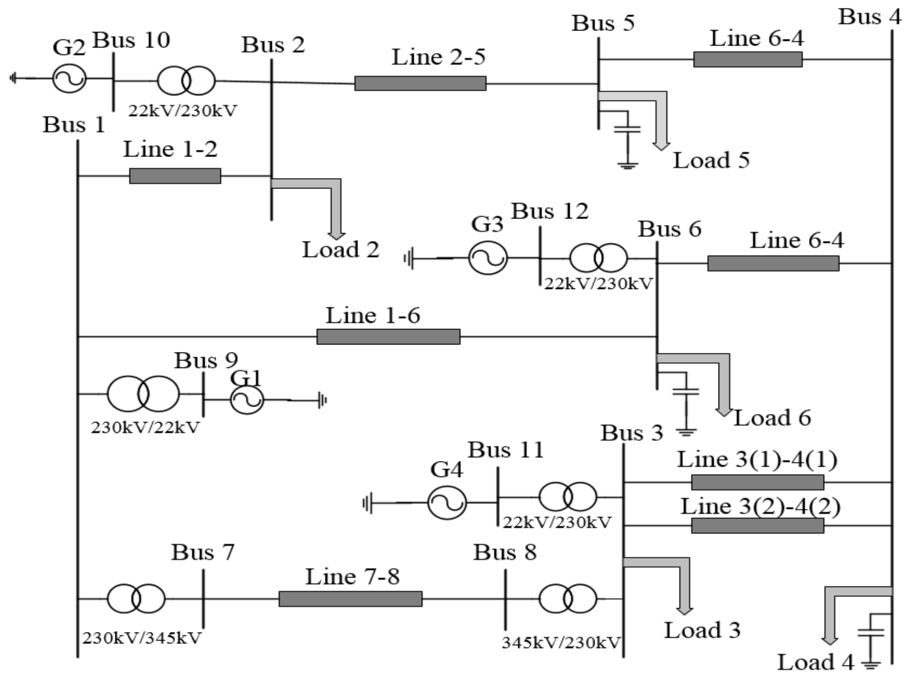



Figure 4.6: Single Line Diagram of the IEEE 12-Bus Power System

## 4.4 Case Study

### 4.4.1 List of Studies

Comparison of power flow results for the IEEE12 bus system is accomplished by using PowerWorld (which used Newton's method to solve the power flow with default tolerances) and ATP (which solved equations using the Trapezoidal rule integration method in time domain to solve the system equations at each time step) for three case studies as follows:

Case 1) the IEEE12 bus system before adding D-FACTS devices;

Case 2) the same system after adding inductive D-FACTS devices to line 1-6;

Case 3) the same system after adding capacitive D-FACTS devices to line 7-8;

### 4.4.2 Case 1: Without D-FACTS Devices

This part represents the comparison between the power flow results for ATP against PowerWorld to validate the ATP model as shown in Table 4.1 and Table 4.2 without D-FACTS devices.

Table 4.1: Comparison of Magnitude and Angle of Bus Voltage for Case 1

| Bus Name | Voltage Level KV | PowerWorld | | ATP | | Difference | |
|---|---|---|---|---|---|---|---|
| | | $\|V\|$ *(pu)* | $\delta(\theta)^\circ$ | $\|V\|$ *(pu)* | $\delta(\theta)^\circ$ | $\|V\|$ *(pu)* | $\delta(\theta)^\circ$ |
| Bus 1 | 230 | 1.041 | 27.3 | 1.041 | 27.4 | 0.00 | -0.1 |
| Bus 2 | 230 | 1.003 | 29.123 | 1.003 | 29.2 | 0.00 | -0.077 |
| Bus 3 | 230 | 0.988 | -8.286 | 0.988 | -8.23 | 0.00 | -0.056 |
| Bus 4 | 230 | 0.956 | -13.436 | 0.956 | -13.38 | 0.00 | -0.065 |
| Bus 5 | 230 | 0.979 | -0.954 | 0.979 | -0.89 | 0.00 | -0.064 |
| Bus 6 | 230 | 0.989 | -4.574 | 0.989 | -4.51 | 0.00 | -0.064 |
| Bus 7 | 345 | 1.048 | 25.566 | 1.048 | 25.6 | 0.00 | -0.034 |
| Bus 8 | 345 | 0.995 | -6.462 | 0.995 | -6.4 | 0.00 | -0.062 |
| Bus9 | 22 | 1.04 | 0.00 | 1.04 | 0.07 | 0.00 | -0.07 |
| Bus10 | 22 | 1.02 | 1.923 | 1.02 | 1.99 | 0.00 | -0.067 |
| Bus11 | 22 | 1.01 | -37.137 | 1.01 | -37.09 | 0.00 | -0.047 |
| Bus12 | 22 | 1.02 | -31.16 | 1.02 | -31.11 | 0.00 | -0.05 |

Table 4.2: Comparison of Real Power (P) and Reactive Power (Q) for Case 1

| From Bus | To Bus | PowerWorld | | ATP | | %Difference | |
|---|---|---|---|---|---|---|---|
| | | *P MW* | *Q Mvar* | *P MW* | *Q Mvar* | *P %DIF* | *P %DIF* |
| 1 | 2 | -30.59 | 36.85 | -30.52 | 36.81 | 0.229 | 0.0109 |
| 1 | 6 | 210.42 | 21.69 | 210.4 | 21.678 | 0.01 | 0.055 |
| 2 | 5 | 189.07 | 7.176 | 189.1 | 7.141 | 0.016 | 0.489 |
| 3-1 | 4-1 | 96.46 | 17.99 | 96.43 | 17.945 | 0.031 | 0.25 |
| 3-2 | 4-2 | 96.46 | 17.99 | 96.43 | 17.945 | 0.031 | 0.25 |
| 5 | 4 | 76.74 | -19.58 | 76.77 | -19.59 | 0.039 | 0.082 |
| 6 | 4 | 55.86 | -17.58 | 55.90 | -17.62 | 0.072 | 0.233 |
| 7 | 8 | 330.01 | -86.36 | 330.1 | -86.34 | 0.027 | 0.02 |
| 9 -G1 | 1 | 509.83 | 6.808 | 510 | 6.797 | 0.033 | 0.162 |
| 10-G2 | 2 | 500.00 | 181.05 | 499.9 | 181.04 | 0.02 | 0.006 |
| 12-G3 | 6 | 300.00 | 165.54 | 300.0 | 165.51 | 0.00 | 0.018 |
| 11-G4 | 3 | 200.00 | 222.97 | 200.01 | 222.93 | 0.005 | 0.018 |

This comparison validates the ATP model of IEEE12 bus system against the PowerWorld model. The power flow results of two models are closely match each other in the magnitude of the bus voltages with percentage difference less than 0.0005%. However, there is a small difference in the voltage angle measured at each bus. Also, there are small difference in real power and reactive power measured in each transmission line.

### 4.4.3 Case 2: Adding Inductive D-FACTS Devices to Line 1-6

This part describes the comparison of the power flow results for ATP against PowerWorld after adding inductive D-FACTS devices to line 1-6. The main goal is to validate the new D-FACTS model in ATP, and to show the impact of these devices on relieving the congestion in line 1-6 as shown in Table 4.3 and Table 4.4. D-FACTS devices are an inductive mode with a total D-FACTS reactance that is 10% of the line impedance (14.101 Ω) as it calculated in Appendix C.

Table 4.3: Comparison of Magnitude and Angle of Bus Voltage for Case 2

| Bus Name | Voltage Level KV | PowerWorld | | ATP | | Difference | |
|---|---|---|---|---|---|---|---|
| | | $\lvert V\rvert$ (pu) | $\delta(\theta)^\circ$ | $\lvert V\rvert$ (pu) | $\delta(\theta)^\circ$ | $\lvert V\rvert$ (pu) | $\delta(\theta)^\circ$ |
| Bus 1 | 230 | 1.04 | 27.297 | 1.04 | 27.4 | 0.00 | -0.103 |
| Bus 2 | 230 | 1.003 | 29.021 | 1.003 | 29.1 | 0.00 | -0.079 |
| Bus 3 | 230 | 0.987 | -9.095 | 0.987 | -9.04 | 0.00 | 0.055 |
| Bus 4 | 230 | 0.955 | -14.404 | 0.955 | -14.35 | 0.00 | 0.054 |
| Bus 5 | 230 | 0.974 | -1.536 | 0.974 | -1.47 | 0.00 | 0.066 |
| Bus 6 | 230 | 0.989 | -6.697 | 0.989 | 6.62 | 0.00 | 0.077 |
| Bus 7 | 345 | 1.047 | 25.528 | 1.047 | 25.6 | 0.00 | 0.072 |
| Bus 8 | 345 | 0.994 | -7.236 | 0.994 | -7.18 | 0.00 | 0.056 |
| Bus9 | 22 | 1.04 | 0.00 | 1.04 | 0.07 | 0.00 | -0.07 |
| Bus10 | 22 | 1.02 | 1.822 | 1.02 | 1.89 | 0.00 | -0.068 |
| Bus11 | 22 | 1.01 | -37.946 | 1.01 | -37.9 | 0.00 | 0.046 |
| Bus12 | 22 | 1.02 | -33.29 | 1.02 | -33.22 | 0.00 | 0.07 |

The power flow results of the two models are very similar. This comparative study validates the new inductive D-FACTS devices module in ATP against the existing D-FACTS devices model in the PowerWorld. However, there are small differences in voltage angle measured at each bus as shown in the last column of table 4.3. Also, the values of the percentage difference of real power and reactive power measured in each transmission line shows that the error is very small. Also the results from cases 1 and 2 indicate that adding

Table 4.4: Comparison of Real Power (P) and Reactive Power (Q) for Case 2

| From Bus | To Bus | PowerWorld | | ATP | | %Difference | |
|---|---|---|---|---|---|---|---|
| | | *P MW* | *Q Mvar* | *P MW* | *Q Mvar* | *P %DIF* | *Q %DIF* |
| 1 | 2 | -28.64 | 36.196 | -28.60 | 36.2 | 0.14 | 0.011 |
| 1 | 6 | 202.39 | 24.797 | 202.37 | 24.786 | 0.01 | 0.044 |
| 2 | 5 | 191.04 | 10.007 | 191.07 | 9.9777 | 0.016 | 0.293 |
| 3-1 | 4-1 | 99.194 | 18.708 | 99.16 | 18.664 | 0.034 | 0.235 |
| 3-2 | 4-2 | 99.194 | 18.708 | 99.16 | 18.664 | 0.034 | 0.235 |
| 5 | 4 | 78.391 | -20.44 | 78.406 | -20.46 | 0.019 | 0.098 |
| 6 | 4 | 48.746 | -17.26 | 48.82 | -17.31 | 0.152 | 0.289 |
| 7 | 8 | 336.21 | -82.55 | 336.3 | -82.56 | 0.027 | 0.012 |
| 9 -G1 | 1 | 509.95 | 13.425 | 510.05 | 13.428 | 0.02 | 0.022 |
| 10-G2 | 2 | 500.00 | 184.53 | 500 | 184.47 | 0.00 | 0.033 |
| 12-G3 | 6 | 300.00 | 166.56 | 300.13 | 166.59 | 0.043 | 0.018 |
| 11-G4 | 3 | 200.00 | 229.80 | 200.02 | 229.82 | 0.01 | 0.009 |

D-FACTS devices as an inductive reactant to the overloaded line 1-6 reduced the power flow through this line and push the power to flow in the other unloaded lines.

### 4.4.4 Case 3: Adding Capacitive D-FACTS Devices to Line 7-8

The next case added capacitive D-FACTS devices to line 7-8. The objective is to validate the capacitive D-FACTS devices model in ATP and to show the impact the capacitive D-FACTS devices on relieving the congestion in line 1-6 as shown in Table 4.5 and Table 4.6. To reduce the loading in line1-6 by the same amount in case 2, the desired capacitive reactance of D-FACTS devices is 21.086 Ω as calculated in Appendix C.

Like the results in case 2, the power flow results of two models are very similar. The comparative study of this case validates the capacitive D-FACTS model in ATP against the existing capacitive D-FACTS model in PowerWorld. It is shown that the steady state behavior of the two models are identical. By comparing the results from case 1 and 3, installing the D-FACTS devices as capacitive reactance in line 7-8 relieved the congestion in the loaded line (line 1-6) by pulling power to flow into this compensated line (line 7-8). Adding inductive D-FACTS device to line 1-6 (equal 14.101 Ω) does the same work of adding capacitive D-FACTS devices to line 7-8 (equal to 21.086 Ω).

Table 4.5: Comparison of Magnitude and Angle of Bus Voltage for Case 3

| Bus Name | Voltage Level KV | PowerWorld | | ATP | | Difference | |
|---|---|---|---|---|---|---|---|
| | | $\|V\|$ (pu) | $\delta(\theta)°$ | $\|V\|$ (pu) | $\delta(\theta)°$ | $\|V\|$ (pu) | $\delta(\theta)°$ |
| Bus 1 | 230 | 1.041 | 27.308 | 1.041 | 27.4 | 0.00 | -0.092 |
| Bus 2 | 230 | 1.004 | 29.376 | 1.004 | 29.4 | 0.00 | -0.024 |
| Bus 3 | 230 | 0.989 | -5.697 | 0.989 | -5.63 | 0.00 | 0.067 |
| Bus 4 | 230 | 0.959 | -11.12 | 0.959 | -11.06 | 0.00 | 0.061 |
| Bus 5 | 230 | 0.991 | 0.433 | 0.99 | 0.5 | 0.001 | -0.067 |
| Bus 6 | 230 | 0.991 | -3.299 | 0.99 | -3.24 | 0.001 | 0.059 |
| Bus 7 | 345 | 1.05 | 25.521 | 1.05 | 25.6 | 0.00 | -0.079 |
| Bus 8 | 345 | 0.996 | -3.819 | 0.996 | -3.76 | 0.00 | 0.059 |
| Bus9 | 22 | 1.04 | 0.00 | 1.04 | 0.07 | 0.00 | -0.07 |
| Bus10 | 22 | 1.02 | 2.175 | 1.02 | 2.24 | 0.00 | -0.065 |
| Bus11 | 22 | 1.01 | -34.55 | 1.01 | -34.49 | 0.00 | 0.06 |
| Bus12 | 22 | 1.02 | -29.89 | 1.02 | -29.84 | 0.00 | 0.055 |

Table 4.6: Comparison of Real Power (P) and Reactive Power (Q) for Case 3

| From Bus | To Bus | PowerWorld | | ATP | | %Difference | |
|---|---|---|---|---|---|---|---|
| | | *P* *MW* | *Q* *Mvar* | *P* *MW* | *Q* *Mvar* | *P* *%DIF* | *Q* *%DIF* |
| 1 | 2 | -35.437 | 37.769 | -35.30 | 37.713 | 0.387 | 0.148 |
| 1 | 6 | 203.10 | 18.074 | 203.15 | 18.06 | 0.025 | 0.077 |
| 2 | 5 | 184.19 | 0.570 | 184.21 | 0.518 | 0.011 | 9.559 |
| 3-1 | 4-1 | 101.50 | 15.202 | 101.52 | 15.144 | 0.02 | 0.382 |
| 3-2 | 4-2 | 101.50 | 15.202 | 101.52 | 15.144 | 0.02 | 0.382 |
| 5 | 4 | 72.629 | -17.57 | 72.632 | -17.58 | 0.004 | 0.057 |
| 6 | 4 | 49.620 | -18.56 | 49.612 | -18.60 | 0.016 | 0.215 |
| 7 | 8 | 340.94 | -93.08 | 340.99 | -93.08 | 0.015 | 0 |
| 9 -G1 | 1 | 508.61 | -1.989 | 508.84 | -2.015 | 0.045 | 1.299 |
| 10-G2 | 2 | 500.00 | 173.58 | 500.04 | 173.61 | 0.008 | 0.017 |
| 12-G3 | 6 | 300.00 | 158.65 | 300.01 | 158.64 | 0.003 | 0.006 |
| 11-G4 | 3 | 200.00 | 212.61 | 200.04 | 212.70 | 0.02 | 0.042 |

Both ways to manage congestion in case 2 and case 3 reduced the loading percentage of line 1-6 from 81 to 78 with significant difference in desired value of this series compensation, and with different impacts on the loading percentage of the other transmission lines, especially line 2-5. Using capacitive D-FACTS devices in line 7-8 has a better effect than using inductive D-FACTS devices in line 1-6 on reducing the load in line 2-5, but at the same time, using the inductive D-FACTS devices required less total series compensation and potentially less devices.

Using inductive and capacitive D-FACTS devices on line 1-6 and line 7-8 respectively can relieve the congestion in line 16 during the steady state and in scenarios of losing line 4-5 or one of the parallel lines between bus 3 and bus 4 as shown in Table 4.7. This table shows the loading percentage of all lines of IEEE 12 bus system with and without series compensation for three scenarios: all lines on, line 5-4 off, and line 3-4 off.

Table 4.7: Comparison of Transmission Lines Loading for Three Scenarios

| From Bus | To Bus | Without D-FACTS (Scenarios) | | | Inductive D-FACTS on Line1-6 (Scenarios) | | | Capacitive D-FACTS on Line 7-8 (Scenarios) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *All On %* | *L 5-4 Off %* | *L 3-4 Off %* | *All On %* | *L 5-4 Off %* | *L 3-4 Off %* | *All On %* | *L 5-4 Off %* | *L 3-4 Off %* |
| 1 | 2 | 18 | 46 | 19 | 18 | 46 | 18 | 20 | 46 | 20 |
| 1 | 6 | 81 | 93 | 86 | 78 | 91 | 84 | 78 | 93 | 81 |
| 2 | 5 | 74 | 38 | 79 | 75 | 38 | 80 | 71 | 38 | 74 |
| 3.1 | 4.1 | 40 | 53 | 0 | 41 | 54 | 0 | 42 | 53 | 0 |
| 3.2 | 4.2 | 40 | 53 | 84 | 41 | 54 | 87 | 42 | 53 | 88 |
| 5 | 4 | 32 | 0 | 35 | 33 | 0 | 36 | 30 | 0 | 31 |
| 6 | 4 | 24 | 33 | 27 | 21 | 30 | 25 | 21 | 33 | 23 |
| 7 | 8 | 65 | 76 | 64 | 66 | 77 | 65 | 67 | 76 | 67 |

In case of losing line 5-4, the inductive D-FACTS devices in line 1-6 have a better effect than the capacitive D-FACTS devices in line 7-8 on reducing the load in line 1-6. On the other hand, in case of losing one of the parallel lines between bus 3 and bus 4, the capacitive D-FACTS devices in line 7-8 have a better effect than the inductive D-FACTS devices in line 1-6 on reducing the load in line 1-6.

## 4.5 Conclusion

The power flow results of the IEEE12 bus power system with different configurations of D-FACTS devices are compared between Power World and ATP in this dissertation. The main goal of this study is to compare the power flow results and validate the ATP model against PowerWorld model of IEEE12 bus system, with D-FACTS devices models. The power flow study is done for three cases: without D-FACTS devices, with inductive D-FACTS devices on line 1-6 and with capacitive D-FACTS devices on line 7-8.

The study of these three cases shows that the power flow results of ATP and PowerWorld models are closely match each other in the magnitude of the bus voltage with percentage difference less than 0.0005%. However, there are small differences in voltage angles measured at each bus. Also, there are small differences in real power and reactive power measured in each transmission line. This comparison validates the ATP model against PowerWorld model of the IEEE12 bus system as well as D-FACTS devices models for steady state operation. It shows that the steady state behavior of the new D-FACTS models in ATP and exciting D-FACTS models in PowerWorld are very similar. Also, these results show that using of capacitive D-FACTS devices on line 7-8 has better advantages than using inductive D-FACTS devices on line 1-6 in terms of relieving the congestion in line 1-6 as well as reducing the load in line 2-5 during steady state and in the case of losing one of parallel lines between buses 3 and 4. Using the inductive D-FACTS devices in line 1-6 is required less total compensation.

The next step is to validate the dynamic response of the test system model with D-FACTS and then move on to perform protection studies and stability studies.

# CHAPTER 5

# An Investigation of the Impact of D-FACTS Devices Implementations on the Mho Distance Elements

This chapter presents a paper that was published in the Proceedings of the 2019 North American Power Symposium [23]. The copyright permission is shown in Appendix K.

## 5.1 Introduction

During the last decade, the demand in electrical power has continued to increase at a significant rate. Furthermore, the concept of active consumers has changed how the grid operates. One of the major facilitators for this change is the need for renewable energy resources. As a result, many renewable energy resources such as wind and solar power have been connected to the transmission system. Factors such as these are adding more complexity to power systems and because of this, new capable technologies have been developed to solve the power flow variations. To meet the needs of solving power flow issues, power electronics devices are being more widely utilized in transmission and distribution systems. These devices have seen use in power systems since the 1950s and 1960s [1].

In cases where fast acting devices are needed to control the power flow in transmission systems and improve transient stability of the power systems, different types of Flexible AC transmission system (FACTS) devices such as Static Synchronous Compensators (STATCOMs), Static Synchronous Series Compensators (SSSCs), and Unified Power Flow Controllers (UPFCs) have been proposed to solve the stability issues. At the same time, their somewhat low reliability and high capital costs limit their penetration into the power system [4],[6]. Series Distributed Flexible AC Transmission System (D-FACTS) devices offer the possibility of solving these drawbacks by presenting a distributed solution at low cost and high reliability [38].

Inductive D-FACTS devices are power electronics based devices that offer the ability to manage congestion in a power system by controlling the power flow for existing transmission lines. They control the power flow by increasing the line impedance of an overloaded line to force the current to flow to lines with larger available capacity [9], [10]. Some electrical utilities have started to install these devices in their overhead lines [12].

In transmission systems, fault currents are interrupted by circuit breakers which are located at the ends of a transmission line, to isolate faulted lines. The circuit breakers receive the tripping signals from the protective relays if a fault disturbance happens on that line. The basic operation of the distance relay is to determine the effective impedance between the relay location and the fault point by using the voltage and fault current measurements [13].

Interactions between the operation of D-FACTS modules and transmission line protection elements, due to the change in the effective line parameters, leads to a few concerns in protection system performance. Using different types of D-FACTS implementations, such as either compressed or dispersed implementation may lead to pseudo-random changes in the line impedance during faults because it is hard to predict how many devices will present in the fault path and how much devices will switch to bypass mode because of high value of fault current.

The first objective of this chapter is to provide a good understanding of the effect of D-FACTS devices on the distance protection function. The second objective is to make recommendations for D-FACTS devices implementation and protective relay settings. These recommendations may help the utilities in making the right decision in where and how they can implement them in their network. That may also help the protection engineers to discern the proper setting of the protective relay in the presence of these devices.

Section 5.2 provides an introduction to D-FACTS devices as well as different methods of their implementation. Section 5.3 provide an information to the mho distance function. Section 5.4 describes the system studied, the relay setting, and the data collection process. Section 5.5 shows the result of D-FACTS devices impact on distance elements for different fault cases. Section 5.6 develops an initial basis for the D-FACTS devices and line protection setting recommendation. Section 5.7 presents conclusions.

## 5.2 The D-FACTS Overview

Figure 5.1 illustrates the D-FACTS devices holding on the transmission line. They are single phase devices; each one of the single devices can clamp easily around one of three conductors at the same site. They can be distributed over the entire length of the transmission line in different configurations. D-FACTS devices provide potential benefits to utilities such as reducing the power flow through the overhead line, minimizing losses and operational costs, improving the system stability and controlling system voltage [38].

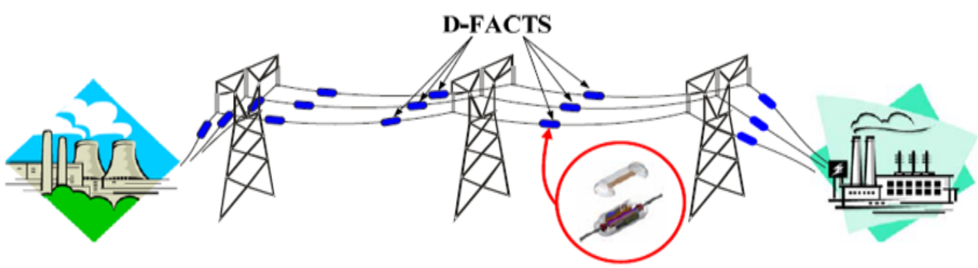



Figure 5.1: Picturing Concept of D-FACTS on Transmission Line [38]

### 5.2.1 An Inductive D-FACTS Devices

Figure 5.2 shows the basic circuit of inductive D-FACTS devices. During the normal mode of operation, the switch $S_M$ is closed, and the injection reactance is zero. The injection reactance will be equal to the magnetizing inductance $X_M$ when switch $S_M$ is open. The thyristor switches are used for quick bypass for this device under disturbance. As the line current exceeds the threshold value which is normally the thermal limit current, the D-FACTS devices start to engage, forcing the current to flow into the under-loaded lines [38].

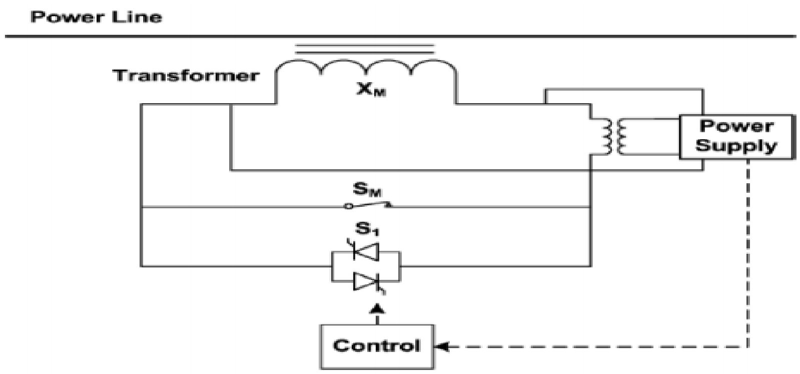



Figure 5.2: Basic Circuit of Inductive D-FACTS
[38]

### 5.2.2 Implementation Methods of the Inductive D-FACTS

Inductive D-FACTS devices provide a distributed solution. There are two methods to implement these devices [12]:

#### 5.2.2.1 Dispersed Implementation

In this technology, the inductive D-FACTS devices are mounted on the line conductor, and they should mount next to each tower along the length of the transmission line as shown in Figure 5.3.

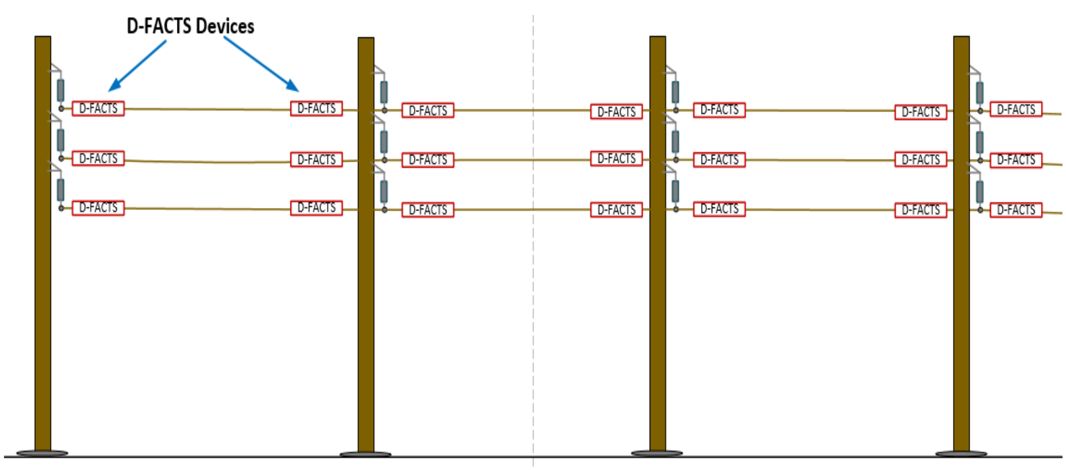



Figure 5.3: Dispersed Implementation of Inductive D-FACTS

#### 5.2.2.2 Compressed Implementation

This technique provides choice for the utilities to select the favored position to install these devices to avoid some issues such as land sensitivity or population zones. In this technique, many much D-FACTS devices may be placed on a short length of the line. That may require adding a new towers or/and re-conducting a small part of transmission line as shown in Figure 5.4 [12].

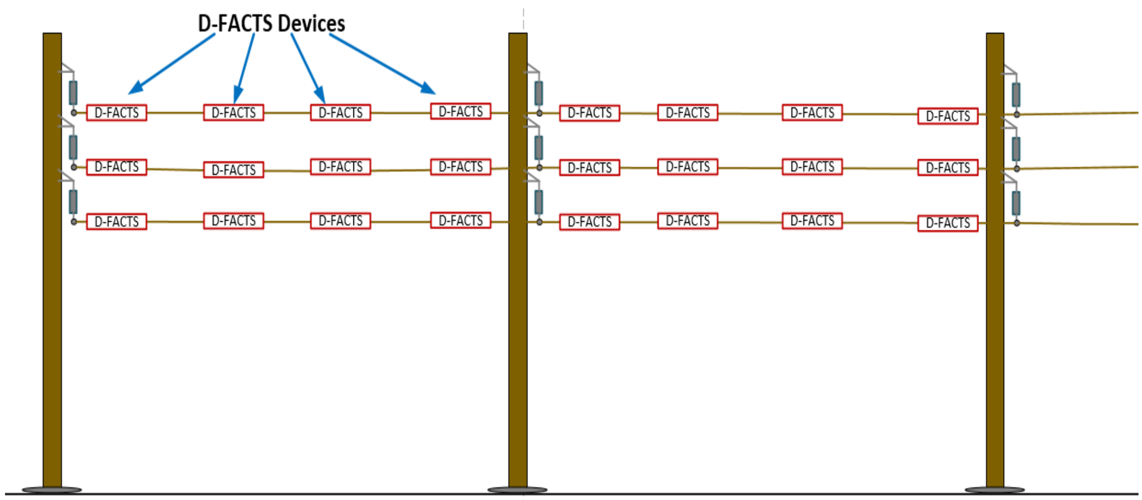



Figure 5.4: Compressed Implementation of Inductive D-FACTS

## 5.3 The Mho Distance Function

At the relay location in the power substation, there is a current transformer (to measure current) and voltage transformer (to measure voltage). The measured voltages and currents are received simultaneously as an input to the distance elements in the protective relay. The measured effective impedance should determine the approximate location of the fault within the transmission line. The distance element will send a trip signal to the circuit breaker if the effective impedance is smaller than the reach setting [20].

The protection area of the mho distance relay is divided into multiple zones as shown in Figure 5.5. Zone 1 and Zone 2 are used as primary protection, and Zone 2 and Zone 4 can be used as backup protection for the adjacent lines [46].

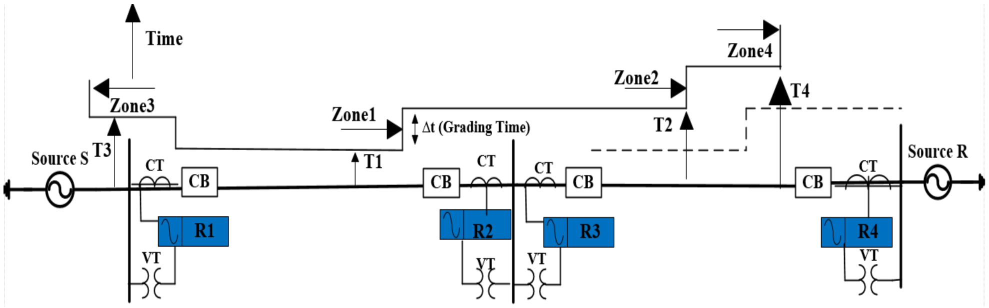



Figure 5.5: Zones of the Distance Protection

Modern mho distance relays can include additional zones (mho circles) as shown in Figure 5.6 for self-polarized elements. The setting of the forward zones (Zone 1, Zone 2, and Zone 4) and the reverse zone (Zone 3) are typically 80%, 120%, 160%, and 40% of line impedance, respectively.

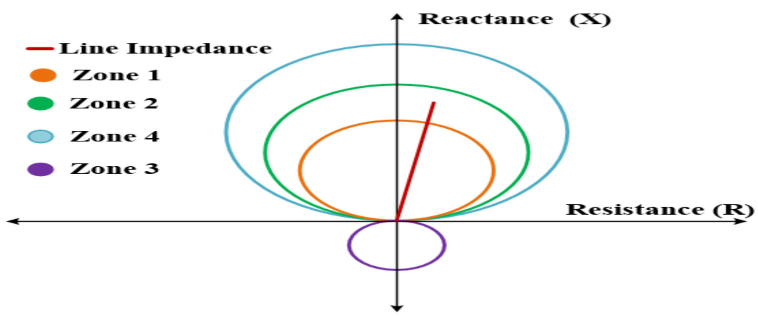



Figure 5.6: Zones (Mho Circles) for Self-Polarized Elements

The distance element calculation inside the relay includes the ground elements and phase elements. For example, the phase A to ground element ($Z_{AG}$) is calculated by using equations (5.1) [20].

$$Z_{AG} = \frac{V_{AG}}{I_A + K_0 3I_0} \tag{5.1}$$

Where $V_{AG}$, $I_A$, $I_0$, and $K_0$ are the phase A voltage, phase A current, and zero sequence current, and zero sequence current compensation factor, respectively.

Based on the relay setting, if the calculated impedance due to a disturbance falls in Zone 1, the relay will send a trip signal to the circuit breaker immediately. If the measured impedance falls in Zone 2, the relay will initiate a trip signal with delay in time.

Communication aided schemes such as the permissive overreaching transfer trip (POTT) scheme added reliability for high speed tripping for Zone 1 underreaching at both ends of the line. The basic operation principle of the POTT scheme is to use the Zone 2 type information from the relays at both ends of the line, such that if both relays pick up in Zone 2 for a fault, both of them will send trip signals to the circuit breakers with high speed tripping [20].

## 5.4 Test Environment

### 5.4.1 System Studied

Figure 5.7 shows the schematic diagram of a 230kV example system [58]. This system is used in this paper to perform a study on the impact of D-FACTS on the transmission line protection system.

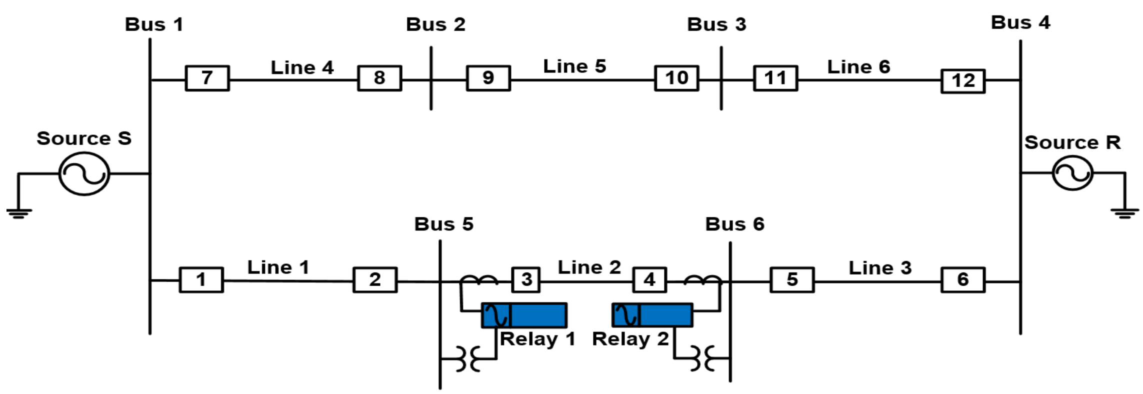



Figure 5.7: A Single Line Diagram of 230 kV Six Bus System

The configuration of transmission lines is modeled in alternative transient program (ATP) as described in [22]. Each transmission line is modeled as constant distributed parameter model (Bergeron Model).

### 5.4.2 Relay Setting

The data for line 2 that is used for setting its protective relays is summarized in Table 5.1.

Table 5.1: List of the 230 KV System Data

| ***Parameter*** | ***Value*** |
|---|---|
| Normal system line to line voltage | 230 kV |
| Normal relay current | 5 A secondary |
| Normal frequency | 60 Hz |
| Line 2 length | 100 mile |
| line 2 impedances $Z_{1L}$ | $77.98\angle 82.7\ \Omega$ |
| line 2 impedances $Z_{0L}$ | $180.98\angle 69.817\ \Omega$ |
| PRT(potential transformer ratio) | 230 kV:115 V=2000 |
| CTR(current transformer ratio) | 500:5=100 |
| Phase rotation | ABC |

### 5.4.3 The Data Collection Process

After developed the model of D-FACTS devices in ATP as it illustrated in [21] , these devices are implemented in line 2 of the study system. The data collection process of this work is performed in the following steps.

- Running the simulation cases in ATP.
- Using ATP analyzer to convert ATP results to COMTRADE files.
- Upload COMTRADE files to Adaptive Multichannel Source (AMS). The study of the impact of D-FACTS on distance protection function is performed for two cases:
  - For dispersed implementation of D-FACTS
  - For compressed implementation of D-FACTS

In these cases, the D-FACTS devices are assumed to be on conducting mode during the fault because the fault current is less than the fault current threshold of the bypass switches.

### 5.4.4 Dispersed Implementation of D-FACTS Devices

The dispersed Implementation of D-FACTS on line 2 is shown in Figure 5.8.

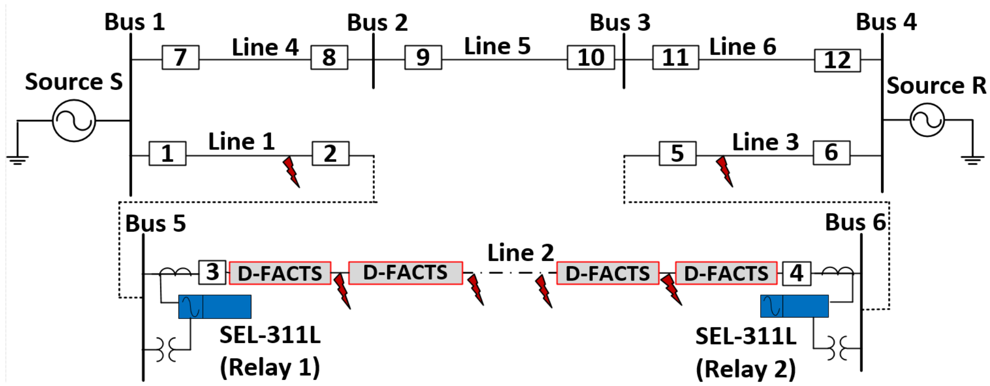



Figure 5.8: Single Line Diagram of Study System With D-FACTS Dispersed Implementation

To examine the response of Relay 1 at the sending end and Relay 2 at the receiving end of line 2 for different percentages of D-FACTS compensation, a SLG fault is applied at each 10% of the line 2 impedance to cover 100% of line 2 and 20% of the adjacent lines (line 1 and 3). The impact of the D-FACTS devices on the distance protection elements is examined in $MathCAD^{®}$ relay model and in commercial relays.

#### 5.4.4.1 The Response of Zone 1 and Zone 2 Distance Elements of the $MathCAD^{®}$ relay Model

By using $MathCAD^{®}$, the fault location and the equivalent reactance of D-FACTS can be calculated at any point of line 2 by using variable parameter M (to represent the fault location) and $X_{inj}$ (to represent the D-FACTS devices) in the fault calculation equations.

Figure 5.9 and Figure 5.10 illustrate the mho ground elements response (Zone 1 and Zone 2) of Relay 1 and Relay 2, respectively for different fault locations and percentages of D-FACTS compensation.

When the fault happened at 75% of line 2, the Zone 1 of AG distance element was underreached (the relay sees an impedance bigger than what it actually is) for equivalent impedance of D-FACTS devices above 7.73 Ω (10% of the line impedance). This means that when the fault occurred at 75% of line 2, the trip decision was based on Zone 2 element with time delay instead of instantaneous trip of Zone 1 element. That can cause stability issues.

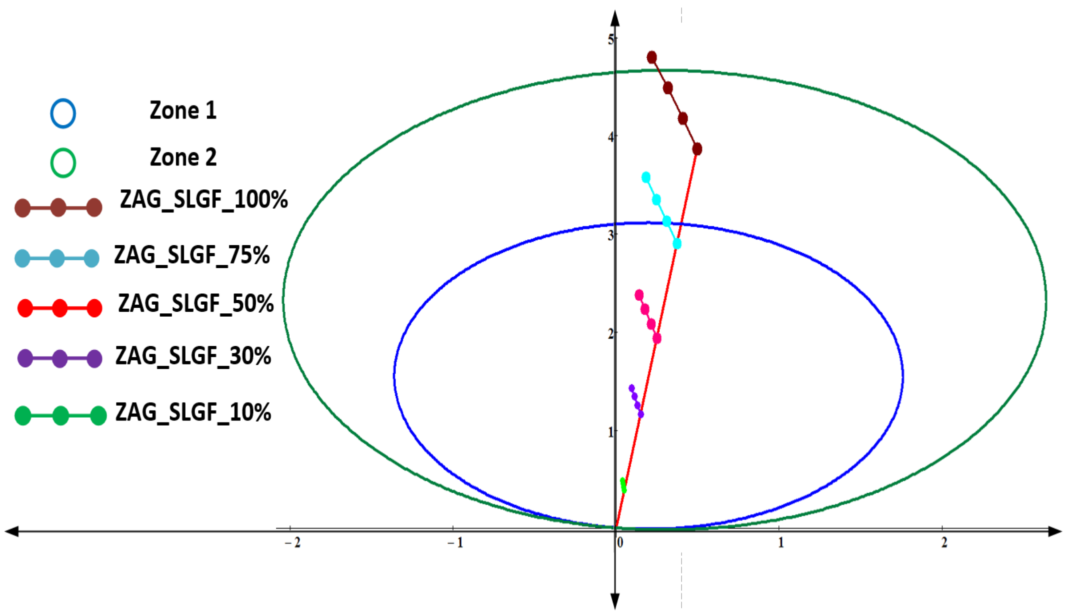



Figure 5.9: Mho Ground Elements (Zone 1 and Zone 2) Response of Relay 1

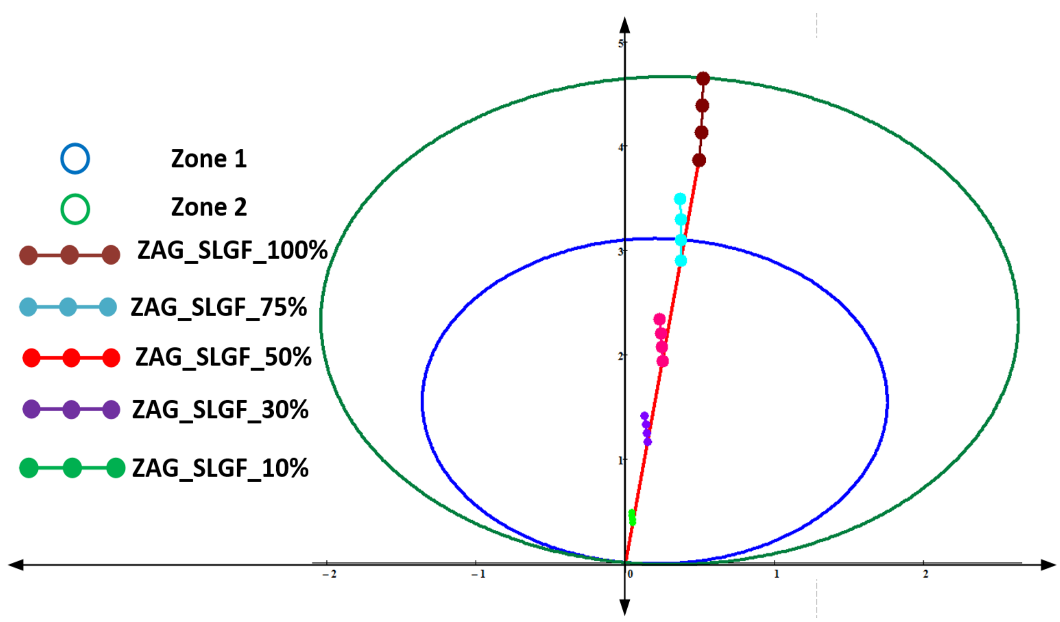



Figure 5.10: Mho Ground Elements (Zone 1 and Zone 2) Response of Relay 2

Also, when the fault happened close to 100% of line 2, the zone 2 distance element was underreached for a equivalent impedance of D-FACTS above 19.34 Ω (25% of the line impedance). This means that when the fault occurred at 100% of line 2, the zone 2 element failed to trip because of D-FACTS implementation.

#### 5.4.4.2 The Response of Zone 1 and Zone 2 Distance Elements of the Commercial Relays

Figure 5.11 and Figure 5.12 illustrate the response of Zone 1 and Zone 2 distance elements for different locations of SLG fault and percentages of D-FACTS compensation.

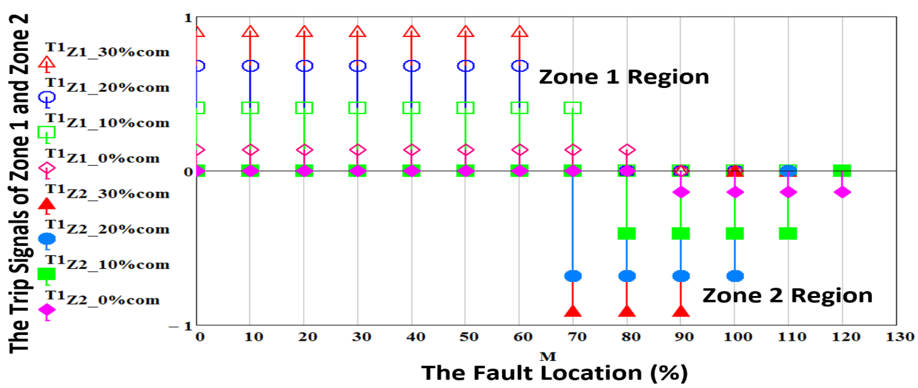



Figure 5.11: Zone 1 and Zone 2 Distance Elements Response of Relay 1

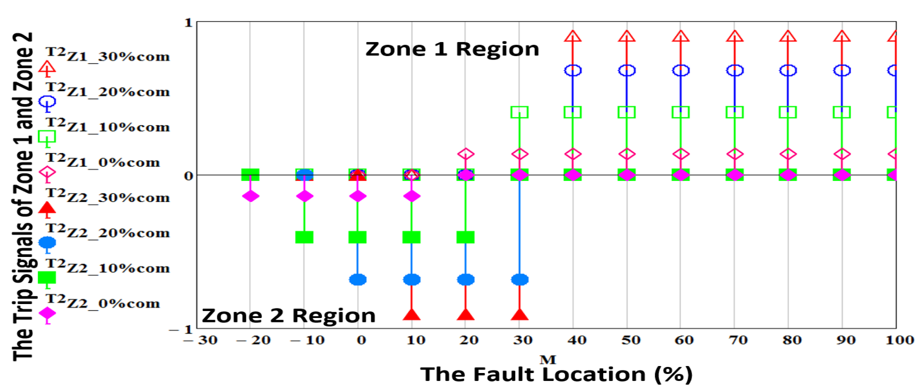



Figure 5.12: Zone 1 and Zone 2 Distance Elements Response of Relay 2

The abscissa represents location of the fault, and ordinate represents the trip signals of Zone 1 and Zone 2 distance elements for different percentages of D-FACTS compensation.

For AG fault at 70% of line 2, the ground element responded in Zone 2 instead of Zone 1. Also, for AG fault at 100% of line 2, the ground distance element failed to trip as a result ofZzone 2 underreaching.

#### 5.4.4.3 The Fault Location Elements Response of the Commercial Relays

Precise information of fault location increase the ability of utilities to overcome some issues in the power system, such as the outage duration and the operating costs. Figure 5.13 illustrates the response of the fault location elements of Relay 1 and Relay 2 for different fault location and percentages of D-FACTS compensation. The abscissa represents location of the fault, and ordinate represents the estimated distance to the fault location.

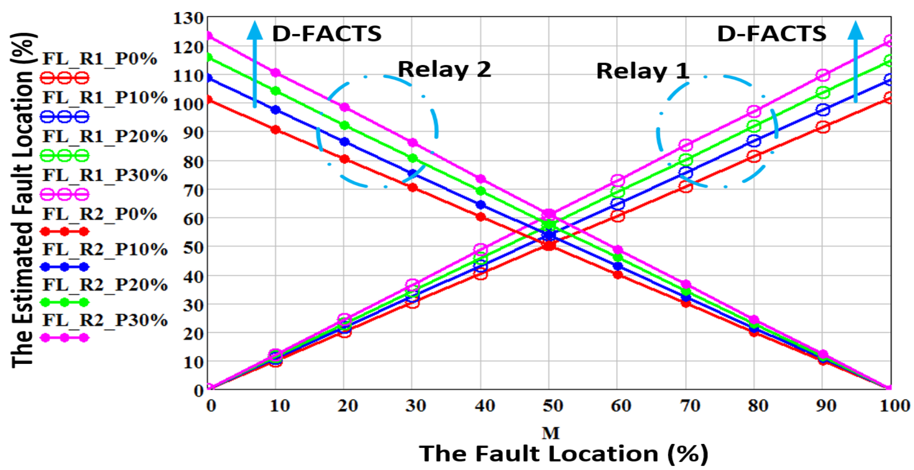



Figure 5.13: Fault Location Elements Response of Relay 1 and Relay 2

Clearly, the D-FACTS implementation can have a huge impact on fault location information. For a single line to ground fault with 30% D-FACTS devices compensation, the percentage error in the estimated distance to the fault is equal to 22%.

#### 5.4.4.4 The POTT Scheme Response of the Commercial Relays

Figure 5.14 illustrates the POTT scheme response for different fault locations and percentages of D-FACTS compensation. The abscissa represents location of the fault and ordinate represents the trip signal of this scheme.

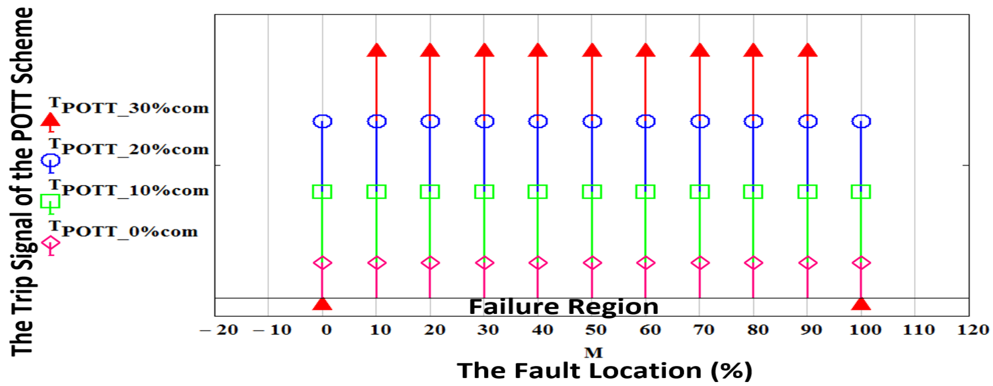



Figure 5.14: Response of the POTT Scheme

For some fault cases, the D-FACTS devices led the relay to see the fault farther than what it actually was, causing POTT scheme fail to trip. This POTT scheme was unable to cover a fault at the far end of line 2 for D-FACTS compensation equal to 30% of line 2 impedance. The implementation of D-FACTS compensation can minimize Zone 2 coverage. Under some fault conditions, that may cause failure of this scheme.

### 5.4.5 Compressed Implementation of D-FACTS Devices

In this case, the D-FACTS devices are installed in the first one-third of line 2 as illustrated in Figure 5.15.

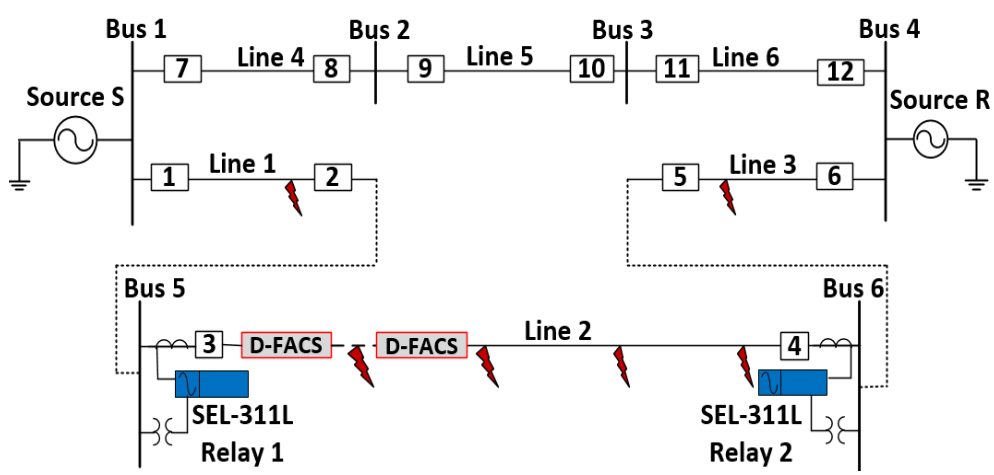



Figure 5.15: Single Line Diagram of Study System With Compressed Implementation of D-FACTS

#### 5.4.5.1 The Response of Zone 1 and Zone 2 Distance Elements of the $MathCAD^{®}$ Relay Model

Figure 5.16 and Figure 5.17 illustrate the response of Zone 1 and Zone 2 of both relays for different percentages of D-FACTS compensation.

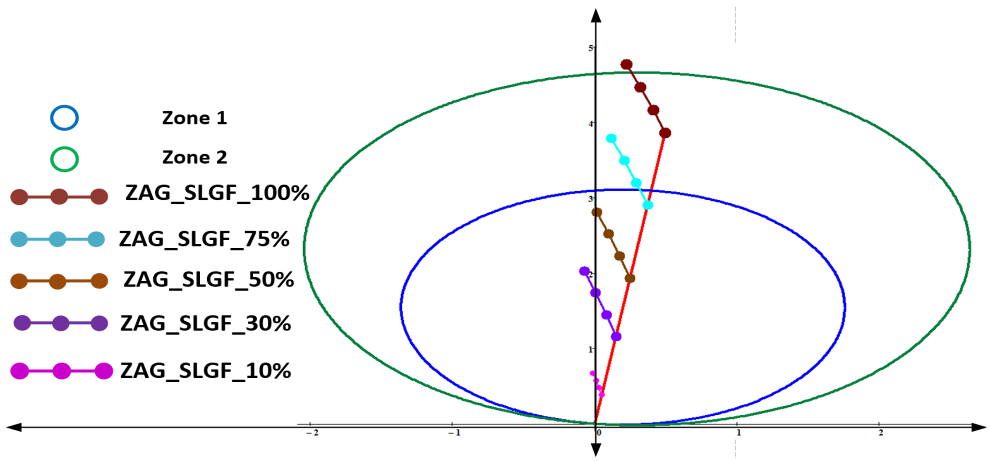



Figure 5.16: Mho Ground Elements Response of Relay 1

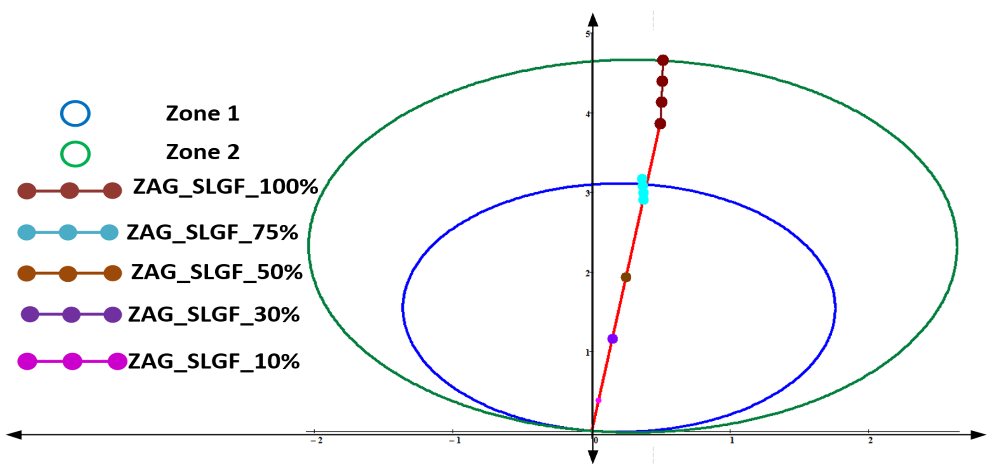



Figure 5.17: Mho Ground Elements Response of Relay 2

For Relay 1, when the fault happened at 75% of Line 2, the Zone 1 ground element was underreached and the relay tripped in Zone 2 element with a delay in time. Also, when the fault happened at 100% of Line 2, the Zone 2 element was underreached, and the relay failed to trip because of D-FACTS implementation.

For Relay 2, the ground distance elements respond correctly for a SLG fault in the uncompensated distance of line 2 because Relay 2 did not see the D-FACTS in this section. When the fault occurred in the compensated section, the Zone 1 and Zone 2 ground distance elements were underreached. That may cause delay in tripping or failure of zone 2 distance element.

#### 5.4.5.2 The Response of the Fault Location Elements of the Commercial relays

Figure 5.18 illustrates the response of the fault location element for different percentages of D-FACTS compensation.

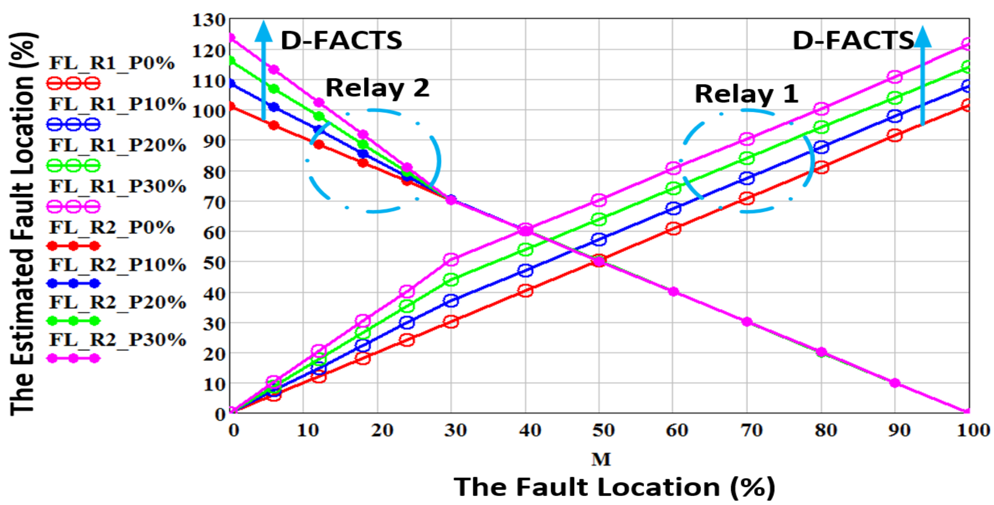



Figure 5.18: Fault Location Elements Response of Relay 1 and Relay 2

For Relay 1, there is an error in the fault location information for all fault locations along line 2 because Relay 1 always sees a part of, or all, D-FACTS devices in the fault path. On the other hand, there is no error in the fault location information of Relay 2 for a fault in the uncompensated distance, but the error starts to increase as the fault location moves inside the compensated area. The accuracy of the fault location information is various from location to another in this line due to the compressed D-FACTS implementation. The rate of error in determining the accurate information of fault location depends on the particular location of the fault, the percentage of D-FACTS compensation, and the number of D-FACTS devices that are presented in the fault path.

#### 5.4.5.3 The POTT Scheme Response of the Commercial Relays

Figure 5.19 illustrates the POTT scheme response for difference percentages of D-FACTS compensation.

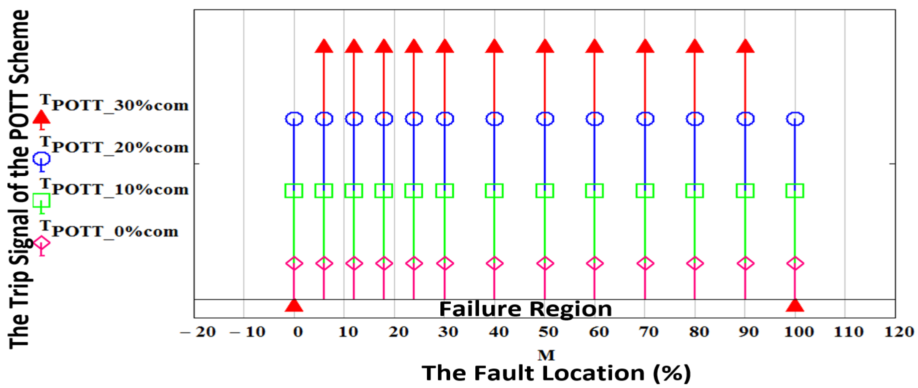



Figure 5.19: POTT Scheme Response for SLG Fault

When the fault is applied close to anyone of the protective relays, the other relay failed to declare a POTT trip because of its Zone 2 element underreaching. For these cases (with 30% D-FACTS compensation), one of the relays did not see the fault in its zone 2, and therefore the other relay did not receive a permissive overreaching signal. Thus, no POTT trips were declared in either relay.

## 5.5 D-FACTS and Line Protection Setting Recommendations

Based on the results, recommendations can be made for selecting a propor setting for D-FACTS installation and the protective relay settings:

- The D-FACTS devices dispersed implementation technique should be applied in the transmission line.
- The basic settings of the protective relay should account for the equivalent impedance of the D-FACTS devices.
- The Zone 2 coverage for POTT scheme should be increased based on the equivalent impedance of the implemented D-FACTS to avoid Zone 2 underreaching.

## 5.6 Summary and Conclusions

The impact of dispersed and compressed implementation of D-FACTS devices on the distance protection of the transmission line is examined in this chapter. The study includes effect of these devices on zone 1 and zone 2 mho distance elements, POTT scheme, and fault location elements, and the results show the following:

In some fault cases and for a fault in the setting reach area of Zone 1, the Zone 2 distance element responded with a time delay trip instead of the instantaneous trip as a result of Zone 1 underreaching because of D-FACTS implementation. This delay in the tripping action may influence the system stability.

For a fault at the far end of the line, the Zone 2 distance element failed to trip as a result of zone 2 underreaching. The D-FACTS implementation can reduce Zone 2 coverage, and under some fault conditions, that may cause failure of the POTT scheme.

The fault location element is no longer capable of telling the operator accurate information about the location of the fault due to D-FACTS implementation.

For the compressed implementation method, the error margin in measured impedance by both relays is not uniform. It is hard to correct for this error because of behavior of D-FACTS (the error margin is not fixed with respect to the fault location along the transmission line). On the other hand, in the dispersed implementation method, the error margin in the measured impedance is mostly uniform and it is easier to compensate for this error in the relay settings.

Before the utilities make a decision to implement the D-FACTS devices on their network, they should consider recommendations for D-FACTS implementation and protective relay setting as described above.

Future studies will examine the influence of D-FACTS devices on the mho ground distance elements in presence of fault resistance and the mutual coupling of the parallel lines.

The output data of ATP simulation for SLG fault for dispersed implementation is shown in Tables D.1, D.2, D.3, and D.4 for percentages of D-FACTS equal to 0% and 30% of the line 2 reactance as shown in Appendix D. The output data of ATP simulation for SLG Fault for compressed implementation is shown in Tables E.1, E.2, E.3, and E.4 for percentages of D-FACTS equal to 0% and 30% of the line 2 reactance as shown in Appendix E. The protection elements response of the commercial relays for SLG fault for dispersed implementation is shown in Tables F.1, and F.2 for percentages of D-FACTS equal to 0% and 30% of the line 2 reactance as shown in Appendix F. The protection elements response of the commercial relays for SLG fault for compressed implementation is shown in Tables G.1, and G.2 for percentages of D-FACTS equal to 0% and 30% of the line 2 reactance as shown in Appendix G.

# CHAPTER 6

# An Exploration of the D-FACTS Influence in the Mho Ground Distance Elements in Presence of Fault Resistance and the Parallel Lines Mutual Coupling

This chapter transcribes a paper that was published in the Proceedings of the 2019 North American Power Symposium [24]. The copyright permission is shown in Appendix K.

## 6.1 Introduction

Different types of Flexible AC Transmission System (FACTS) devices have been used to control power flow in transmission systems and improve transient stability of power systems [1]. Series Distributed FACTS (D-FACTS) devices offer the possibility of solving some of the FACTS drawbacks by presenting a distributed solution at low cost and high reliability [38].

Inductive D-FACTS are power electronics based devices that offer the ability to manage congestion in a power system by controlling the power flow for existing transmission lines. They control power flow by increasing the line impedance of an overloaded line to force the current to flow instead in lines with larger available capacity [9], [10]. Some electrical utilities have started to install these devices in their overhead lines [12].

In transmission systems, fault currents are interrupted by circuit breakers which are located at the ends of a transmission line, to isolate faulted lines. The circuit breakers receive the tripping signals from the protective relays if a fault happens on that line. The basic operation of the distance relay is to determine the effective impedance between the relay location and the fault point from voltage and current measurements [13].

Typically, there is a resistance due to the arc because of a fault between two conductors or between conductor and the tower, and from the ground return path including any objects such as trees, buildings and animals during a ground fault. This resistance is called fault resistance. Usually, the ground fault resistance is much larger than the phase fault resistance because of the typically larger resistance of ground return path [20].

Mutual coupling can occur between two or more parallel conductors in single circuit lines or double circuit lines. In single circuit lines, the conductors run on the same tower, but in double circuit lines, the conductors lines run in different towers with a bigger space between them. In either case, they may operate at the same voltage level or at different voltage levels [20].

Interactions between the operation of D-FACTS and transmission line protection elements may influence the fault resistance coverage of the mho ground distance elements. Also that may effect the zero sequence mutual coupling of the parallel lines due to the change in the effective line parameters.

The first objective of this chapter is to provide a good comprehension of the impact of D-FACTS on mho ground distance elements in presence of a fault resistance. The second objective is to examine the effect of these devices on the mutual coupling between parallel lines. This chapter demonstrates how the fault resistance and mutual coupling may impact the distance protection performance in the presence of D-FACTS devices.

Section 6.2 provides an introduction about D-FACTS devices. Section 6.3 reviews information about mho ground distance elements. Section 6.4 describes the system studied, the relay settings, and the data collection process. Section 6.5 shows the results of the impact of D-FACTS on the fault resistance coverage of the ground distance function. Section 6.6 illustrates the effect of these devices on the mutually coupled parallel lines. Section 6.7 presents conclusions.

## 6.2 Overview of D-FACTS

Figure 6.1 illustrates inductive D-FACTS devices clamping on a transmission line. D-FACTS are single phase devices and can be distributed over the length of the transmission line in different configurations. D-FACTS provide potential benefits to utilities such as reducing the power flow through the overhead line, minimizing losses and operational costs, improving system stability, and controlling system voltage [38].

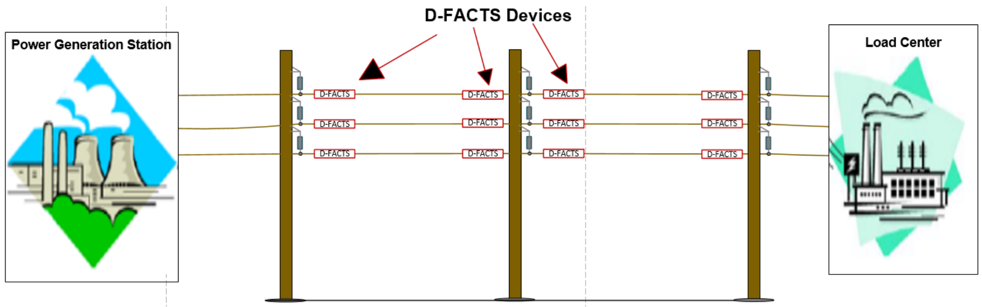



Figure 6.1: Picturing Concept of D-FACTS on Transmission Line

Figure 6.2 shows the basic circuit of inductive D-FACTS devices. The injection reactance is equal to zero when the switch is closed for normal operation. For controlling the power flow, the injection reactance will be equal to the magnetizing inductance of the transformer when switch is open. Thyristor switches are used for quick bypass for this device under disturbance. When the line current exceeds the threshold value, the inductive D-FACTS

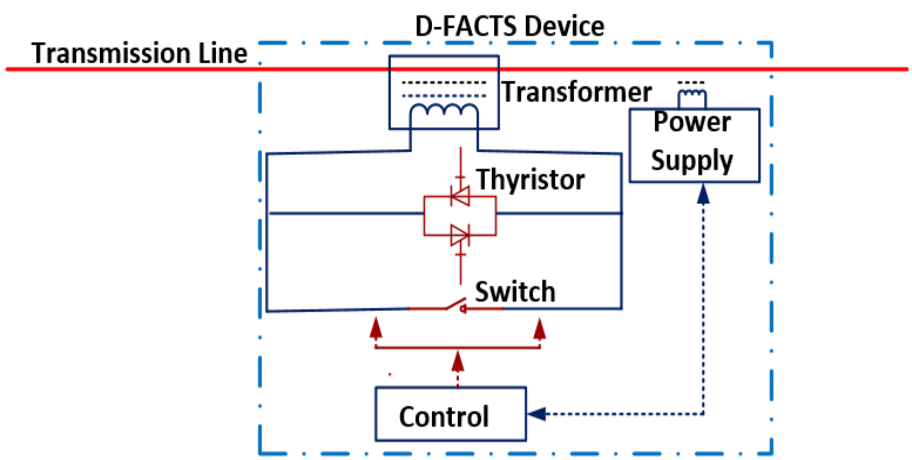



Figure 6.2: Basic Circuit of Inductive D-FACTS

devices start to switch on (open the switch) to force some of the current to flow into the under-loaded lines [38].

## 6.3 The Mho Ground Distance Function

At the relay location in the power substation, there is a current measurement unit (current transformer) and voltage measurement unit (voltage transformer) to provide a scalable input to the distance elements in the protective relay. The calculated effective impedance should determine the approximate location of the fault within the transmission line. The distance element will send a trip signal to the circuit breaker if the effective impedance is smaller than the reach setting [20], [19].

Modern mho distance relays can include multiple protection zones, for example three forward zones and one reverse zone as shown in Figure 6.3 for self-polarized elements. The setting of zone 1, zone 2, zone 4, and reverse zone (zone 3) are typically 80%, 120%, 160%, and 40% of line impedance, respectively.

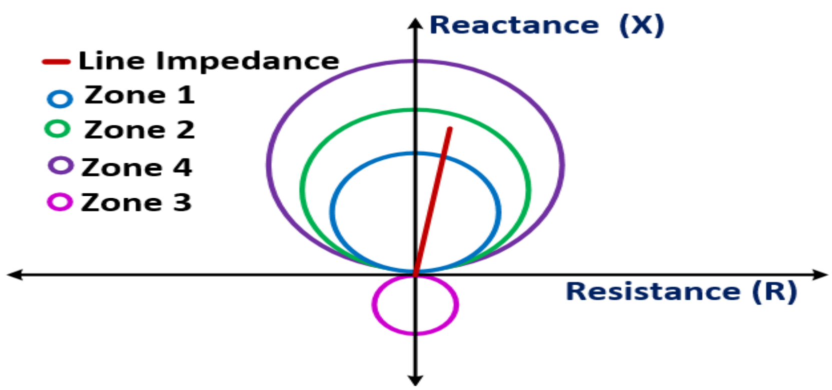



Figure 6.3: Mho Circles (Zones) for Self-Polarized Elements

The distance element calculation inside the relay includes the ground elements. For example, the phase A to ground element ($Z_{AG}$) is calculated using equation (6.1) [20].

$$Z_{AG} = \frac{V_{AG}}{I_A + K_0 3I_0} \tag{6.1}$$

Where $V_{AG}$, $I_A$, $I_0$, and ($K_0$) are the phase A voltage, phase A current, zero sequence current, and zero sequence current compensation factor, respectively.

To improve the mho distance protection performance, communication aided schemes such as the permissive overreaching transfer trip (POTT) scheme are implemented in modern protective relays. The POTT scheme uses the zone 2 type information such that if the relays at each end of the line picked up in zone 2 for a fault, both of them will initiate a trip signal with high speed tripping [19].

### 6.3.1 The Fault Resistance Coverage

Fault resistance causes an error in the measured impedance on the distance elements. That might cause the distance elements to see the fault as farther than it actually is (zone underreaching) or to see the fault closer than what it really is (zone overreaching), based on system states [67], [47].

The distance function must have a polarizing reference value to compare it to an operating point. There are three commonly used types of polarizing references (self, cross, and memory polarizing reference) [20].

In modern distance relays, memory polarization is the most commonly used scheme. Self polarization is static. Self polarized elements are easily described, but are rarely used in practice. Cross and memory polarizing elements have similar behavior during the faults, but they are not identical. the Cross or memory polarizing elements exhibit dynamic response with dynamic expansion for forward faults or contraction for reverse faults. This can improve security and also help in gaining more fault resistance coverage, especially for close-in forward faults as it is illustrated in Figure 6.4.

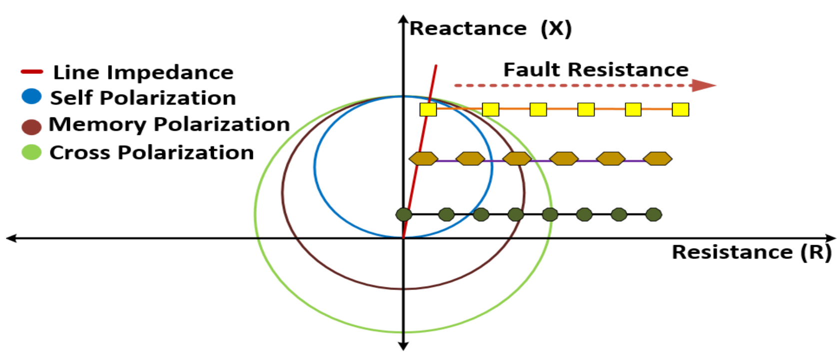



Figure 6.4: Fault Resistance Coverage of the Self, Cross and Memory Polarized Reference

The effective (calculated) impedance at the relay location can be impacted by the power system structure and operating conditions prior to the fault occurrence. For example, the measured impedance can be greatly affected by the fault resistance. This may happen because the ground impedance has significant value. As a result of that, the effective (calculated) impedance will be impacted by the presence of the ground impedance in the ground return path [47].

### 6.3.2 The Mutually Coupled Parallel Lines

During the disturbances or during some types unbalanced steady state operation conditions, zero sequence currents flow in parallel lines. Because of these abnormal conditions, a zero sequence voltage is induced in one line due to the flowing of a zero sequence current in the other line. Some protection elements use zero sequence voltages and/or currents as polarizing (reference) quantities to compare them to an operating quantities to protect the transmission line.

If the required fault study is done well for parallel line configurations, these polarizing quantities can work well. Practically, the system configuration can change in steady state operation or during the disturbances, and the response of the protection elements are impacted by the state of the mutual coupling between the parallel lines. The impact of the mutual coupling depends on connection configuration of power system and the fault location. The strongest mutual zero sequence coupling that can be seen is for two parallel lines electrically isolated (no bus connection on both ends). The zero sequence mutual coupling may cause underreaching or overreaching of the mho distance elements, error in the fault location, and the directional misleading of the protective relay [20].

## 6.4 Test Environment

### 6.4.1 System Studied

Figure 6.5 shows the schematic diagram of a 230 kV setting example system [58]. This system with D-FACTS devices is used in this paper to perform this study. The configuration of transmission lines is modeled in the Alternative Transient Program (ATP) as described in [22].

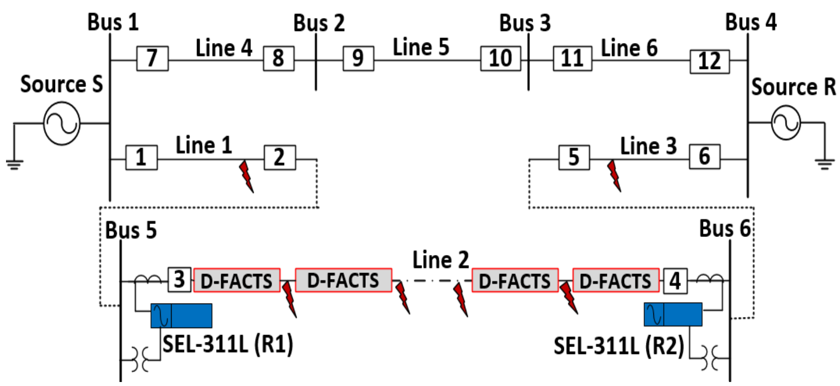



Figure 6.5: A Single Line Diagram of 230 kV Six Bus System with D-FACTS Devices

### 6.4.2 Relay Setting

The date for line 2 that is used for setting its protective relays is summarized in Table 6.1.

Table 6.1: Line 2 Data

| ***Parameter*** | ***Value*** |
|---|---|
| Normal system line to line voltage | 230kV |
| Normal relay current | 5 A secondary |
| Normal frequency | 60Hz |
| Line 2 length | 100 mile |
| Line 2 impedances $Z_{1L}$ | $77.98\angle 82.7\ \Omega$ |
| Line 2 impedances $Z_{0L}$ | $180.98\angle 69.817\ \Omega$ |
| PRT (potential transformer ratio) | 230 kV:115 V=2000 |
| CTR (current transformer ratio) | 500:5=100 |
| Phase rotation | ABC |

### 6.4.3 The Data Collection Process

The D-FACTS device model was developed in [21]. This study is performed in ATP by applying the generated fault simulation results to commercial relays. Also, $MathCAD^{®}$ models of distance relays were used.

The data collection process of this work is performed as shown in Figure 6.6.

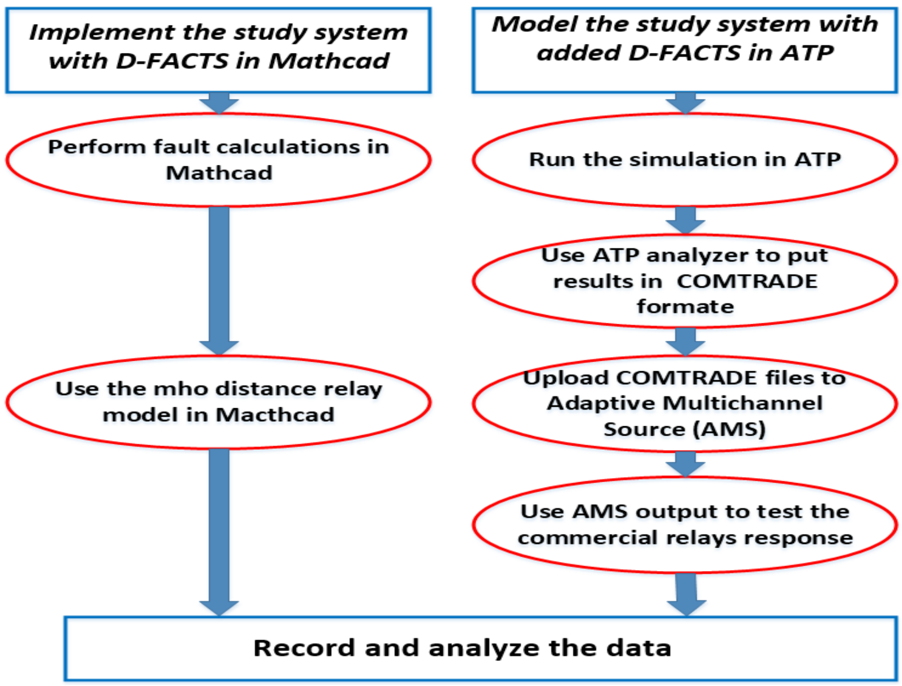



Figure 6.6: The Data Collection Process

## 6.5 D-FACTS Impact on Fault Resistance Coverage

In this section, the effect of fault resistance on protection elements of transmission line 2 in presence of the D-FACTS for single line to ground (SLG) faults is examined in the $MathCAD^{®}$ relay model and in commercial relays.

### 6.5.1 The Response of the Zone 1 and Zone 2 Distance Elements

The fault resistance and the equivalent impedance of D-FACTS devices are added to the fault calculation in $MathCAD^{®}$ tool. Also, a $MathCAD^{®}$ distance elements model is used in this part. Figure 6.7 and Figure 6.8 give an illustration of the impact of fault resistance on distance mho elements of Relay 1 (R1) and Relay 2 (R2), respectively with different values of both D-FACTS compensation and of fault resistance. To illustrate this effect, different values of fault resistance have been used (0 Ω, 4 Ω, and 8 Ω).

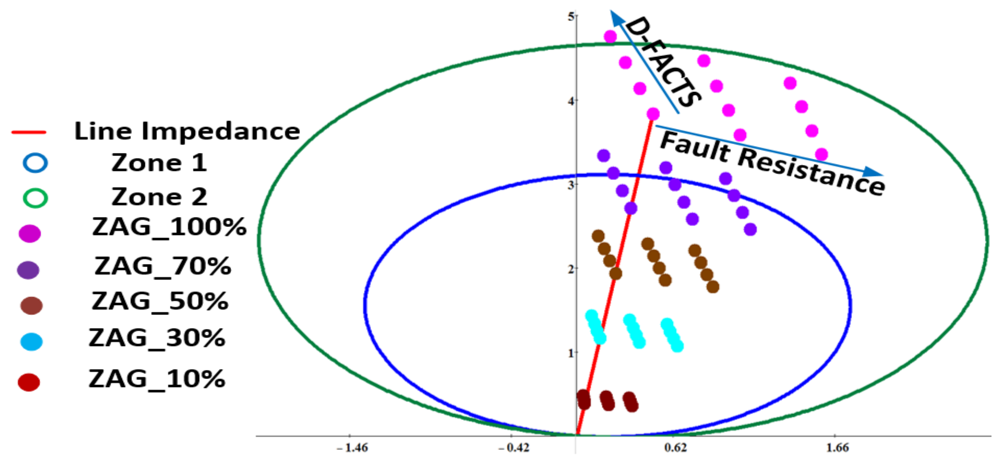



Figure 6.7: Mho Ground Elements Response of R1 for SLG Fault with Different Values of Fault Resistance and D-FACTS Compensation for Forward Power Flow

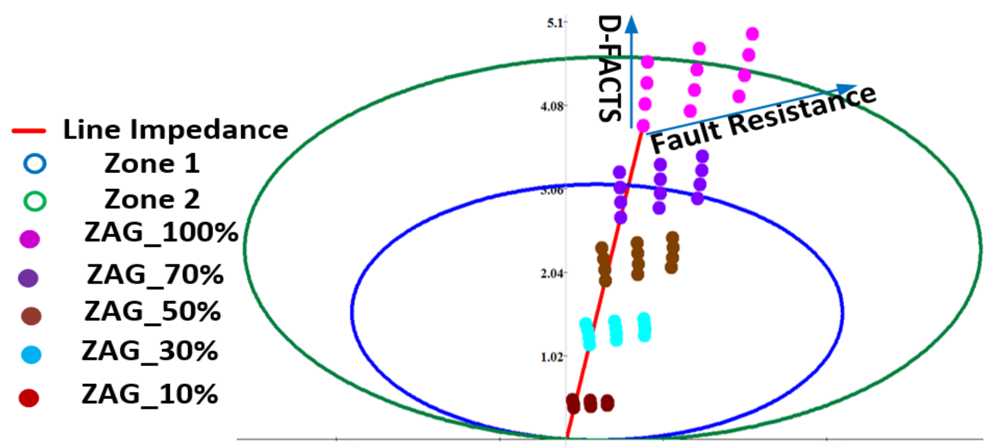



Figure 6.8: Mho Ground Elements Response of R2 for SLG Fault with Different Values of Fault Resistance and D-FACTS Compensation for Reverse Power Flow

In presence of the fault resistance, the actual direction of power flow, forward or reverse with respect to the relay location impacts the measured apparent impedance causing it to move down or up compared to the actual impedance from the relay to the fault location (without fault resistance) as illustrated in Figure 6.7 and Figure 6.8.

The measured effective reach to the fault for Relay 1 moved down gradually as the fault resistance is increased, and that can be seen for different percentages of D-FACTS compensation and fault locations. For SLG fault at 100% of line 2 with D-FACTS compensation equal to 30% of line 2 impedance, the final response position of the effective impedance moved from the point outside zone 2 to the point inside this zone, which helps reduce the underreaching of zone 2 as shown in Figure 6.7.

On the other hand, the measured effective reach to the fault from Relay 2 moved up gradually as the fault resistance is increased for different percentages of D-FACTS compensation and fault locations. For SLG fault at 100% of line 2 with D-FACTS compensation equal to 30% of line 2 impedance, the effective impedance moved from the point inside zone 2 to the point outside this zone, and that causes zone 2 to underreach as shown in Figure 6.8.

### 6.5.2 The Response of the POTT Scheme

Figure 6.9 illustrates the POTT scheme response of the commercial relays. The x-axis represents the fault location. The y-axis represents the trip decision of POTT scheme for different SLG fault locations, different percentages of D-FACTS compensation, and different values of fault resistance.

By observing the response of both relays, the D-FACTS may affect the response of POTT scheme and cause the scheme failed to trip for some fault cases in presence of fault resistance.

The POTT scheme failed to trip for a fault close to the remote end of the line 2 with 20% and 30% D-FACTS compensation. This happened due to zone 2 underreach with fault resistances of 4 Ω or more.

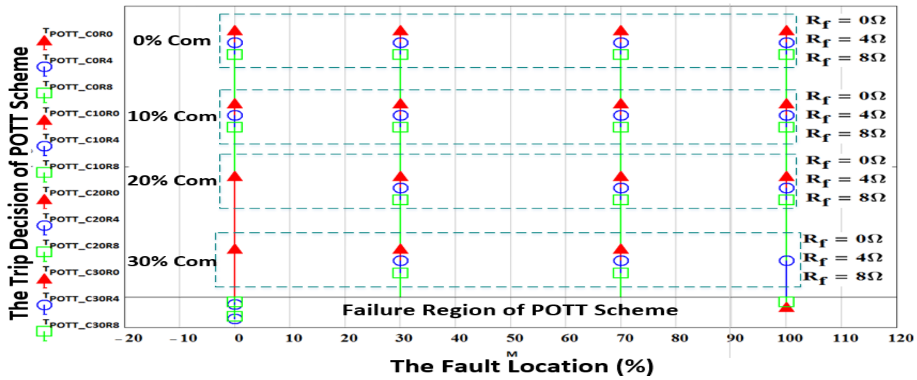



Figure 6.9: POTT Scheme Response of R1 and R2

In general, the implementation of D-FACTS can reduce zone 2 coverage of either end of the transmission line, and that has direct impact on the POTT scheme. The zone 2 element can then underreach in presence of a fault resistance based on the percentage of D-FACTS compensation. For this case, the zone 2 element is underreached with 20% D-FACTS compensation and more.

### 6.5.3 The Response of the Fault Location Element

Figure 6.10 illustrates the response of the fault location elements of protection relays on line 2. The x-axis represents the different values of fault resistance, and the y-axis represents the estimated fault location for different percentages of D-FACTS compensation, different fault locations, and different values of fault resistance.

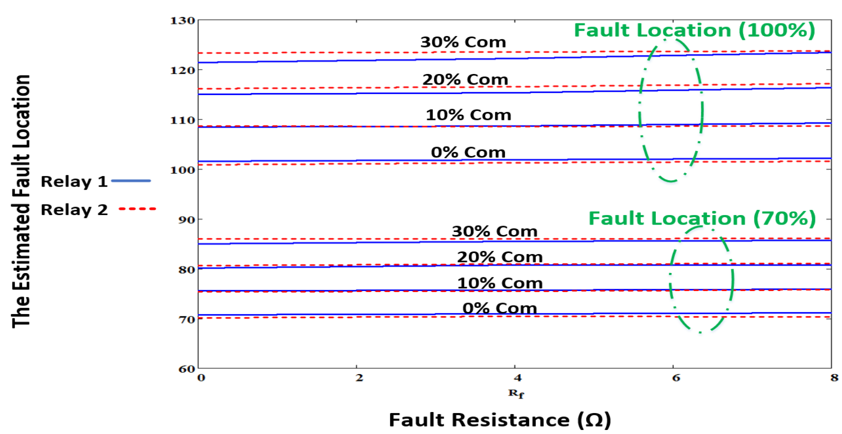



Figure 6.10: Fault Location Element Responses of R1 and R2

The solid blue lines represent the relay 1 fault location element response, and the dashed red lines represent the relay 2 fault location element response. It can be observing that the fault resistance has an insignificant impact on determining the fault location.

## 6.6 The Impact of D-FACTS on The Mutual Coupling of Parallel Lines

The presence of the D-FACTS on one of two or more lines, or on multiple lines may add more complexity and challenge for the protection system of these lines because the changing in transmission line parameters due to this variable series compensation.

The study is performed on double circuit lines in a worst case of connecting configuration of the parallel lines (mutually coupled parallel lines that are magnetically coupled but electrically isolated). The goal here is to determine if the D-FACTS devices have an impact on the mutual coupling between the parallel lines, and as a result, impact the protection system performance of these lines.

Figure 6.11 illustrates this system diagram with mutually coupled parallel lines (line 2 and line 8) in a double circuit configuration. Both ends of these lines are connected to different sources (electrically isolated). The D-FACTS are on conducting mode during the fault. The study is performed for the following two cases:

- The fault on the compensated line (line 2)
- The fault on the uncompensated line (line 8)

### 6.6.1 The Fault on the Compensated Line

The fault is applied on line 2 (compensated line) at different locations and for different percentages of D-FACTS compensation. Figure 6.12 and Figure 6.13 show the response of ground distance elements (zone 1 and zone 2) of relay 1 and relay 2 of line 2, respectively.

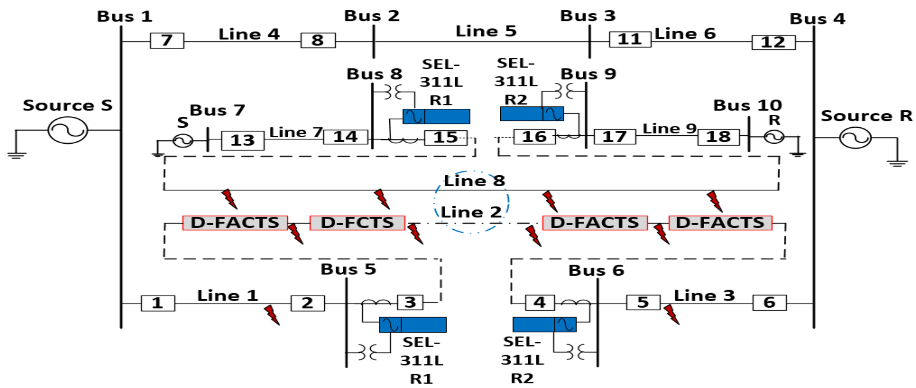



Figure 6.11: Single Line Diagram of 230 kV Study System with D-FACTS on Parallel Lines 2 and 8

The x-axis represents the fault location, and the y-axis represents the trip signal of zone 1 and zone 2 distance elements for different percentages of D-FACTS compensation.

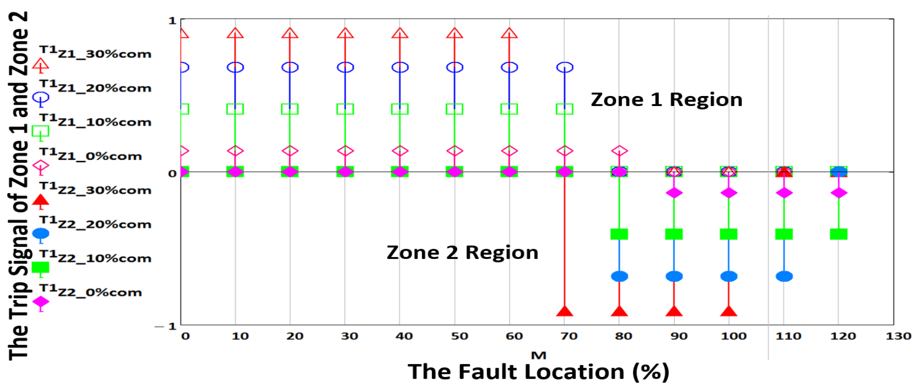



Figure 6.12: Zone 1 and Zone 2 Distance Elements Response of R1 for Different Fault Locations and D-FACTS Percentages

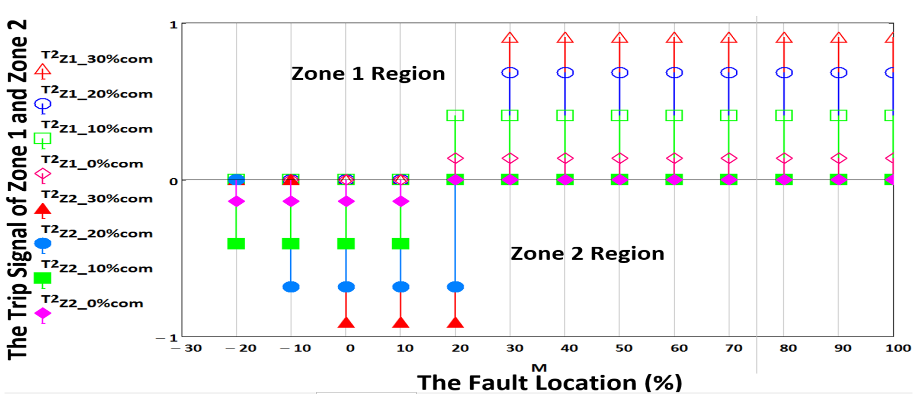



Figure 6.13: Zone 1 and Zone 2 Distance Elements Response of R2 for Different Fault Locations and D-FACTS Values

Figure 6.14 shows the response of the fault location elements of relay 1 and relay 2. The x-axis represents the fault location, and the y-axis represents the estimated fault location.

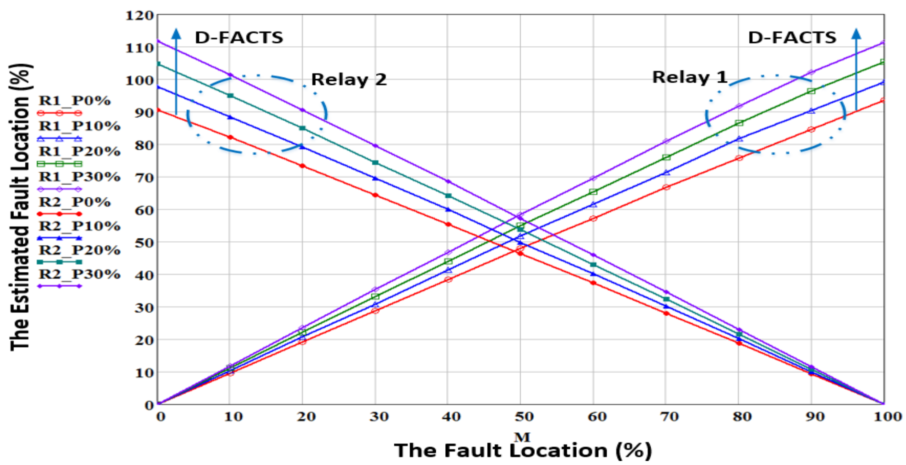



Figure 6.14: Fault Location Elements Response of R1 and R2

The response of zone 1 and zone 2 ground distance elements and the fault location element illustrate that the error in measured impedance by both relays occurred only due to the impact of the existing mutual coupling between the parallel lines (line 2 and line 8) and the presence of D-FACTS in the protected line. Implementing the D-FACTS devices on line 2 would not have significant effect on the mutual coupling between parallel lines 2 and 8 during a fault on the compensated line.

### 6.6.2 The Fault on the Uncompensated Line

In this section, the fault is applied on line 8 (uncompensated line) for different values of D-FACTS compensation on line 2. Figure 6.15 and Figure 6.16 show the response of ground distance elements (zone 1 and zone 2) of relay 1 and relay 2 of line 8, respectively. Figure 6.17 shows the response of fault location elements of relay 1 and relay 2.

The ground distance elements (zone 1 and zone 2) and the fault location elements respond correctly for all generated fault cases. There is no impact of changing the percentage of D-FACTS compensation on the other parallel line. Implementing the D-FACTS devices on line 2 did not have any effect on the mutual coupling between parallel lines 2 and 8 during a

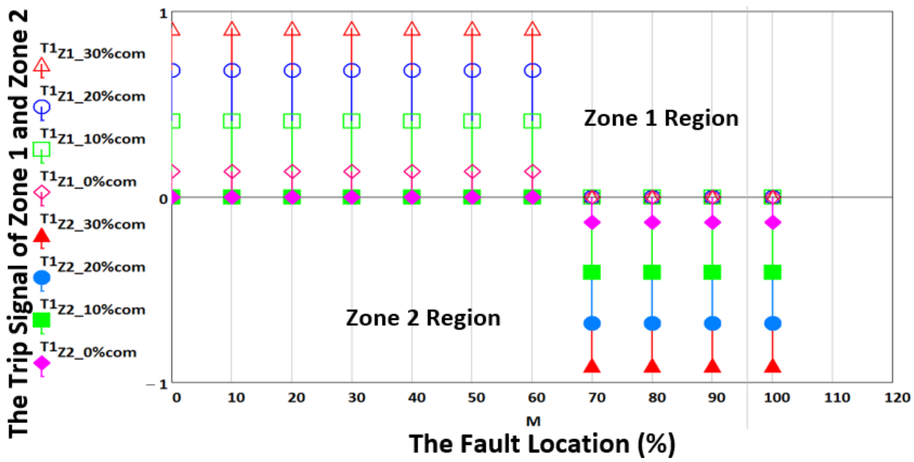



Figure 6.15: Zone 1 and Zone 2 Distance Elements Response of R1 for Different Fault Locations and D-FACTS Compensation Percentages

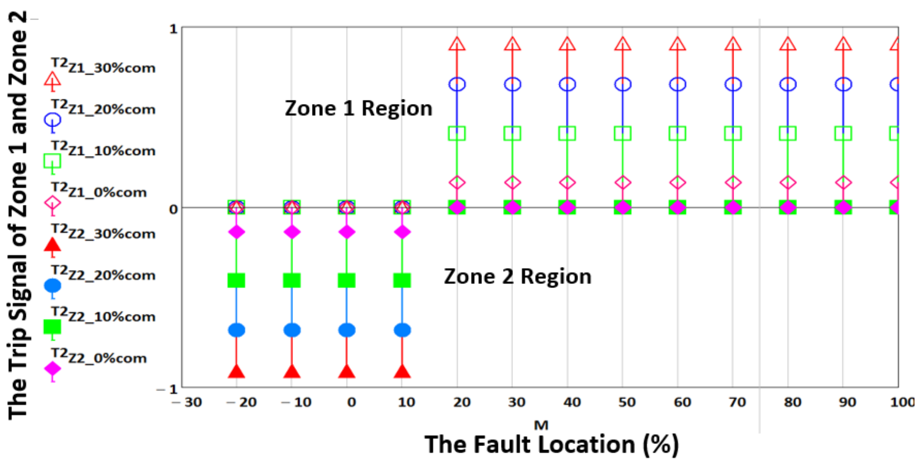



Figure 6.16: Zone 1 and Zone 2 Distance Elements Response of R 2 for Different Fault Locations and D-FACTS Compensation Percentages

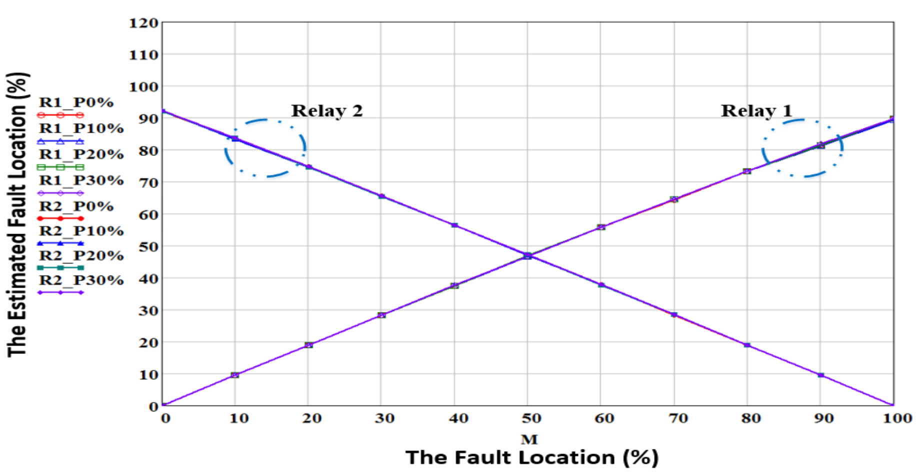



Figure 6.17: Fault Location Elements Response of R1 and R2

fault on the uncompensated line.

## 6.7 Summary and Conclusions

The results illustrate that D-FACTS implementation has significant impact on the response of mho ground distance elements in presence of fault resistance. The effective impedance will be moved down for forward power flow and moved up for reverse power flow as the percentage of D-FACTS devices compensation is increased.

The D-FACTS may help in reducing the zone 1 and zone 2 elements' underreach error when fault resistance is present for forward power flow. On the other hand, these devices may contribute in increasing underreaching behavior when fault resistance is present for reverse power flow. The D-FACTS may cause failure of POTT scheme in the presence of fault resistance because of zone 2 distance element underreach at either end of the line.

D-FACTS devices have an insignificant impact on the fault location elements of these particular commercial relays in presence of fault resistance. These elements are just impacted by the percentage of D-FACTS compensation. There is no impact of the change in the fault resistance on the estimated distance to the fault location. The fault location scheme that is implemented in these commercial relays is not impacted by the change in the fault resistance in general.

The implementation of D-FACTS on either line of the double circuit lines that are magnetically coupled but electrically isolated has insignificant impact on the zero sequence mutual coupling between the parallel lines during the ground faults. The implementation of D-FACTS on one of the parallel lines or on both lines would not add additional complexity and challenge for setting of the ground distance function because the mutual coupling between these lines.

The correction for the estimated value of fault resistance should be employed in the presence of D-FACTS devices. The protection engineers need to increase the apparent fault resistance when doing setting studies. Also, the setting of zone 2 coverage for POTT scheme should be increased to account for the equivalent impedance of D-FACTS.

Future studies will explore the impact of D-FACTS on the dynamic behavior of mho and quadrilateral ground distance elements in presence of fault resistance.

The protection elements response of the commercial relays for SLG fault on line 2 for mutual coupling parallel lines electrically isolated is shown in Tables H.1, and H.2 for percentages of D-FACTS equal to 0% and 30% of the line 2 reactance in Appendix H. The protection elements response of the commercial relays for SLG fault on line 8 for mutual coupling parallel lines electrically isolated is shown in Tables I.1, and I.2 for percentages of D-FACTS equal to 0% and 30% of the line 2 reactance in Appendix I. The protection elements response of the commercial relays for SLG fault with fault resistance in present of D-FACTS devices is shown in Tables J.1, J.2, J.3, and J.4 for percentages of D-FACTS equal to 0% and 30% of the line 2 reactance in Appendix J.

# CHAPTER 7

# An Examination of the Impact of D-FACTS on the Dynamic Behavior of Mho and Quadrilateral Ground Distance Elements

This chapter transcribes a paper that was published in the Proceedings of the 2020 Innovative Smart Grid Technologies (ISGT) [25]. This paper is still pending.

## 7.1 Introduction

Certain factors have led to ever-increasing complexity in power grids such as the addition of renewable energy sources, cost of building new lines and environmental considerations. Flexible AC transmission system (FACTS) devices have been utilized in some cases to solve the power flow variations and overcome these issues since the 1970s [36].

FACTS devices such as Static Synchronous Compensators (STATCOMs) and Static Synchronous Series Compensators (SSSCs) have provided a fast acting solution to solve stability issues. The penetration of these devices is limited because of their high capital costs and somewhat low reliability [6]. A new generation of power electronic devices called series Distributed Flexible AC Transmission System (D-FACTS) devices was proposed to solve the drawbacks of FACTS by providing a distributed solution at low cost and high reliability [68].

D-FACTS have the ability to manage and control the power flow by changing the effective line impedance. They are single phase devices. They can be distributed along the length of a transmission line in different configurations [10]. These devices have been installed on some electrical utilities' lines [12].

The principal work of the distance elements is to ascertain the effective impedance between the relay location and the fault point if a fault occurs. If the effective impedance is smaller than the reach setting, the relay will send a trip signal to the circuit breaker [13], [15], [18].

D-FACTS implementation in an adjacent line can lead to different changes in the expansion and contraction shape of the mho circle of the cross and memory polarized distance elements. Also, the implementation of these devices may impact the response of the quadrilateral distance elements because of effect on the tilt angle setting.

The first objective of this chapter is to provide a demonstration of the effect of D-FACTS on the dynamic expansion and contraction of the mho circle of the distance element. The second goal is to study the effect of D-FACTS devices on the tilt angle setting of the quadrilateral distance elements. This chapter shows how these changes may impact the fault resistance coverage.

Section 7.2 describes the D-FACTS devices concept. Section 7.3 provides an introduction to mho and quadrilateral distance elements. Section 7.4 describes the system studied and the relay settings. Section 7.5 presents results demonstrating the impact of D-FACTS on the expansion and contraction of mho distance elements. Section 7.6 studies the impact of these devices on the tilt angle setting of quadrilateral distance elements and section 7.7 concludes the chapter.

## 7.2 The D-FACTS Concept

Figure 7.1 illustrates how the inductive D-FACTS technology works for a transmission system.

This system includes a generation station which is far from the load center. There are two transmission lines to deliver the electric power to a load center. In such parallel lines, the problem is that one of these lines may constrain the amount of power flow in the whole system because this line reached its capacity before the other line. Traditionally, a utility may reconductor an existing line or build a new line to solve this problem. These solutions are associated with cost, delay, and environmental issues. It is possible to solve such problems at least in the short term by implementing inductive D-FACTS devices in more utilized line to push the power away to flow into less utilized line [10], [44].

Figure 7.2 shows the basic circuit of an inductive D-FACTS device. The injection reac-

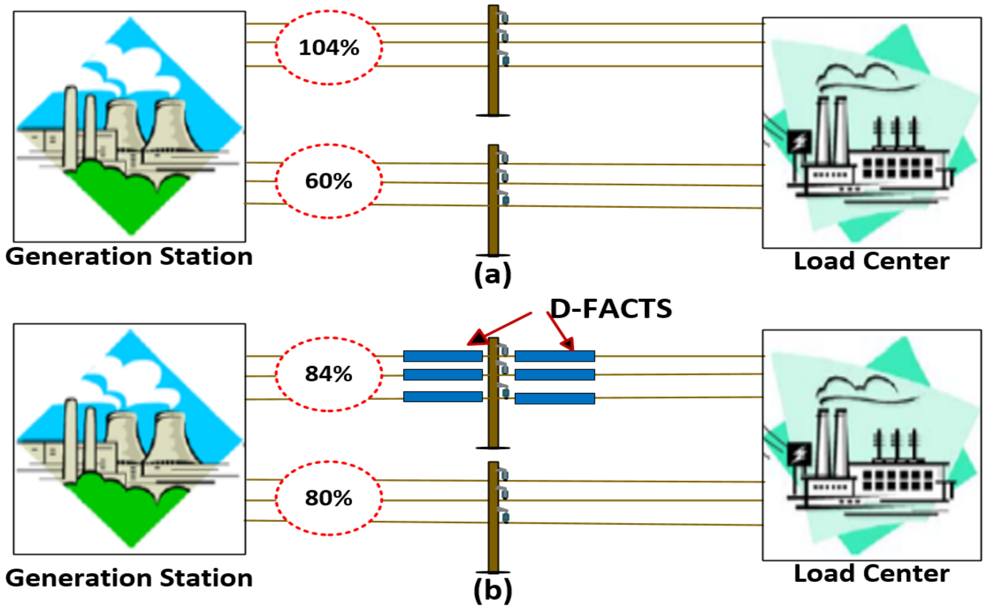



Figure 7.1: The Transmission System Power Flow (a) Without D-FACTS Devices and (b) With D-FACTS Devices

tance is equal to zero during normal operation. When the line current exceeds the setting value, the injection reactance will be equal to the magnetizing inductance of the transformer. The thyristor switches are used for quick bypass for this device, for example, under disturbances.

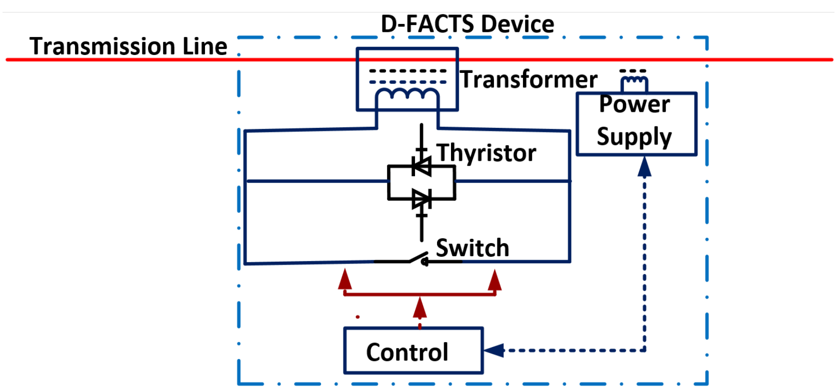



Figure 7.2: The Basic Circuit of the Inductive D-FACTS [7]

In general, D-FACTS devices provide potential benefits to the power system such as reducing the power flow through selected overhead lines, minimizing losses and operation cost, improving the system stability, and controlling the system voltages [7], [43].

## 7.3 Distance Protection

There are two commonly applied types of distance protection elements: mho distance elements and quadrilateral distance elements. The following two subsections discuss each in details.

### 7.3.1 Mho Distance Element

The protection area of the mho distance relay is divided into multiple zones. Modern distance relays can include multiple zones. For example, one configuration is three forward protection zones and one reverse zone as shown in Figure 7.3 [46].

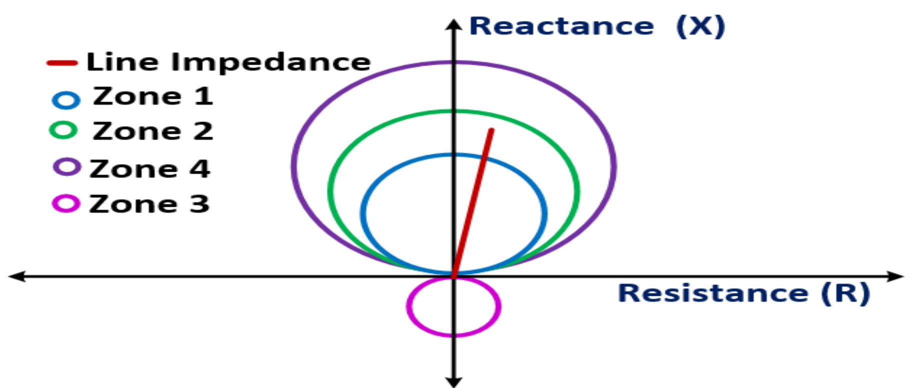



Figure 7.3: Mho Circles (zones) for Self-polarized Elements

The distance elements' calculations inside the relay includes ground elements and phase elements. The mho function will compare the result of the ground and phase element calculation to the mho circle in the current processing interval as these vary with time. During normal operation, the effective distance calculation will be far from the mho circles but when a fault occurs, the effective impedance of the faulted phase will move towards the protection zones. As soon as this effective impedance falls inside the mho circle and stays inside it for a certain period of time, the distance function will pick up and generate a trip command [20].

To make these distance elements more secure and improve the sensitivity, different types of reference polarization have been used in the mho distance elements such as self, cross, and memory polarization. The self polarized mho circle cannot change dynamically, but by using the other two types, it is possible to change the behavior of mho circles to become dynamic and vary with time as a result of the fault [20]. The mho circles of the self, memory, and cross polarized reference for forward and reverse faults are illustrated in Figure 7.4 and Figure 7.5, respectively.

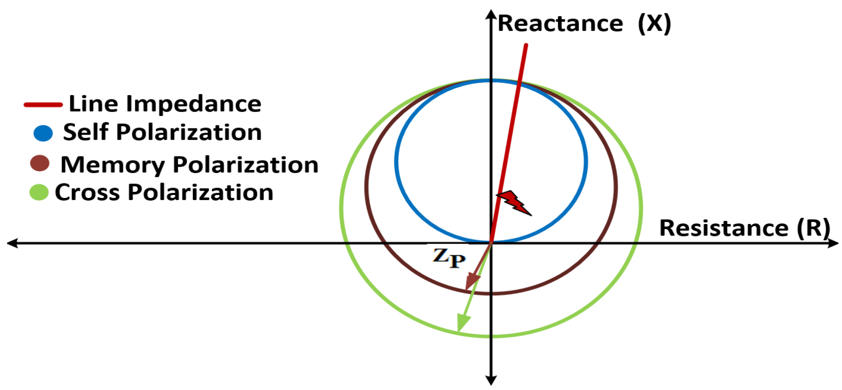



Figure 7.4: Mho Circle Response for the Self, Memory, and Cross Polarized Reference for a Forward Fault

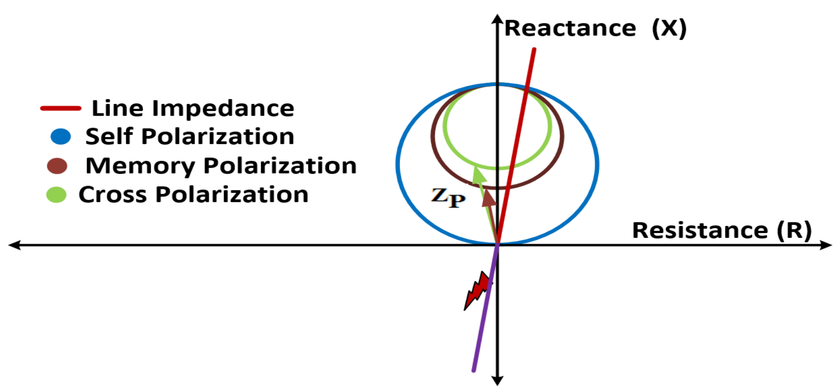



Figure 7.5: Mho Circle Response for the Self, Memory, and Cross Polarized Reference for a Reverse Fault

The $Z_p$ vector in theses figures represents an effective source impedance (the impedance behind the relay), and this term determines the expansion and contraction shape of the mho circle. For a forward fault, the $Z_p$ term will expand back making the mho circle bigger. For a reverse fault, this term will contract to the front and that makes the mho circle smaller and can reduce the issue of having mis-operation due to the response of unfaulted phases to the fault [20], [69].

The calculated impedance can be impacted by the power system structure and the operation conditions prior to the fault occurrence. For example, the measured impedance can be greatly affected by the fault resistance, due to the fault arc or due to presence of objects such as trees, buildings and animals in the ground fault path [47]. Using cross or memory polarizing reference can help in gaining more fault resistance coverage especially for close-in forward faults as illustrated in Figure 7.6.

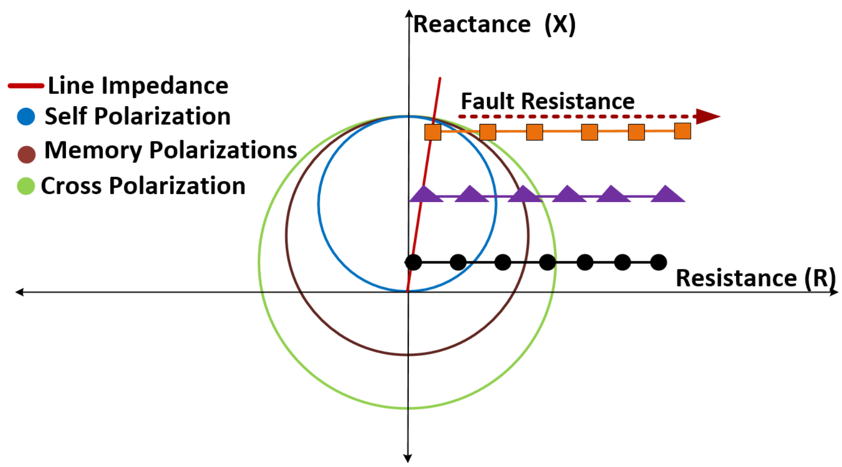



Figure 7.6: The Fault Resistance Behavior of the Self, Cross Polarized Reference as $R_f$ Varies from 0 Ω to 24 Ω

### 7.3.2 Quadrilateral Distance Elements

The quadrilateral distance elements have the ability to handle bigger value of fault resistance specially for a fault close to the reach setting as shown in Figure 7.7. The horizontal line is the reactive reach setting, and the vertical line is the resistive reach setting. The bottom line is the directional element setting. In order for this element to trip, the real and the imaginary part of the effective impedance should fall between the resistive and reactive reach setting and be supervised by the directional elements [20].

If the system is not homogeneous (the angle of the source impedance is not the same as the angle of the line impedance), the effective impedance calculation will have a tilt that

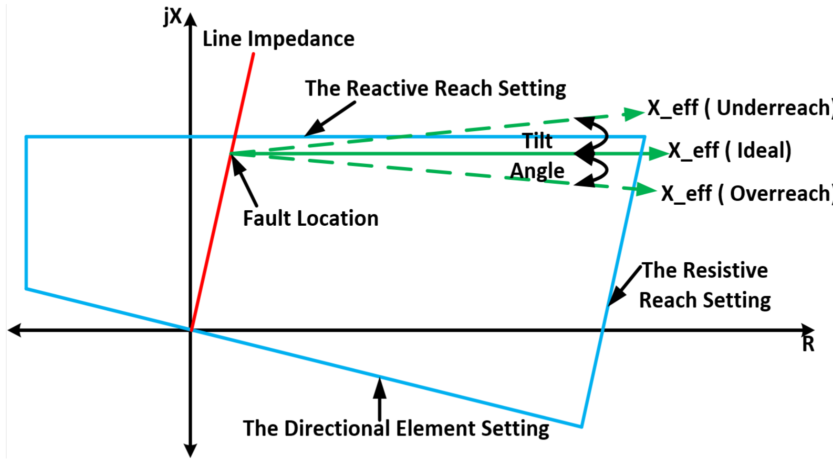



Figure 7.7: The Quadrilateral Distance Element Response with Fault Resistance under Different Power Flow Conditions for Non-Homogeneous System

is associated with its axis and make the effective impedance with fault resistance move up or down based on the power flow conditions. To improve the performance of this scheme, correction for this tilt have been implemented in calculating the effective reactance by one of the protective relays manufacturers. For example, the effective reactance of phase A to ground element ($X_{eff_{AG}}$) can be calculated by using equation (7.1) [20].

$$X_{eff_{AG}} = \frac{Im[V_{AG}[\overline{3I_0\angle\theta_T}]]}{Im[(1\angle\theta_{Z1_{ANG}})[I_A + K_0 3I_0][\overline{3I_0\angle\theta_T}]]} \tag{7.1}$$

Where $\theta_{Z1_{ANG}}$ is the angle of the positive sequence impedance and $\theta_T$ is the angle of the tilt. Without doing the tilt correction, the distance element may underreach or overreach in the presence of a fault resistance as shown in Figure 7.7 [20].

## 7.4 Test Environment

### 7.4.1 System Model

Figure 7.8 shows the schematic diagram of the system studied [58]. The fault study is performed by simulation using $MathCAD^{®}$ models of the Mho and quadrilateral distance relays.

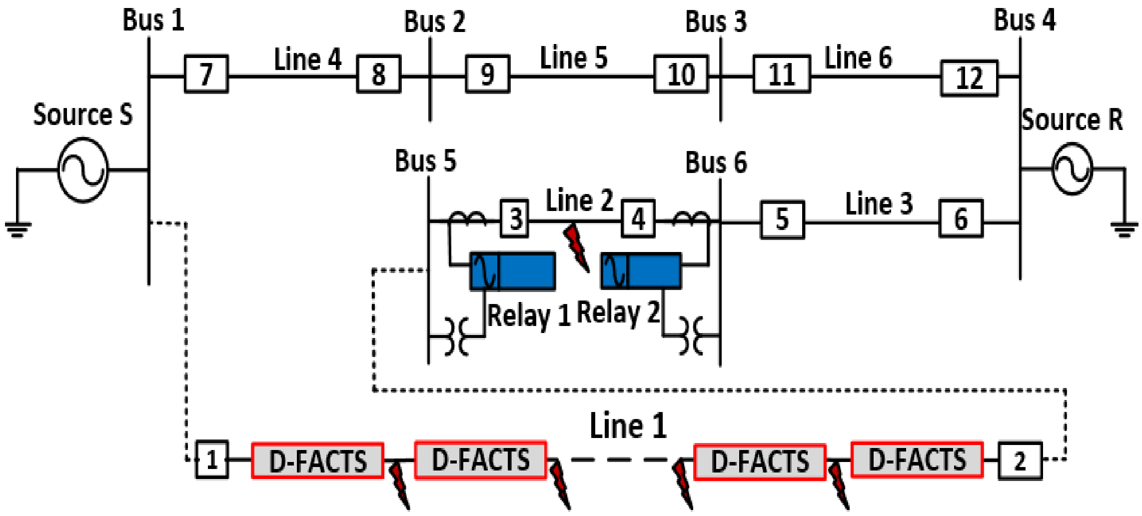



Figure 7.8: A Single Line Diagram of 230 kV Six Bus System with D-FACTS

### 7.4.2 Relay Model and Setting

The data of line 2, which is the one used for setting its protective relay model is summarized in Table 7.1.

Table 7.1: Line 2 Data

| ***Parameter*** | ***Value*** |
|---|---|
| Normal system line to line voltage | 230 kV |
| Normal relay current | 5 A secondary |
| Normal frequency | 60 Hz |
| Line 2 length | 100 miles |
| line 2 impedances $Z_{1L}$ | $77.98\angle 82.7\ \Omega$ |
| line 2 impedances $Z_{0L}$ | $180.98\angle 69.817\ \Omega$ |
| PRT (potential transformer ratio) | 230 kV:115 V=2000 |
| CTR (current transformer ratio) | 500:5=100 |
| Phase rotation | ABC |

## 7.5 The Expansion and Contraction of Mho Distance Elements

As illustrated above, the mho circle expansion and contraction can help in gaining more fault resistance coverage and reduce the issue of having mis-operation, respectively.

### 7.5.1 The D-FACTS Impact on the Expansion of Mho Circle

In this case, D-FACTS are implemented in line 1 of the system (behind the protective relay). They are in conducting mode during single line to ground (SLG) fault in line 2 (in front of the protective relay). Figure 7.9 illustrates how D-FACTS compensation (increasing the line impedance by 30%) impacts the expansion of zone 1 and zone 2 memory polarized mho circles of Relay 1.

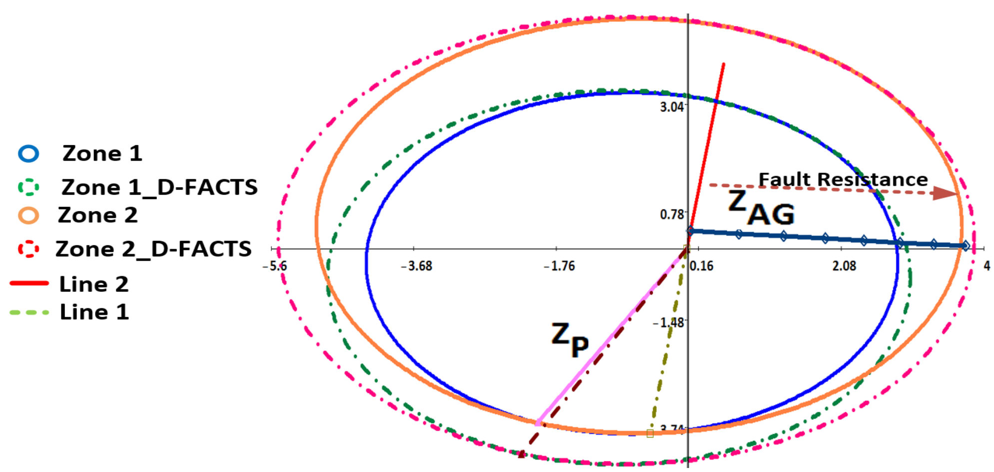



Figure 7.9: The Expansion of Zone 1 and Zone 2 Memory Polarized Mho Circles With (Solid Circle) and Without (Dashed Circle) D-FACTS

The solid and dashed circles represent mho circles' expansion of zone 1 and zone 2 distance elements with and without D-FACTS, respectively. The expansion of mho circles increases as the percentage of D-FACTS compensation increases. In this case, implementing the D-FACTS on the adjacent line (behind the protective relay) can help in gaining more fault resistance coverage especially for close-in forward faults.

### 7.5.2 The Impact of D-FACTS on the Contraction of Mho Circle

In this case, D-FACTS are implemented in line 1 (behind the relay) and an SLG fault occurs in the adjacent compensated line (line 1). Figure 7.10 illustrates how the D-FACTS compensation impacts the contraction of zone 1 and zone 2 of memory polarized mho circles of Relay 1. For a reverse fault, the D-FACTS in the faulted line (behind the relay) impacts

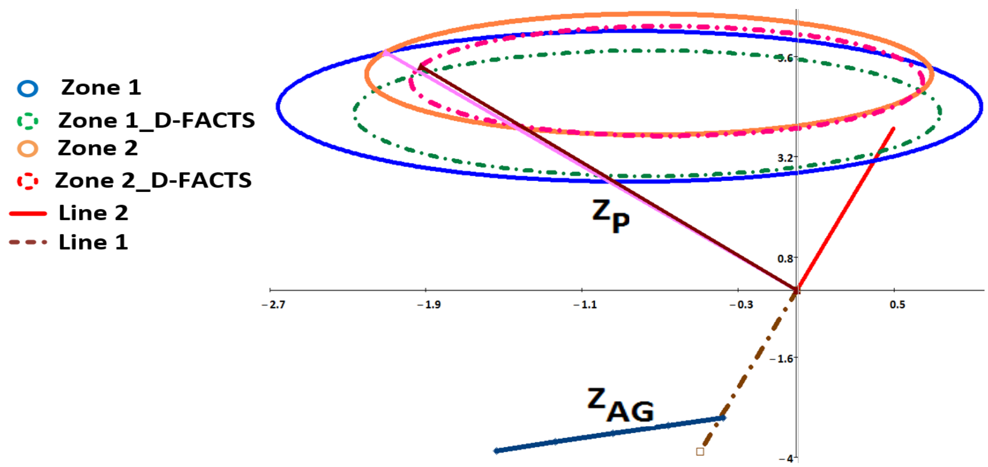



Figure 7.10: The Contraction of Zone 1 and Zone 2 Memory Polarized Mho Circles With (Solid Circle) and Without (Dashed Circle) D-FACTS

the contraction of the mho circles (increases the contraction of the mho circles).

In the second case, the D-FACTS are implemented in line 2 and an SLG fault is applied in line 1 (behind the protective relay). Figure 7.11 illustrates the impact of D-FACTS compensation on the contraction of zone 1 and zone 2 memory polarized mho circles of Relay 1.

Figure 7.11 shows that for a reverse fault, the D-FACTS implementation on the protected line (line 2) can limit the contraction of the mho circles, and this may cause an unwanted trip. The mho circles should shrink enough to avoid the unwanted trip of the faulted or unfaulted distance element. However, because the faulted phase element ($Z_{AG}$) may not move directly in a straight line towards the fault location, it is possible to see a transient associated with the change in ($Z_{AG}$). As a result, the effective impedance may briefly fall in the mho circle. Also, for this case, the unfaulted phase elements ($Z_{BG}$ and $Z_{CG}$) may end up

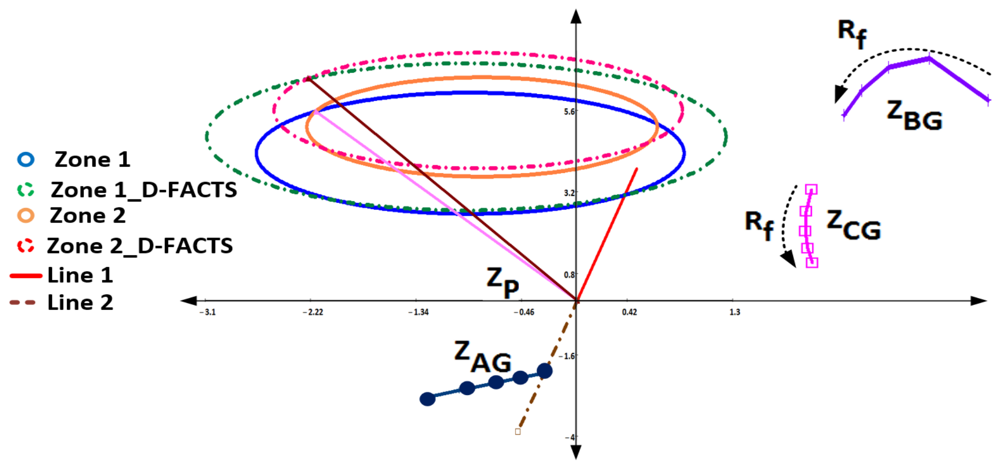



Figure 7.11: The Contraction of Zone 1 and Zone 2 of Memory Polarized Mho Circles With (Solid Circle) and Without (Dashed Circle) D-FACTS

close to mho circles. They may also fall within the protection zones if the D-FACTS devices limit the contraction in the mho circles; especially in the presence of the fault resistance as shown in Figure 7.11.

The D-FACTS implementation may affect the expansion and contraction positively or negatively based on the location of the fault, and placement and percentage of D-FACTS compensation. For forward or reverse faults, implementing the D-FACTS on the adjacent line (behind the relay) can improve the distance elements performance. On the other hand, for a reverse fault, implementing the D-FACTS on the protected line (in front of the relay) may degrade the distance elements security and reliability.

## 7.6 The Impact of D-FACTS on the Tilt Angle Setting of Quadrilateral Distance Elements

As was illustrated above, for a non-homogeneous system, normally the effective impedance calculation of this scheme will have a tilt associated with its axis and make the effective impedance with the fault resistance move up or down. To fix this problem, correction for this tilt is implemented in some relays in the effective impedance equations. Because the tilt correction is based on the predicted relationship between the zero sequence fault current at the relay location and the zero sequence fault current at the fault location, implementing D-FACTS behind the relay may impact this correction negatively as the source impedance varies rapidly. Figure 7.12 and Figure 7.13 illustrate the effects of implementing D-FACTS behind the relay 1 (on line 1) on the existing tilt angle setting of the quadrilateral distance elements with D-FACTS (Blue Line) and without D-FACTS (Green Line) as $R_f$ Varies for an SLG forward fault.

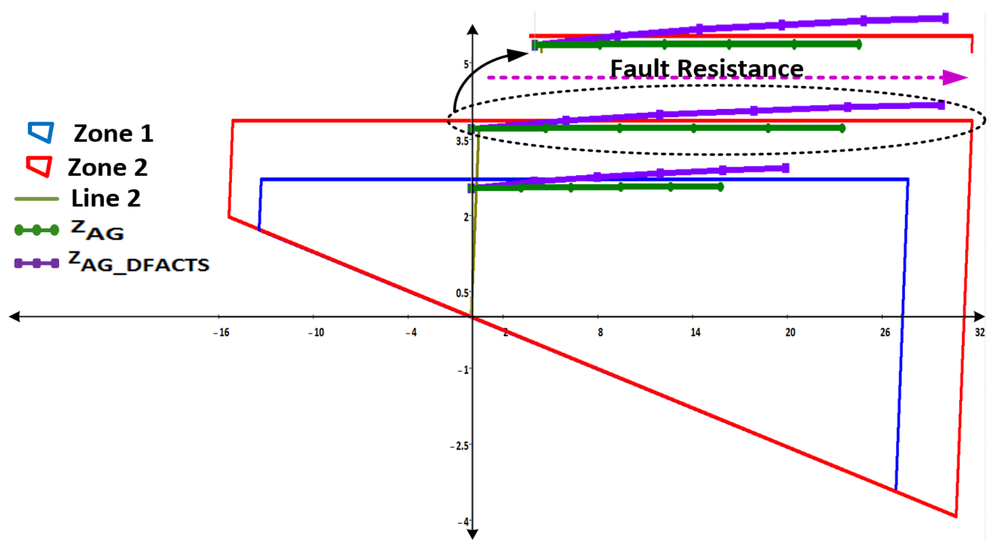



Figure 7.12: The Effect of the Tilt Angle Setting of Relay 1 Quadrilateral Distance Elements With D-FACTS (Blue Line) and Without D-FACTS (Green Line) as $R_f$ Varies

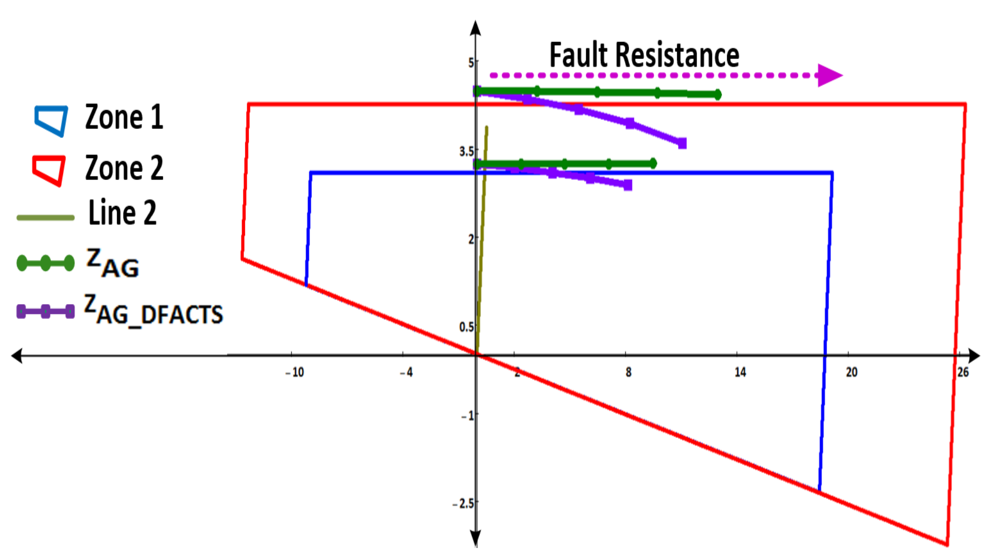



Figure 7.13: The Effect of the Tilt Angle Setting of Relay 2 Quadrilateral Distance Elements With D-FACTS (Blue Line) and Without D-FACTS (Green Line) as $R_f$ Varies

Since it is hard to tell how many D-FACTS devices are going to be in conducting mode or on bypass mode when a fault occurs, or how they may then change state, the value of the tilt correction will not be a fixed value that can be entered in the relay setting. Therefore, this tilt may go up or down as the fault resistance increases for different power flow conditions. In Figure 7.12, the effective impedance tilt of relay 1 moved up as $R_f$ increased. This could cause underreaching (mis-operation) of the zone 1 and zone 2 distance element for a large resistance fault. In Figure 7.13, the effective impedance tilt of relay 2 moved down as $R_f$ increased and that may cause overreaching (unwanted trip) of the zone 1 or zone 2 distance element for a far fault of large resistance.

## 7.7 Summary and Conclusions

D-FACTS devices can provides a distributed solution for managing and controlling the power flow. The presence of these devices may impact protective relay performance because of unpredictable changes on the dynamic behavior of mho circles of the distance function and the change in the tilt response of quadrilateral distance element.

For a forward fault, the D-FACTS implementation in the adjacent line (behind the relay) causes the mho circle to extend back and that increases mho circle expansion and helps in gaining more fault resistance coverage. For a reverse fault, the D-FACTS implementation in the adjacent line (behind the relay) causes the mho circle to shrink and that increases the mho circle contraction and helps in avoiding unwanted trip of the unfaulted distance elements. On the other hand, for a reverse fault, the D-FACTS implementation in a protected line (line 2) limits the mho circle contraction and that may expose this line to unwanted trip.

Implementing the D-FACTS behind the relay makes the tilt of the effective impedance response of the quadrilateral distance element move up or down, and that may cause underreaching or overreaching of zone 1 and zone 2 distance elements for faults with big resistances.

# CHAPTER 8

# Solutions and Recommendations

As it is illustrated in Chapters 5, 6, and 7, the implementation of D-FACTS devices creates challenges for protection. These challenges must be addressed by protection engineers. To deal with these challenges and minimize the influence of these devices, corrections and choices of proper protection schemes for D-FACTS implementation should be made. Based on the results, this chapter provides recommendations for protection schemes for inductive D-FACTS operation and D-FACTS implement.

## 8.1 Corrections and Solutions for D-FACTS and Their Limitations

The corrections and solutions for D-FACTS implementation can be performed by following the approach below:

- Correction to settings for basic distance elements for tripping decision and fault location
- POTT scheme settings correction for the tripping decision
- Current differential scheme solution for the tripping decision
- Fault location relabel update fault location mapping scheme for line crews

### 8.1.1 Possible Distance Element Settings Correction and Their Impacts

Corrections to the relay's settings can be made to minimize the error in the measured (effective) impedance by including the equivalent impedance of the D-FACTS devices in the basic settings of the protective relay (line impedance information and distance elements settings). The new settings of the relay should be implemented based on the maximum value of net inductive reactance D-FACTS installed on the protected transmission line. Note that the inductive D-FACTS are assumed to be:

- Installing D-FACTS devices in a dispersed implementation.
- Assume that all D-FACTS devices remain in conducting mode during the disturbance because the fault current is less than the emergency bypass current threshold of these devices.

The correction for the dispersed implementation when all D-FACTS are in conducting mode during the fault can be made by accounting for the equivalent impedance of these devices in the relay's settings. The new setting for the relay should include the D-FACTS as it is shown in Table 8.1 when zone 1 is set at 80% and zone 2 is set 120% of the total impedance (Line impedance + the equivalent impedance of D-FACTS devices).

Table 8.1: The Correction of the Relay Settings for Different Amounts of D-FACTS Devices

| D-FACTS Devices Compensation | | | Line 2 Impedance | | Impedance of Line 2 + D-FACTS | | Relay setting in the Secondary Side | | |
|---|---|---|---|---|---|---|---|---|---|
| Percentage Of Compensation | Equivalent Reactance (X.com) Ω | Equivalent Inductance ($Z_{Lcom}$) mH | Positive Sequence ($Z_{L1}$) Ω | Zero Sequence ($Z_{L0}$) Ω | Positive Sequence ($Z_{L1com}$) Ω | Zero Sequence ($Z_{L0}$com) Ω | Zone 1 Ω | Zone 2 Ω | k0 Factor |
| Case 1: 0% | j0.00 | 0.00 | 9.91 + j77.35 | 62.44 + j169.86 | 9.91 + j77.35 | 62.44 + j169.86 | 3.119 | 4.679 | 0.421 - j0.172 |
| Case 2: 5% | j3.867 | 0.513 | 9.91 + j77.35 | 62.44 + j169.86 | 9.91 + j81.21 | 62.44 + j173.73 | 3.273 | 4.909 | 0.400 - j0.167 |
| Case 3: 10% | j7.735 | 1.026 | 9.91 + j77.35 | 62.44 + j169.86 | 9.91 + j85.08 | 62.44 + j177.62 | 3.426 | 5.139 | 0.381 - j0.161 |
| Case 4: 15% | j11.60 | 1.539 | 9.91 + j77.35 | 62.44 + j169.86 | 9.91 + j88.95 | 62.44 + j181.47 | 3.580 | 5.415 | 0.364 - j0.156 |
| Case 5: 20% | j15.47 | 2.052 | 9.91 + j77.35 | 62.44 + j169.86 | 9.91 + j92.82 | 62.44 + j185.33 | 3.734 | 5.601 | 0.348 - j0.151 |
| Case 6: 25% | j19.33 | 2.565 | 9.91 + j77.35 | 62.44 + j169.86 | 9.91 + j96.68 | 62.44 + j189.20 | 3.888 | 5.831 | 0.334 - j0.147 |
| Case 7: 30% | j23.20 | 3.078 | 9.91 + j77.35 | 62.44 + j169.86 | 9.91 + j100.55 | 62.44 + j193.07 | 4.042 | 6.113 | 0.321 - j0.143 |

This correction is performed in the relays for the same fault cases for the dispersed implementation that are studied in Chapter 5. Figures 8.1 and 8.2 show the response of the ground distance elements (zone 1 and zone 2) of Relay 1 and Relay 2, respectively. Figure 8.3 shows the response of the fault location elements of Relay 1 and Relay 2 for SLG fault by using the single end Takagi method.

The distance elements of Relay 1 and Relay 2 responded correctly for all generated fault cases for different percentages of D-FACTS compensation. The conventional zone 1 and zone 2 elements detected the fault and generated a trip signals correctly for all implemented values of D-FACTS as illustrated in Figure 8.1 and Figure 8.2. Also, the fault location elements of both relays responded precisely as shown in Figure 8.3. The error in the effective impedance

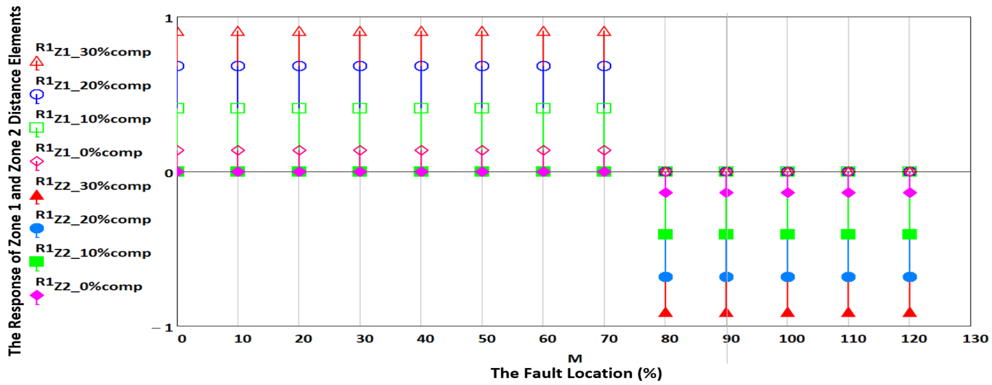



Figure 8.1: Zone 1 and Zone 2 Responses of Relay 1 for SLG Faults

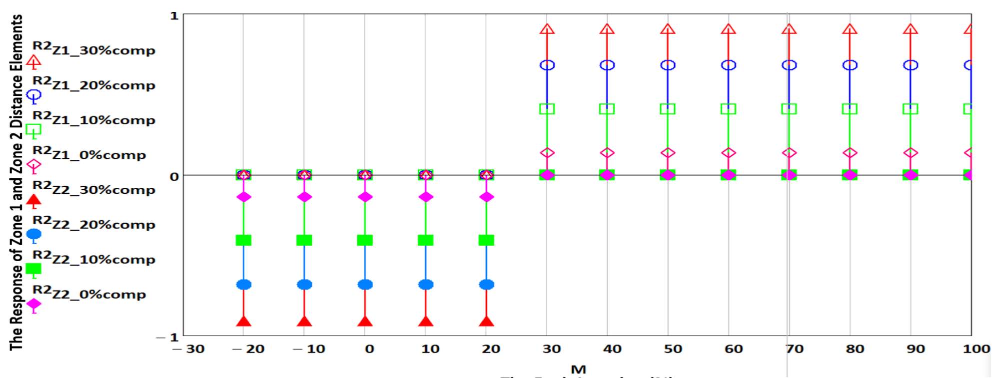



Figure 8.2: Zone 1 and Zone 2 Responses of Relay 2 for SLG Faults

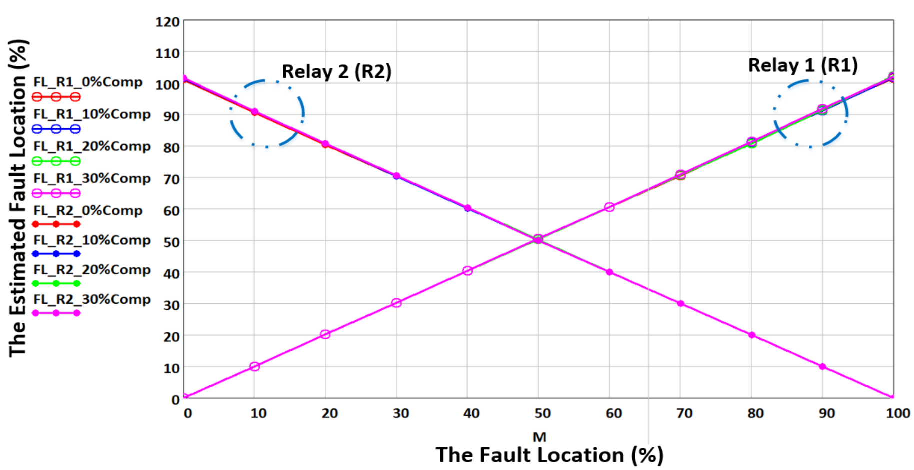



Figure 8.3: Fault Location Element Responses of R1 and R2 for SLG Faults

and the estimated distance to the fault is very small compared to the results from Chapter 5, Section 5.4.4.2 and Section 5.4.4.3.

There are some limitations on the corrections for basic distance element settings:

- First concern that in some fault cases, the fault current may exceed the threshold current of the D-FACTS and that causes part of or all these devices to bypass during the disturbances.
- Second concern that in some D-FACTS implementation cases, it is hard to guarantee a dispersed implementation of D-FACTS with equal spacing.

To illustrate the impact of the dynamic operating mode of D-FACTS during a disturbance on corrections for distance element settings, two additional cases are studied.

- All of the D-FACTS are in bypass mode during the disturbances.
- Some of the D-FACTS partially in bypass mode during the disturbances.

#### 8.1.1.1 All of the D-FACTS in Bypass Mode During the Fault

This section gives an illustration of the impact of D-FACTS when they all switch to bypass mode during fault after the settings correction for D-FACTS performed. As explained earlier, each D-FACTS device has its own protection circuit to protect this device from very high values of fault current. When fault current exceeds the threshold, the protection circuit will bypass this device. In this section, all of the D-FACTS devices are set to switch to bypass mode during the fault.

Figure 8.4 and Figure 8.5 show the response of the ground distance elements (zone 1 and zone 2) of Relay 1 and Relay 2, respectively. Figure 8.6 shows the response of the fault location elements of Relay 1 and Relay 2 for the SLG faults.

Figure 8.4 and Figure 8.5 illustrate the impact of bypassing the D-FACTS devices has on distance elements (zone 1 and zone 2) response when faults accrued in line 2 of the studied

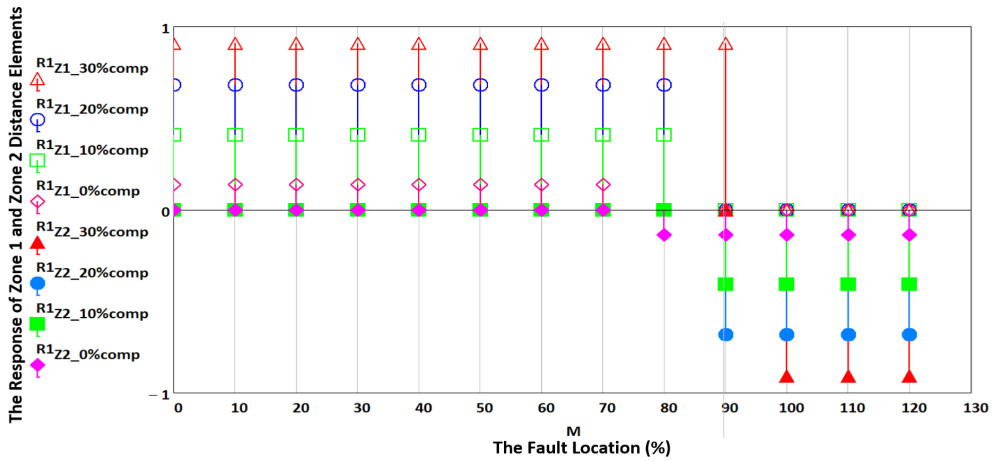



Figure 8.4: Zone 1 and Zone 2 Distance Element Responses of Relay 1 for SLG Faults

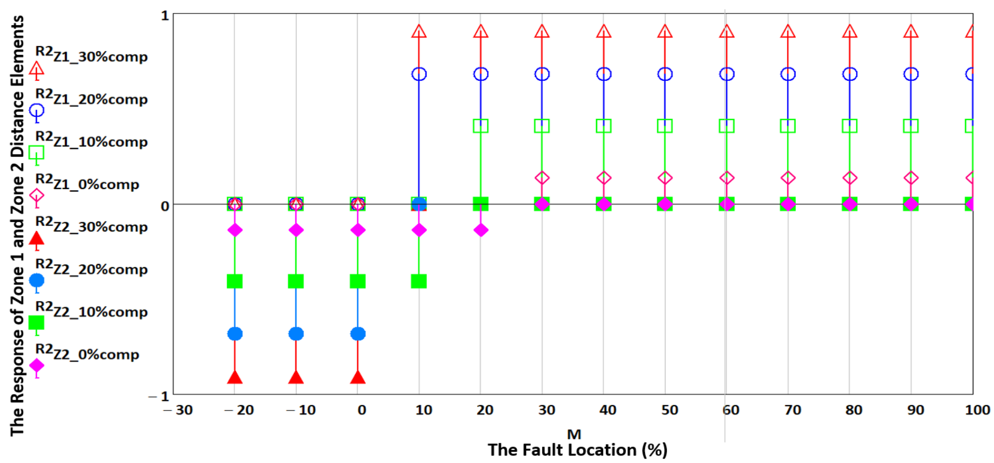



Figure 8.5: Zone 1 and Zone 2 Distance Element Responses of Relay 2 for SLG Faults

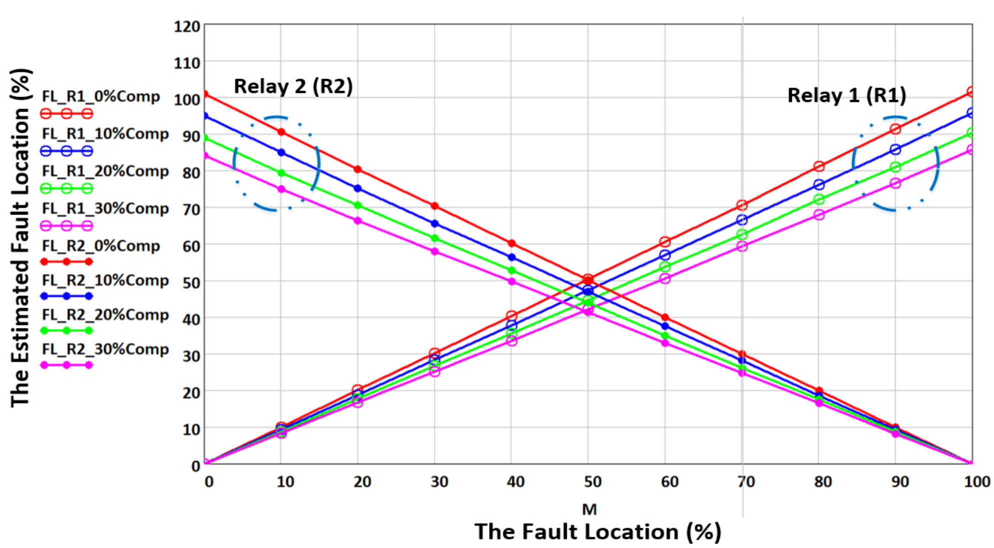



Figure 8.6: Fault Location Element Responses of Relay 1 and Relay 2 for SLG Faults

system. This operating condition caused zone 1 and zone 2 overreach (the relay sees the fault closer than what the actual location) for both relays. The overreaching of zone 1 may cause tripping for a fault beyond the remote bus.

As can be seen from Figure 8.6, switching the D-FACTS devices to bypass mode during a fault with corrected settings can have large impact on fault location results. Both relays were unable to determine the correct fault location due to overreach the fault location elements. The relay displayed fault locations much shorter than the actual especially for high values of D-FACTS compensation.

#### 8.1.1.2 Some of the D-FACTS Devices Switch to the Bypass Mode During the Fault

In this section, part of D-FACTS devices are set to operate in bypass mode during the fault. Based on the fault location, some of the devices switched to bypass mode because the fault current exceeds their bypass threshold. For a fault farther away from the relay, the fault current is less than the bypass threshold and the D-FACTS devices to remain in the conducting mode during the fault.

Figure 8.7 and Figure 8.8 illustrate the impact of D-FACTS on the distance elements (zone 1 and zone 2) response when some of the devices switched to the bypass mode during the fault. As shown in Figure 8.7, the distance elements of Relay 1 responded correctly for most fault cases, but these elements overreached for some fault locations. Figure 8.8 shows that when a SLG fault is applied at 80% of line 2, the zone 1 pickup for Relay 2 responded incorrectly for the D-FACTS equivalent impedances of 5%, and 10% of the line 2 impedance. The distance elements of Relay 2 overreached for the fault locations from 0% to 70% of line 2 with D-FACTS compensation equal to 30% of line 2 impedance. Figure 8.9 shows the fault location element responses of Relay 1 and Relay 2.

As can be seen in Figure 8.9, operation with some of the D-FACTS devices partially in bypass mode during a fault can create undetermined response behavior for fault location

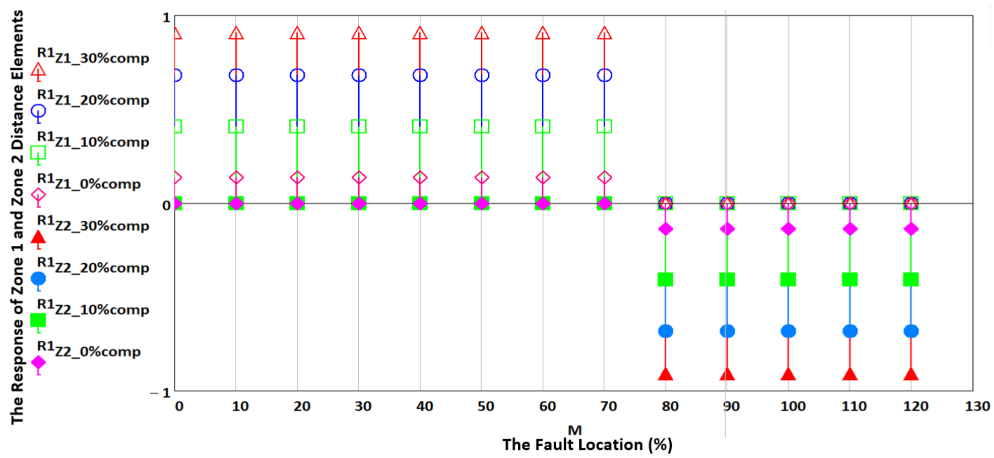



Figure 8.7: Zone 1 and Zone 2 Distance Element Responses of Relay 1 for SLG Faults

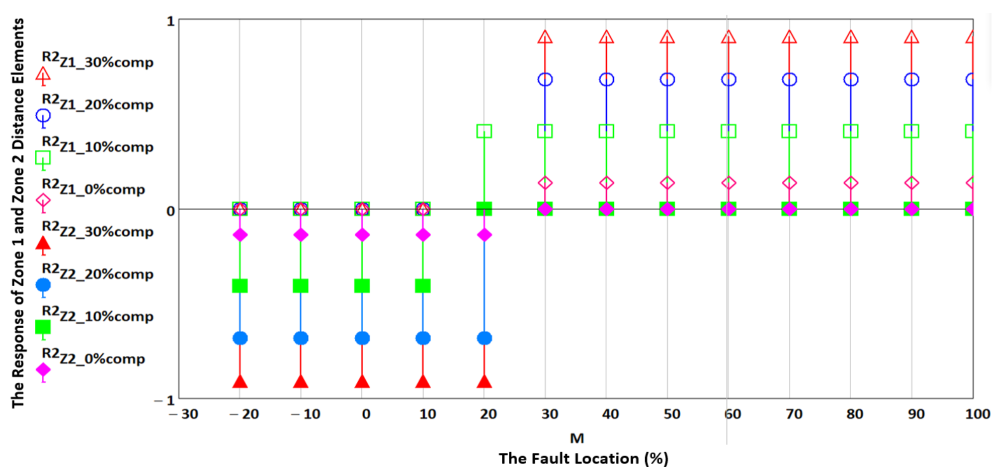



Figure 8.8: Zone 1 and Zone 2 Distance Element Responses of Relay 2 for SLG Faults

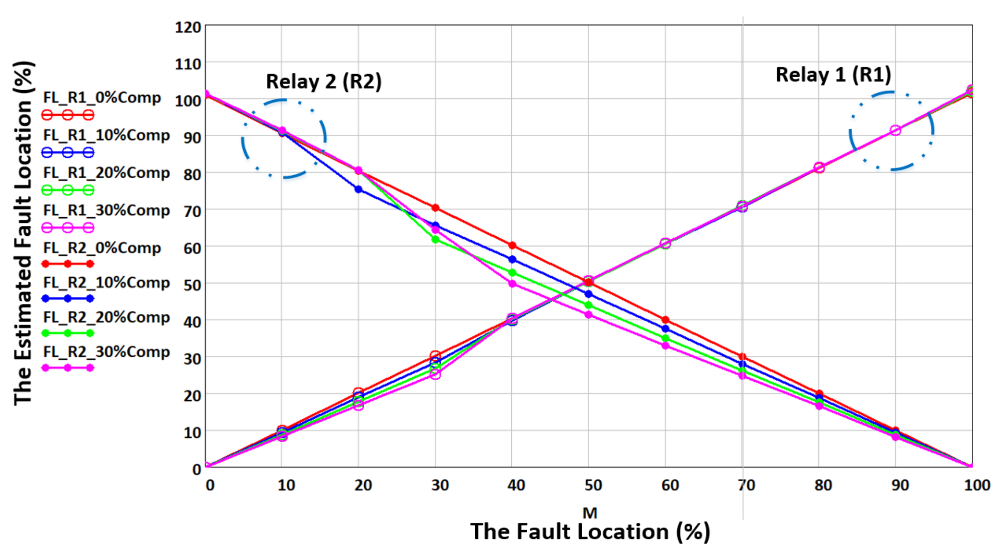



Figure 8.9: Response of the Fault location Elements of Relay 1 and Relay 2 for SLG Fault

elements. Also, for these particular cases, the POTT scheme was not impacted by these fault cases because the zone 2 was overreaching, not underreaching.

### 8.1.2 The POTT Scheme Correction

In some cases, operation of D-FACTS devices in conducting mode during a faults is not guaranteed, and dispersed implementation of D-FACTS is impossible. The POTT scheme correction solution should be chosen to minimize the D-FACTS influence on the trip response of distance elements to avoid the zone 2 distance element underreach for the elements used in the communication aided scheme to improve protection system performance. The zone 2 reach setting should be increased to account for the expected maximum equivalent impedance of the D-FACTS in the protected line. This option works best in relays with a large enough number of distance elements to use different zone 2 for the backup zone and the POTT scheme.

Figure 8.10 illustrates the POTT scheme response on line 2 for different locations of SLG faults, and different values of the D-FACTS compensation (from 0% to 30% of the line 2 reactance) before increasing the zone 2 reach setting for POTT scheme.

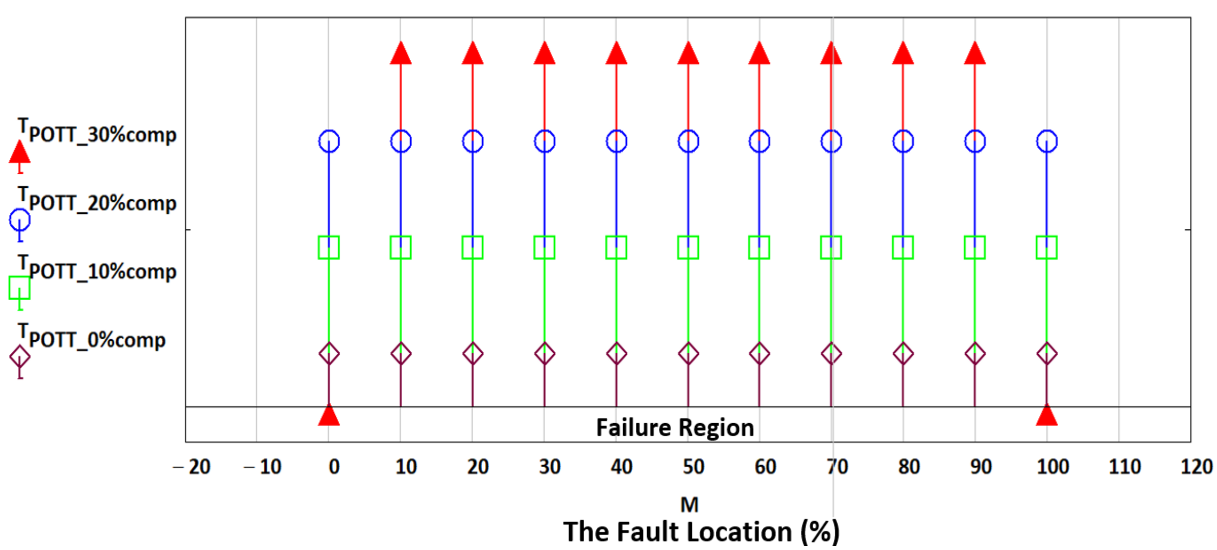



Figure 8.10: POTT Scheme Response for SLG Faults for Different Fault Locations and Different Degrees of Compensation with Uncompensated Zone 2 Reach

By observing the response of both relays in Figure 8.10, the D-FACTS devices reduce the zone 2 coverage, and that can cause failure of POTT scheme for some fault cases (for 30% D-FACTS devices compensation and higher).

To determine the new zone 2 reach setting to use with the POTT scheme, it is important to know the maximum equivalent impedance of D-FACTS compensation implemented in the protected line. For this study, the highest percentage of D-FACTS compensation is 30% of the protected line impedance. Based on Table 8.1, the new zone 2 reach setting of POTT scheme should be at least 160% of the protected line (line 2) impedance.

Figure 8.11 illustrates the POTT scheme response for different locations of SLG faults of line 2 and different degrees of D-FACTS compensation after increasing the POTT zone 2 reach setting to 160%.

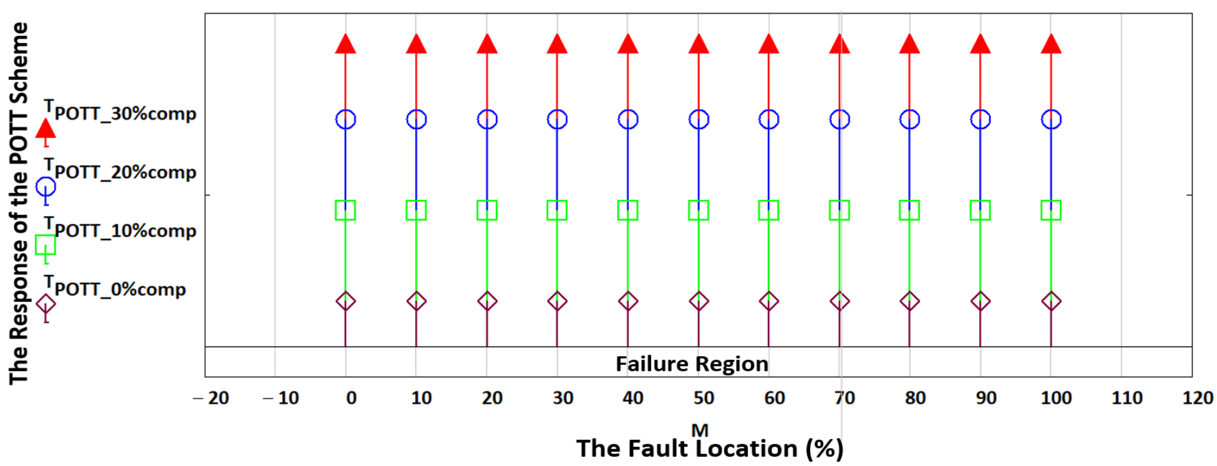



Figure 8.11: POTT Scheme Response for SLG Faults for Different Fault Locations and Different Degrees of Compensation with Corrected Zone 2 Reach

The POTT scheme responded correctly to different degrees of D-FACTS compensation after implementing the zone 2 settings correction.

### 8.1.3 The Current Differential Scheme Solution

For high degrees of D-FACTS compensation, line current differential schemes can be the best solution to deal with most of the D-FACTS implementations challenges. Figure 8.12

illustrates the current differential element responses for high percentages of D-FACTS compensation (up to 70% of the protected line impedance).

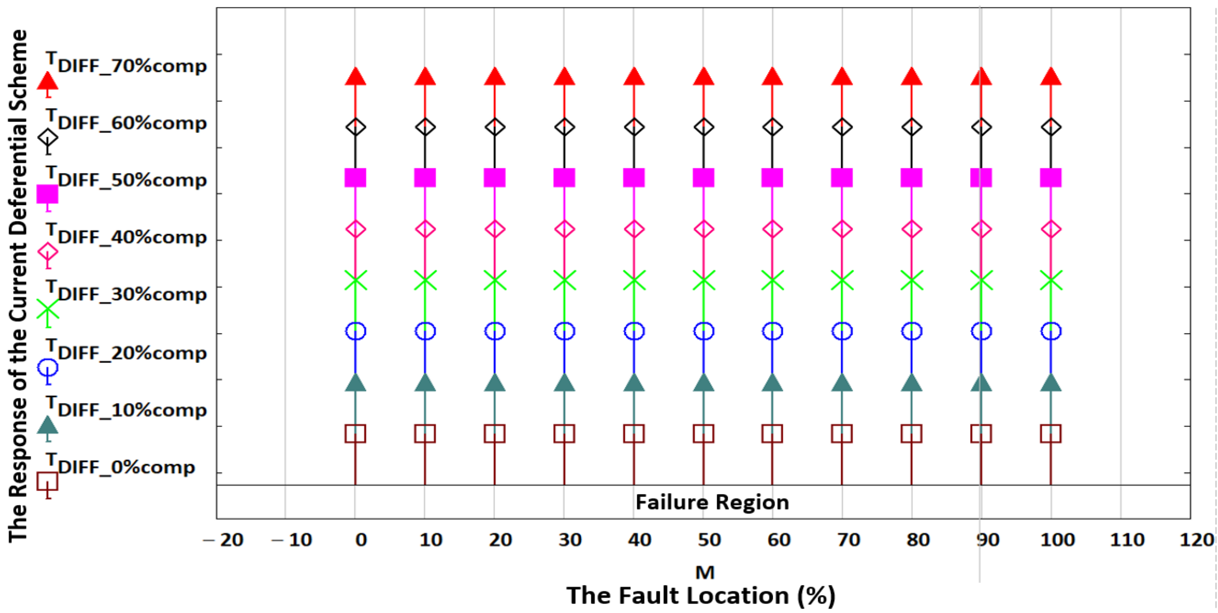



Figure 8.12: The Responses of the Differential Scheme for SLG Faults at Different Locations and Degrees of D-FACTS Compensation

The current differential scheme can be used as a primary protection for a line with high percentages of D-FACTS compensation.

### 8.1.4 More Reliable Fault Location Scheme Settings for D-FACTS Compensated Lines

Fault location elements are often implemented in protective relays to determine the approximate location of the fault. Based on the fault location information, line crews can be sent to inspect short distance of the line. This can provide significant benefits to the utility such as increasing the customers' satisfaction by reducing the outage duration and operating cost. In most protective relays, the fault location elements estimate the fault location based on the measured voltages and currents that are seen by this relay. The accuracy of the fault location element is based on its algorithm and the fault environment such as the presence of a fault resistance, load flow and/or mutual coupling with parallel lines [70], [71], [72], [73].

There are different schemes that are commonly used to estimate the fault location that can be classified as single-ended impedance based schemes and double-ended impedance based schemes, and traveling wave schemes. In this section, the influence of D-FACTS implementations on the accuracy of the single-ended reactance method, the single-ended modified Takagi method, and the doubled-ended Takagi method are examined to determine the recommended scheme to use on D-FACTS compensated lines.

#### 8.1.4.1 Single-Ended Reactance Method

In this method, the fault location relative to each end of the transmission line ($m_{Relay1R}$ and $m_{Relay1R}$) is determined based on the measured voltages and currents by using equations (8.1) and (8.2) and for phase A to ground fault at Relay 1 (sending end) and Relay 2 (receiving end), respectively [73]. This method is mainly used in older relays and they are prone to error caused by fault resistance and power flow.

$$m_{Relay1_{reactance}} = \frac{Im(\frac{V_{AG}}{I_A + k_0 3I_0})}{Im(Z_1)} \tag{8.1}$$

$$m_{Relay2_{reactance}} = \frac{Im(\frac{V_{AG}}{I_A + k_0 3I_0})}{Im(Z_1)} \tag{8.2}$$

Where $V_{AG}$, $I_A$, $I_0$, $Z_1$ and $k_0$ represents the phase voltage, faulted phase current, positive sequence impedance and the zero sequence correction factor for each relay, as was used in the distance calculation.

#### 8.1.4.2 Single-Ended Modified Takagi Method

The modified Takagi method was developed to reduce the influence of the power flow on the fault location calculation. The distance elements for both ends of the line ($m_{Relay1T}$ and $m_{Relay1T}$) use the negative sequence current as a polarizing reference instead of using just the faulted phase currents. Equations (8.3) and (8.4) are used to calculating the distance to the fault relative Relay 1 and Relay 2, respectively [73].

$$m_{relay1_{Takagi}} = \frac{Im[V_{AG}(\overline{I_2})]}{Im[(Z_1)(I_A + K_0 3I_0)(\overline{\overline{I_2})]}} \tag{8.3}$$

$$m_{relay2_{Takagi}} = \frac{Im[V_{AG}(\overline{I_2})]}{Im[(Z_1)(I_A + K_0 3I_0)(\overline{\overline{I_2})]}} \tag{8.4}$$

Where $V_{AG}$, $I_A$, $I_0$, $k_0$ and $I_2$ represent the phase voltage, faulted phase current, the zero sequence current, the zero sequence correction factor, and the negative sequence current for each relay, respectively.

#### 8.1.4.3 Double-Ended Method

Double-Ended methods were developed to overcome challenges faced by fault location algorithms such as the presence of fault resistance, zero sequence mutual coupling, and load flow. The only drawback of this method that it requires a time alignment of the measured voltages and currents from both ends of the protected line. This method uses the calculated negative sequence response for unbalance fault (negative sequence voltages and currents) as inputs to equations (8.5) and (8.6) [70].

$$m_{relay1_{twoended}} = \frac{(V_{S2} - V_{R2} + I_{R2}Z_2)}{(I_{S2} + I_{R2}Z_2)} \tag{8.5}$$

$$m_{relay2_{twoended}} = \frac{(V_{R2} - V_{S2} + I_{R2}Z_2)}{(I_{R2} + I_{S2}Z_2)} \tag{8.6}$$

Where $V_{S2}$, $V_{R2}$, $I_{S2}$, $I_{R2}$, and $Z_2$ represent the negative sequence voltage of the sending end relay, the negative sequence voltage of the receiving end relay, the negative sequence current of the sending end relay, the negative sequence current of the receiving end relay, and the negative sequence impedance, respectively.

To evaluate the fault location algorithms with D-FACTS devices, power flow and fault calculation are performed in $MathCAD^{®}$ for the studied system with D-FACTS devices. The D-FACTS are implemented on line 2 of the study system with different degrees of D-FACTS compensation (up to 30% of the line 2 reactance). The measured voltages and currents used in fault location equations are impacted by the changes in the percentages of D-FACTS compensation. The zero sequence correction value ($k_0$) and line impedance $Z_1$ and $Z_2$) are based on the settings of the protective relays (without D-FACTS devices), which were determined base on the conductor and tower characteristics.

Figure 8.13 and Figure 8.14 show the estimated fault location calculated by Relay 1 and Relay 2 for different fault locations and percentages of D-FACTS compensation using the three different method to determine the distance to the fault. The x-axis represents the percentages of D-FACTS compensation (from 0% to 30% of the line reactance) and the y-axis represents the estimated fault location found using the reactance, Takagi, and double-ended methods.

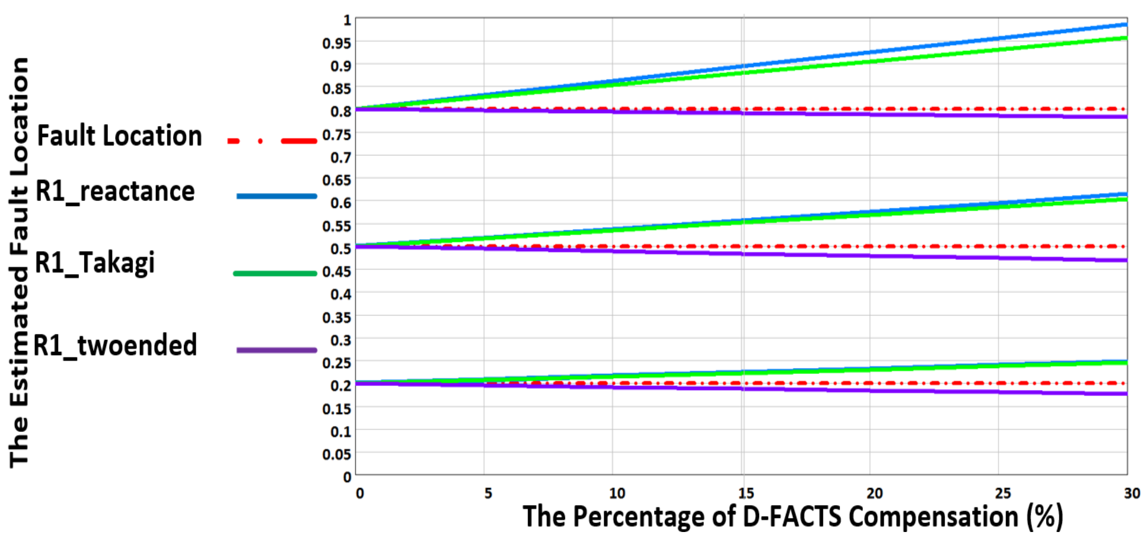



Figure 8.13: The Response of the Different Fault Location Schemes of Relay 1 for SLG Faults at 20%, 50%, and 80% of Line 2 for Different Degrees of D-FACTS Compensation

As is illustrated by Figure 8.13 and Figure 8.14, the reactance and Takagi methods are directly impacted by the D-FACTS implementation. The error in the estimated fault location increased as the percentage of D-FACTS compensation increased. On the other hand, the

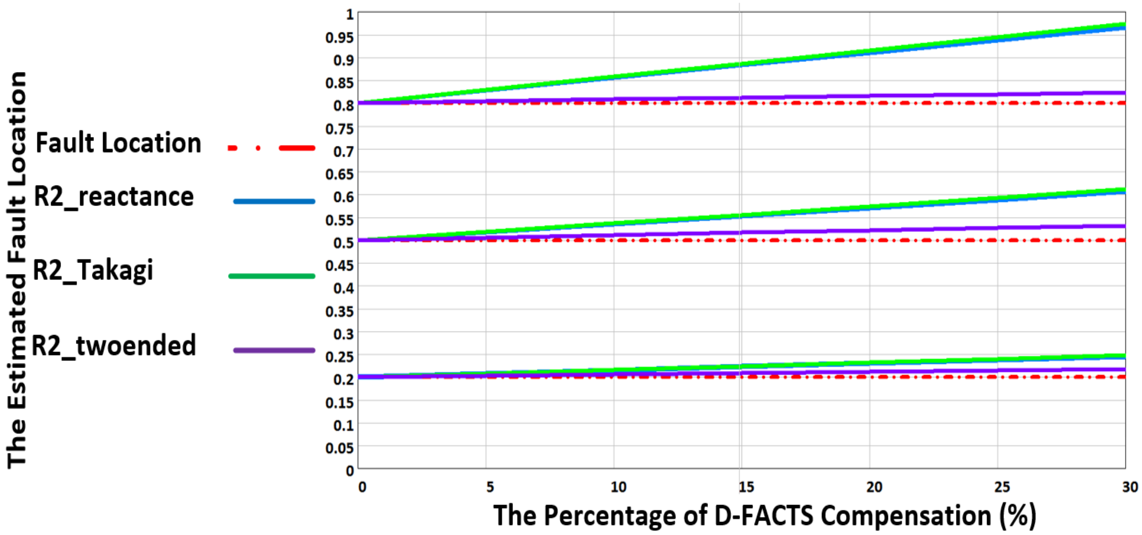



Figure 8.14: The Response of the Different Fault Location Schemes of Relay 2 for SLG Faults at 20%, 50%, and 80% of Line 2 for Different Degrees of D-FACTS Compensation

double-ended method did a good job in reducing the error in the estimated distance to the fault in presence of D-FACTS devices.

Table 8.2 shows the percentage error on the estimated distance to fault for the reactance, Takagi, and double-ended methods when applying faults with no fault resistance at 20%, 50%, and 80% of line 2 and for different degrees of D-FACTS devices compensation.

Table 8.2: The Percentage Error on the Estimated Distance to Fault of Reactance, Takagi, and Double Ended Methods as D-FACTS Compensation Varies

| Percentage of D-FACTS Compensation | Fault Location | Fault Location Error (Relay 1) | | | Fault Location Error (Relay 2) | | |
|---|---|---|---|---|---|---|---|
| | | Reactance (%) | Takagi (%) | Two-Ended (%) | Reactance (%) | Takagi (%) | Two-Ended (%) |
| 0% of the line reactance | 20% | 0 | 0 | 0 | 0 | 0 | 0 |
| | 50% | 0 | 0 | 0 | 0 | 0 | 0 |
| | 80% | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | | |
| 10% of the line reactance | 20% | 7.83 | 7.465 | -4.085 | 6.872 | 7.214 | 1.022 |
| | 50% | 7.586 | 6.824 | -2.21 | 6.998 | 7.388 | 2.21 |
| | 80% | 7.734 | 6.536 | -0.779 | 7.585 | 7.925 | 3.115 |
| | | | | | | | |
| 20% of the line reactance | 20% | 15.665 | 14.94 | -7.855 | 13.755 | 14.436 | 1.966 |
| | 50% | 15.178 | 13.64 | -4.272 | 14.006 | 14.786 | 4.276 |
| | 80% | 15.475 | 13.045 | -1.513 | 15.165 | 15.845 | 6.055 |
| | | | | | | | |
| 30% of the line reactance | 20% | 23.5 | 22.42 | -11.35 | 20.65 | 21.67 | 2.841 |
| | 50% | 22.774 | 20.45 | -6.202 | 21.022 | 22.194 | 6.208 |
| | 80% | 23.221 | 19.525 | -2.204 | 22.745 | 23.755 | 8.82 |

## 8.2 Recommended Practices for D-FACTS Implementations

To minimize the negative impact of D-FACTS devices on protection system performance with little impact on compensation performance, the implementation of inductive D-FACTS devices should satisfy the following requirements:

- The D-FACTS should be installed with the dispersed implementation technique. This will minimize the error in the effective impedance seen by the protective relays.
- The D-FACTS should be installed with equal spacing over the length of the transmission line. This balances the distribution of the total impedance over the length of the line. These devices should be attached next to the towers because of their weight.
- A fault calculation study should be conducted to determine the operational mode during likely fault scenarios. These devices can operate on two modes, conducting mode and bypass mode based on the value of the fault current. Each device may switch to a bypass mode to protect itself from high fault current.

## 8.3 Recommended Practices for Protective Relay Settings for D-FACTS Compensated Lines

To minimize the impact of D-FACTS on the protection system, the following relay settings corrections should be implemented:

- The settings of the distance element zones should account for the equivalent impedance of D-FACTS devices. These settings are usually based on the calculated impedance of the transmission line from tower geometry, conductor parameters, and earth characteristics. The distance element response is based on the effective impedance measured by the protective relay. To ensure that the relay responds correctly, the equivalent impedance of the D-FACTS must be included in the line impedance settings of the protective relay. This is only valid when the dispersed implementation is used, and the D-FACTS are operating in conducting mode during the faults.

- Increasing the zone 2 reach setting for the distance elements in the POTT scheme is the best solution to improve reliability of the schemes if D-FACTS either are not dispersed evenly or if are not all inserted during faults. The increased setting should be based on maximum impedance with all D-FACTS devices inserted on that line.

- Line current differential protection should be implemented as a primary protection scheme to handle variations in the D-FACTS implementation and unexpected fault scenarios when suitable communication channels are available.

- D-FACTS implementations do not change the impacts of mutually coupled lines on relay response.

- The double-ended Takagi method provides the best estimate of the distance to the fault when the relay settings only use the line impedance.

- Fault location performance with D-FACTS remains an open challenge, especially for the following:

  - Random distribution of inserted D-FACTS along the transmission line.

  - Unpredictable behavior of D-FACTS devices during faults. For example, the case when a number of or all of D-FACTS devices switch to the bypass mode during a disturbance.

  - Cases with significant fault resistance and power flow.

# CHAPTER 9

# Summary, Conclusions, and Future Work

## 9.1 Summary

The operation of the D-FACTS devices in a power transmission line may lead to an unexpected impact on the performance of transmission protection elements because of their ability to change the effective line impedance and the dynamic behavior of these devices during a disturbance. The change in the measured impedance and limitation on the fault current as a result of the presence of D-FACTS on the fault path may lead to one of the following: an unwanted trip, failure to trip or incorrect fault location information.

This dissertation focused on the most common protection schemes: distance protection elements, communication aided distance schemes (POTT), line current differential schemes, and fault location schemes. The influence of D-FACTS implementations on the protected line and adjacent lines is examined for different: levels of D-FACTS compensation, methods of D-FACTS implementations, fault locations, and system configurations. The possibility of changes in the fault resistance coverage and the effect of mutual coupling between the parallel lines on protection due to the D-FACTS devices are also explored.

## 9.2 Conclusions

The results of this dissertation show that the dispersed implementation of D-FACTS has less negative influence on the response of the transmission line protection elements than the compressed implementation. When using the compressed implementation, the error in the fault location information and the trip decision by the protective relay would be large because the error margin for different fault locations along the line is not uniform since all of these devices are compressed on a short distance of the line. On the other hand, by using the dispersed implementation, the error in the fault location information and the trip decision of protective relays would be smaller and error margin along the transmission line is uniform if all D-FACTS devices switch to conduction mode during the faults.

The implementation of inductive D-FACTS devices may cause distance elements to underreach (see the fault farther down the line than it actually is). This may lead to failure in the POTT scheme or a delay in trip time for a fault in an instantaneous trip zone, which may affect system reliability and stability. The presence of the inductive D-FACTS in the fault path can reduce the relay's coverage of the protection zones. The single ended fault location method which is implemented in some commercial relays to determine the distance to the fault can experience a big error in fault location determination due to D-FACTS devices.

If there is a fault resistance in the fault path, the D-FACTS devices may contribute to increasing the underreach of distance elements under reverse power flow prefault conditions. On the other hand, this may reduce the underreach of the distance elements for forward power flow. If a zone 2 distance element underreaches too badly for fault close to the far end of the transmission line for a fault with fault resistance, the POTT scheme may fail to operate.

Implementing the D-FACTS on parallel lines does not influence the zero sequence mutual coupling between the lines during the ground faults. Therefore, D-FACTS will only impact the effective impedance of the protected line as described above and will not change the mutual coupling between parallel lines.

The D-FACTS implementation on an adjacent line (behind the protective relay) can positively effect the dynamic response of the mho distance elements by increasing the mho expansion for the forward fault while increasing the contraction of these elements for a reverse fault. On the other hand, the D-FACTS implementation on the protected line may limit the mho contraction for a reverse fault and that may decrease element security against false trips.

The D-FACTS implementation on the adjacent line (behind the relay) may increase the tilt of the calculated effective impedance of the quadrilateral distance elements. This may cause ground distance elements to underreach or overreach based on the power flow conditions and that can negatively effect the fault resistance coverage.

This dissertation provided an insight into the influence of D-FACTS devices on transmission line protection systems and offered corrections and recommendations on implementing the most reliable protection schemes that can be used in presence of these devices. Also, it proposed recommendations for D-FACTS implementations and protective relay settings to minimize the error in trip decision and fault location information without sacrificing overall D-FACTS performance.

## 9.3 Future Work

There are problems that remain open with respect to the D-FACTS implementation on transmission lines and their impact on system response. A description of the most important problems is given below:

- Design of a reliable scheme for estimating the distance to the fault in the presence of D-FACTS devices would be useful. Getting accurate fault location information is still a challenge. Therefore, development of the fault location schemes is needed to reduce the error in the estimated distance to the fault for line crews.

- The possible positive or negative influence of the D-FACTS devices on the transient stability of the power system needs to be assessed. The D-FACTS devices may effect power system stability because these devices are designed to control the power flow in the transmission system.

- The effect of D-FACTS on travelling wave relays needs be investigated. The D-FACTS interaction with the wave propagation has not been analyzed and as a result, nor has how they may impact the response of the travelling wave relay. This may influence the design of travelling wave protection schemes, especially fault location schemes.

- This thesis focuses on the effect of one class of D-FACTS devices (inductive D-FACTS devices) on the transmission line protection. Further study is needed to study the effects of capacitive D-FACTS devices and other potential D-FACTS implementations.

- To fully assess protection interaction with D-FACTS, it is necessary to perform closed-loop relay testing. Tests need to be performed using a real time digital simulator for modeling the practical impact of D-FACTS.

- The possibility of implementing a communication scheme between the D-FACTS devices and the protective relays needs to be studied. This communication scheme may improve the performance of the protection elements in presence of the D-FACTS devices.

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# APPENDIX A

## The IEEE 12 Bus Test System Data

Data for the IEEE 12 bus power system is provided below. The transformer data is given in Table A.1, generators, bus data and load data is given Table A.2 and the transmission lines data is given in Table A.3 [22].

Table A.1: Data of Transformer (System Base: 100MVA)

| From-To Bus | Capacity (MVA) | Voltage Ratio (KV) | Leakage reactance (pu) |
|---|---|---|---|
| 9-1 | 1000 | 22-230 | 0.01 |
| 10-2 | 1000 | 22-230 | 0.01 |
| 12-6 | 500 | 22-230 | 0.02 |
| 11-3 | 1000 | 22-230 | 0.01 |
| 1-7 | 1000 | 230-345 | 0.01 |
| 3-8 | 1000 | 22-345 | 0.01 |

Table A.2: Generator Set points, Bus Data and Load Data

| Bus# | Rating V(KV) | Bus Type | Generator Setting V(pu) | Load | | Shunt Mvar | Generator Setting P(G) MW |
|---|---|---|---|---|---|---|---|
| | | | | *P MW* | *Q Mvar* | | |
| 1 | 230 | PQ | - | - | - | - | - |
| 2 | 230 | PQ | - | 280 | 200 | - | - |
| 3 | 230 | PQ | - | 320 | 240 | - | - |
| 4 | 230 | PQ | - | 320 | 240 | 160 | - |
| 5 | 230 | PQ | - | 100 | 60 | 80 | - |
| 6 | 230 | PQ | - | 440 | 300 | 180 | - |
| 7 | 345 | PQ | - | - | - | - | - |
| 8 | 345 | PQ | - | - | - | - | - |
| 9 | 22 | Slack | 1.04 | - | - | - | - |
| 10 | 22 | PV | 1.02 | - | - | - | 500 |
| 11 | 22 | PV | 1.01 | - | - | - | 200 |
| 12 | 22 | PV | 1.02 | - | - | - | 300 |

Table A.3: Line Data (System Base: 100MVA)

| Line Name | L (km) | Capacity (MVA) | V (Rated) (KV) | R (pu) | X (pu) | B (pu) |
|---|---|---|---|---|---|---|
| 1-2 | 100 | 250 | 230 | 0.01144 | 0.0911 | 0.18261 |
| 2-5 | 300 | 250 | 230 | 0.03356 | 0.26656 | 0.55477 |
| 1-6 | 300 | 250 | 230 | 0.03356 | 0.26656 | 0.55477 |
| 5-4 | 300 | 250 | 230 | 0.03356 | 0.26656 | 0.55477 |
| 6-4 | 300 | 250 | 230 | 0.03356 | 0.26656 | 0.55477 |
| 3.1-4.1 | 100 | 250 | 230 | 0.01144 | 0.0911 | 0.18261 |
| 3.2-4.2 | 100 | 250 | 230 | 0.01144 | 0.0911 | 0.18261 |
| 7-8 | 600 | 500 | 345 | 0.01595 | 0.17214 | 3.28530 |

# APPENDIX B

## The Summary of the SEL-311L Relay Settings

The SEL-311L Settimgs used for the studies are given in B.1.

Table B.1: The Summary of the Commercial Relay Settings

| **Setting** | **Description** | **Entry** |
|---|---|---|
| | *Line Configuration Setting (Group)* | |
| CTR | Current Transformer Ratio | 100 |
| PTR | Potential Transformer Ratio | 2000 |
| VNOMY | PT Nominal Voltage (L-L) | 115 |
| Z1MAG | Positive Sequence Line Impedance Magnitude | 3.899 |
| Z1ANG | Positive Sequence Line Impedance Angle | 82.70 |
| Z0MAG | Positive Sequence Line Impedance Magnitude | 9.05 |
| Z0MAG | Positive Sequence Line Impedance Angle | 69.817 |
| EFLOC | Fault Location | Y |
| LL | Line Length | 100 |
| | *Relay Configuration* | |
| E21P | Mho Phase Distance Zones | 3 |
| ECDTD | Enable Distance Element Common Time Delay | Y |
| ESOTF | Enable Switch Onto Fault | Y |
| E50P | Enable Phase Instantaneous Elements | 1 |
| E50G | Enable Ground Instantnouse Elements | N |
| E50Q | Enable Negative sequence Instantaneous Elements | N |
| E51S | Enable Inverse Time Overcurrent Elements | 1 |
| E32 | Enable Directional Control | AUTO |
| ECOMM | Enable Communications Assisted Tripping | Y |
| LOP | Loss of Potential | Y1 |
| EADVS | Advanced Setting | N |
| | *Mho Phase Distance element Reach(group)* | |
| Z1P | Zone 1 Reach (Secondary) Ohms | 3.119 |
| Z2P | Zone 2 Reach(Secondary) Ohms | 4.679 |
| Z3P | Zone 3 Reach(Secondary) Ohms | 1.17 |
| | *Mho Phase Distance Overcurrent Fault Detector Settings* | |
| 50PP1 | Phase to Phase Overcurrent Detector (Zone 1) | 2.88 |
| 50PP2 | Phase to Phase Overcurrent Detector (Zone 2) | 1.95 |
| 50PP3 | Phase to Phase Overcurrent Detector (Zone 3) | 2.4 |
| | *Mho Phase Distance Element Time Delay (Group)* | |
| Z1PD | Zone 1 Time Delay (Cycles) | 0 |
| Z2PD | Zone 2 Time Delay (Cycles) | 20 |

| **Setting** | **Description** | **Entry** |
| --- | --- | --- |
| | *Mho Ground Distance Element Reach (group)* | |
| Z1MG | Zone 1 Reach (Secondary) | 3.119 |
| Z2MG | Zone 2 Reach(Secondary) | 4.679 |
| Z3MG | Zone 3 Reach(Secondary) | 1.17 |
| | *Mho Ground Distance Overcurrent Fault Detector Settings* | |
| 50L1 | Phase to Phase Overcurrent Detector (Zone 1) A | 3.78 |
| 50L2 | Phase to Phase Overcurrent Detector (Zone 2) A | 3.14 |
| 50L3 | Phase to Phase Overcurrent Detector (Zone 3) A | 3.39 |
| 50GZ1 | Phase to Phase overcurrent Detector (Zone 1) A | 3.38 |
| 50GZ2 | Phase to Phase overcurrent Detector (Zone 2) A | 2.28 |
| 50GZ3 | Phase to Phase Overcurrent Detector (Zone 3) A | 1.602 |
| | *Zero Sequence Current Compensation Settings (Group)* | |
| k0M1 | Zone 1 ZSC Factor Magnitude | 0.445 |
| k0A1 | Zone 1 ZSC Factor Angle (Degree) | -22.298 |
| | *Mho Phase Distance Element Time Delay (Group)* | |
| Z1GD | Zone 1 Time Delay (Cycles) | 0 |
| Z2GD | Zone 2 Time Delay (Cycles) | 20 |
| | *Distance Element Common Time Delay (Group)* | |
| Z1D | Zone 1 Time Delay (Cycles) | 0 |
| Z2D | Zone 2 Time Delay (Cycles) | 20 |
| | *SOTF Scheme Setting (Group)* | |
| ESPSTF | Enable Single Pole Switch onto Fault | N |
| EVRST | Enable Switch onto Voltage Reset | Y |
| 52AEND | 52A Pole Open Delay | OFF |
| Cloend | CLSMON or Single Pole Delay (Cycles) | 10 |
| SOTFD | Switch onto Fault Duration (Cycles) | 10 |
| CLSMONT | Close Single Monitor | IN102 |
| | *Phase Instantaneous Overcurrent Pickup Setting (Group)* | |
| 50P1P | Level 1 Pickup (A Secondary) | 10 |
| | *Phase Overcurrent Definite Time delay (Group)* | |
| 67P1D | Level 1 Time Delay (Cycles) | 0 |
| | *Phase Overcurrent Torque Control (Group)* | |
| 67P1TC | Level 1 Torque Control | 1 |
| | *Selectable Operating Quantity Time Overcurrent Element Setting (Group)* | |
| 51S1O | 51S1 Operating Quantity | 3I0L |
| 51S1P | Overcurrent Pickup | 2 |
| 51S1C | 51S1 Inverse Time Overcurrent | U3 |
| 51S1TD | 51S1 Inverse Time Overcurrent Time Dial | 2 |
| 51S1RS | Enable 51S1 Inverse Time Overcurrent Electromechanical | Y |
| 51S1TC | 51S1 Torque Control | 32GF |

| **Setting** | **Description** | **Entry** |
|---|---|---|
| | *Directional Control (Group)* | |
| ORDER | Ground Directional Priory (Q,V,I) | QV |
| E32IV | Zero Sequence Current and Voltage Enable | 1 |
| | *Pole Open Detection Setting (Group)* | |
| EPO | Pole Open Detection (52,V) | 52 |
| SPOD | Single Pole Open Dropout Delay (Cycles) | 5 |
| 3POD | Three Phase Pole Open Dropout Delay1 Inverse Time Overcurrent A | 5 |
| | *Trip Logic Setting(Group)* | |
| TR | Trip (SELogic Equation) | Z1T OR Z2T OR 51S1T |
| TRSOTF | Switch Onto Fault Trip | M2P OR Z2G OR 50P1 |
| DTA | Direct Transfer Trip A Phase | NA |
| DTB | Direct Transfer Trip B Phase | NA |
| DTC | Direct Transfer Trip C Phase | NA |
| ULTR | Unltch Trip | TRGTR |
| TTOPD | Trip During Open Pole Time Delay(Cycles) | 2 |
| TULO | Trip Unltch Option | 3 |
| Z2GTSP | Zone 2 Ground Distance Time Delay SPT | N |
| 67QGSP | Zone 2 Dir Neg Seq/Residual/O/C Single Pole Trip | N |
| TDUR1D | SPT Minimum Trip Duration Time Delay | 6 |
| TDUR3D | 3PT Minimum Trip Duration Time Delay | 9 |
| E3PT | Three Pole Trip Enable | 1 |
| E3PT1 | Breaker 1 3PT | 1 |
| | *Main Board (Output)* | |
| OUT101 | T (SELogic Equation) | 3PT |

# APPENDIX C

## Calculation the Desired Value of D-FACTS

To calculate the desired number of D-FACTS (inductive reactance) for case 2 in chapter 4:

The line 1-6 impedance = (0.03356 + j0.26656) pu

The system power base = 100MVA

The system voltage base = 230kV

The line 1-6 impedance base = 529 Ω

The actual line 1-6 impedance = (0.03356 + j0.26656) pu*529 Ω = (17.753+j141.01) Ω

The desired value of inductive reactance compensation = 10%*141.01 = 14.101 Ω (total compensation).

Calculating the desired set points for D-FACTS devices (capacitive reactance) in case 3 in chapter 4:

The line 1-6 impedance = (0.01595+ j0.17214) pu

The system power base = 100MVA

The system voltage base = 345kV

The line 1-6 impedance base = 1190.25 Ω

The actual line 1-6 impedance = (0.01595+ j0.17214) pu *1190.25 Ω = (18.984+j204.89) Ω

The desired value of capacitive reactance compensation = 10.29%*204.89= 21.083 Ω (total compensation).

# APPENDIX D

# The Output Data of ATP Simulation for SLG Faults for Dispersed Implementation from Chapter 5

Table D.1: Bus 5 Data From ATP for SLG Faults With 0% Compensation

| SLGF Com 0% | The output data from ATP simulation (VTs and CTs at bus 5) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fault Location | IA | | VA | | IN | | I1 | | I2 | | V0 | | V1 | | V2 | |
| | Mag A | Ang ° | Mag V | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° |
| 0% | 11.22 | -69.01 | 0.00 | -88.53 | 10.28 | -90.35 | 5.548 | -43.14 | 3.254 | -90.14 | 34.44 | 159.8 | 49.96 | -16.06 | 15.75 | 173.2 |
| 10% | 10.41 | -68.52 | 5.373 | 1.285 | 9.468 | -91.7 | 5.324 | -41.6 | 2.996 | -91.45 | 31.74 | 158.4 | 51.14 | -15.47 | 14.51 | 171.9 |
| 20% | 9.714 | -68.06 | 9.96 | 1.387 | 8.782 | -93.07 | 5.135 | -40.19 | 2.778 | -92.77 | 29.44 | 157 | 52.16 | -14.98 | 13.45 | 170.6 |
| 30% | 9.116 | -67.61 | 13.92 | 1.476 | 8.193 | -94.45 | 4.974 | -38.89 | 2.59 | -94.11 | 27.47 | 155.7 | 53.02 | -14.57 | 12.55 | 169.2 |
| 40% | 8.594 | -67.18 | 17.39 | 1.556 | 7.682 | -95.84 | 4.836 | -37.7 | 2.429 | -95.46 | 25.76 | 154.3 | 53.79 | -14.22 | 11.77 | 167.9 |
| 50% | 8.133 | -66.77 | 20.44 | 1.629 | 7.235 | -97.23 | 4.715 | -36.6 | 2.288 | -96.82 | 24.26 | 152.9 | 54.46 | -13.91 | 11.1 | 166.5 |
| 60% | 7.724 | -66.37 | 23.15 | 1.697 | 6.84 | -98.63 | 4.609 | -35.57 | 2.164 | -98.2 | 22.95 | 151.5 | 55.06 | -13.65 | 10.5 | 165.1 |
| 70% | 7.357 | -65.99 | 25.58 | 1.761 | 6.489 | -100 | 4.515 | -34.63 | 2.055 | -99.58 | 21.77 | 150.1 | 55.59 | -13.41 | 9.982 | 163.8 |
| 80% | 7.026 | -65.61 | 27.77 | 1.827 | 6.174 | -101.4 | 4.431 | -33.74 | 1.958 | -101 | 20.72 | 148.7 | 56.06 | -13.2 | 9.523 | 162.4 |
| 90% | 6.725 | -65.25 | 29.74 | 1.885 | 5.889 | -102.8 | 4.355 | -32.92 | 1.871 | -102.4 | 19.78 | 147.3 | 56.48 | -13 | 9.118 | 161 |
| 100% | 6.451 | -64.9 | 31.54 | 1.949 | 5.629 | -104.2 | 4.286 | -32.16 | 1.794 | -103.8 | 18.92 | 145.9 | 56.86 | -12.82 | 8.764 | 159.5 |
| 110% | 6.198 | -64.57 | 34.65 | 2.100 | 5.388 | -105.6 | 4.224 | -31.46 | 1.726 | -105.3 | 18.12 | 144.6 | 57.19 | -12.65 | 8.459 | 158.1 |
| 120% | 5.964 | -64.25 | 35.97 | 2.215 | 5.158 | -107 | 4.165 | -30.82 | 1.666 | -106.8 | 17.38 | 143.2 | 57.48 | -12.49 | 8.209 | 156.6 |
| B10% | 7.474 | 59.3 | 4.067 | -35.03 | 6.597 | 92.2 | 4.385 | 24.86 | 2.384 | 91.87 | 32.3 | 161.1 | 50.84 | -16.3 | 14.93 | 174.6 |
| B20% | 7.086 | 58.75 | 7.679 | -35.05 | 6.202 | 93.49 | 4.293 | 23.72 | 2.27 | 93.19 | 30.37 | 162.4 | 51.6 | -16.51 | 14.22 | 175.9 |

Table D.2: Bus 6 Side Data From ATP for SLG Faults With 0% Compensation

| SLGF Com 0% | The output data from ATP simulation (VTs and CTs at bus 6) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fault Location | IA | | VA | | IN | | I1 | | I2 | | V0 | | V1 | | V2 | |
| | Mag A | Ang ° | Mag V | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° |
| 0% | 7.593 | -120.1 | 43.32 | -35.08 | 7.565 | -90.67 | 4.041 | -159.6 | 2.636 | -89.79 | 12.27 | 159.8 | 60.49 | -29.54 | 5.668 | 173.5 |
| 10% | 8.123 | -119.5 | 41.68 | -35.08 | 8.099 | -91.98 | 4.161 | -157.8 | 2.799 | -91.14 | 13.13 | 158.4 | 60.12 | -29.54 | 6.011 | 172.1 |
| 20% | 8.734 | -118.9 | 39.79 | -35.09 | 8.71 | -93.3 | 4.303 | -155.8 | 2.988 | -92.49 | 14.12 | 157.1 | 59.69 | -29.54 | 6.415 | 170.7 |
| 30% | 9.444 | -118.3 | 37.6 | -35.1 | 9.416 | -94.63 | 4.474 | -153.7 | 3.212 | -93.86 | 15.26 | 155.8 | 59.19 | -29.55 | 6.891 | 169.4 |
| 40% | 10.28 | -117.7 | 35.04 | -35.11 | 10.25 | -95.96 | 4.683 | -151.5 | 3.477 | -95.23 | 16.6 | 154.4 | 58.5 | -29.56 | 7.459 | 168 |
| 50% | 11.28 | -117.2 | 31.99 | -35.14 | 11.23 | -97.3 | 4.941 | -149 | 3.797 | -96.62 | 18.19 | 153.1 | 57.89 | -29.58 | 8.142 | 166.6 |
| 60% | 12.48 | -116.6 | 28.3 | -35.17 | 12.43 | -98.64 | 5.266 | -146.3 | 4.187 | -98.02 | 20.13 | 151.8 | 57.03 | -29.6 | 8.978 | 165.2 |
| 70% | 13.98 | -116 | 23.74 | -35.2 | 13.91 | -99.99 | 5.681 | -143.4 | 4.674 | -99.43 | 22.53 | 150.4 | 55.96 | -29.62 | 10.02 | 163.7 |
| 80% | 15.88 | -115.5 | 17.96 | -35.26 | 15.8 | -101.4 | 6.227 | -140.3 | 5.295 | -100.9 | 25.58 | 149 | 54.6 | -29.66 | 11.35 | 162.3 |
| 90% | 18.38 | -114.9 | 10.38 | -35.33 | 18.28 | -102.7 | 6.967 | -137 | 6.113 | -102.3 | 29.58 | 147.7 | 52.82 | -29.7 | 13.11 | 160.9 |
| 100% | 21.79 | -114.4 | 0.00 | -102 | 21.68 | -104.1 | 8.011 | -133.6 | 7.239 | -103.8 | 35.08 | 146.3 | 50.38 | -29.75 | 15.52 | 159.4 |
| 110% | 6.428 | 114.1 | 5.815 | 2.881 | 4.805 | 76.88 | 4.377 | 140.8 | 1.595 | 75.3 | 33.59 | 144.9 | 50.88 | -29.23 | 14.96 | 157.9 |
| 120% | 6.211 | 114.3 | 8.372 | 3.004 | 4.599 | 75.48 | 4.318 | 141.3 | 1.539 | 73.81 | 32.18 | 143.5 | 51.32 | -28.75 | 14.48 | 156.5 |
| B10% | 7.129 | -120.6 | 44.76 | -35.18 | 7.092 | -89.36 | 3.94 | -161.2 | 2.497 | -88.46 | 11.51 | 161.1 | 60.82 | -29.54 | 5.374 | 174.8 |
| B20% | 6.721 | -121.2 | 46.05 | -35.18 | 6.667 | -88.06 | 3.854 | -162.6 | 2.378 | -87.15 | 10.83 | 162.4 | 61.09 | -29.54 | 5.125 | 176.2 |

Table D.3: Bus 5 Data From ATP for SLG Faults With 30% Compensation

| SLGF Com 30% | The output data from ATP simulation (VTs and CTs at bus 5) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fault Location | IA | | VA | | IN | | I1 | | I2 | | V0 | | V1 | | V2 | |
| | Mag A | Ang ° | Mag V | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag V | Ang ° | Mag V | Ang ° | Mag V | Ang ° |
| 0% | 11.26 | -69.74 | 0.0008 | -88.43 | 10.01 | -89.74 | 5.509 | -45.42 | 3.308 | -89.66 | 33.54 | 160.4 | 49.31 | -15.37 | 16.01 | 173.7 |
| 10% | 10.28 | -69.48 | 6.42 | 4.442 | 9.088 | -91.64 | 5.217 | -43.74 | 2.992 | -91.5 | 30.46 | 158.5 | 50.75 | -14.58 | 14.48 | 171.9 |
| 20% | 9.46 | -69.21 | 11.75 | 4.356 | 8.335 | -93.53 | 4.979 | -42.19 | 2.732 | -93.31 | 27.94 | 156.6 | 51.96 | -13.96 | 13.23 | 170 |
| 30% | 8.77 | -68.91 | 16.24 | 4.283 | 7.708 | -95.39 | 4.782 | -40.74 | 2.515 | -95.12 | 25.84 | 154.7 | 52.99 | -13.47 | 12.18 | 168.2 |
| 40% | 8.179 | -68.61 | 20.09 | 4.224 | 7.18 | -97.24 | 4.616 | -39.39 | 2.33 | -96.9 | 24.07 | 152.9 | 53.88 | -13.06 | 11.29 | 166.4 |
| 50% | 7.666 | -68.29 | 23.43 | 4.175 | 6.731 | -99.08 | 4.474 | -38.12 | 2.171 | -98.68 | 22.57 | 151.1 | 54.65 | -12.73 | 10.52 | 164.6 |
| 60% | 7.216 | -67.95 | 26.35 | 4.135 | 6.347 | -100.9 | 4.352 | -36.92 | 2.031 | -100.4 | 21.29 | 1492 | 55.34 | -12.44 | 9.857 | 162.9 |
| 70% | 6.817 | -67.6 | 28.93 | 4.104 | 6.018 | -102.7 | 4.245 | -35.77 | 1.908 | -102.2 | 20.19 | 147.5 | 55.95 | -12.2 | 9.27 | 161.1 |
| 80% | 6.46 | -67.22 | 31.22 | 4.082 | 5.737 | -104.5 | 4.151 | -34.66 | 1.798 | -103.9 | 19.26 | 145.7 | 56.51 | -12 | 8.746 | 159.4 |
| 90% | 6.138 | -66.8 | 33.28 | 4.068 | 5.499 | -106.3 | 4.068 | -33.57 | 1.696 | -105.6 | 18.47 | 143.9 | 57.02 | -11.83 | 8.269 | 157.7 |
| 100% | 5.842 | -66.32 | 35.12 | 4.067 | 5.305 | -108 | 3.995 | -32.45 | 1.599 | -107.3 | 17.83 | 142.2 | 57.5 | -11.69 | 7.823 | 156 |
| 110% | 5.634 | -65.95 | 36.48 | 3.913 | 5.096 | -109.3 | 3.946 | -31.8 | 1.544 | -108.7 | 17.14 | 140.9 | 57.78 | -11.57 | 7.581 | 154.7 |
| 120% | 5.438 | -65.6 | 37.72 | 3.807 | 4.895 | -110.6 | 3.899 | -31.22 | 1.495 | -110 | 16.49 | 139.7 | 58.01 | -11.45 | 7.387 | 153.4 |
| B10% | 6.605 | 55.81 | 3.614 | -37.6 | 5.985 | 91.32 | 4.062 | 20.55 | 2.042 | 91.23 | 31.69 | 161.7 | 50.08 | -15.65 | 15.29 | 175.1 |
| B20% | 6.302 | 55.35 | 6.864 | -37.54 | 5.665 | 92.63 | 3.992 | 19.62 | 1.958 | 92.56 | 30 | 163 | 50.76 | -15.9 | 14.66 | 176.4 |

Table D.4: Bus 6 Data From ATP for SLG Faults With 30% Compensation

| SLGF Com 30% | The output data from ATP simulation (VTs and CTs at bus 6) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fault Location | IA | | VA | | IN | | I1 | | I2 | | V0 | | V1 | | V2 | |
| | Mag A | Ang ° | Mag V | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag V | Ang ° | Mag V | Ang ° | Mag V | Ang ° |
| 0% | 6.614 | -123.7 | 46.12 | -37.12 | 6.842 | -91.58 | 3.721 | -165 | 2.256 | -90.47 | 11.1 | 158.9 | 61.29 | -32 | 4.851 | 172.9 |
| 10% | 7.13 | -123.1 | 44.56 | -37.06 | 7.31 | -93.18 | 3.835 | -163 | 2.418 | -92.16 | 11.86 | 157.2 | 60.91 | -32 | 5.195 | 171.1 |
| 20% | 7.727 | -122.4 | 42.76 | -37 | 7.86 | -94.78 | 3.972 | -160.8 | 2.608 | -93.85 | 12.74 | 155.6 | 60.48 | -32 | 5.597 | 169.4 |
| 30% | 8.426 | -121.7 | 40.64 | -36.93 | 8.51 | -96.38 | 4.139 | -158.4 | 2.832 | -95.52 | 13.79 | 154 | 59.97 | -32.01 | 6.074 | 167.7 |
| 40% | 9.255 | -121.1 | 38.13 | -36.85 | 9.292 | -97.96 | 4.345 | -155.8 | 3.099 | -97.18 | 15.05 | 152.4 | 59.37 | -32.02 | 6.645 | 166 |
| 50% | 10.26 | -120.4 | 35.1 | -36.76 | 10.24 | -99.53 | 4.604 | -153 | 3.425 | -98.83 | 16.59 | 150.9 | 58.65 | -32.03 | 7.342 | 164.4 |
| 60% | 11.49 | -119.7 | 31.37 | -36.65 | 11.43 | -101.1 | 4.935 | -149.9 | 3.829 | -100.5 | 18.5 | 149.3 | 57.75 | -32.05 | 8.207 | 162.7 |
| 70% | 13.05 | -119 | 26.65 | -36.52 | 12.93 | -102.6 | 5.369 | -146.6 | 4.344 | -102.1 | 20.94 | 147.8 | 56.63 | -32.07 | 9.309 | 161.1 |
| 80% | 15.09 | -118.3 | 20.49 | -36.35 | 14.91 | -104.1 | 5.956 | -143 | 5.019 | -103.6 | 24.14 | 146.3 | 55.15 | -32.12 | 10.76 | 159.6 |
| 90% | 17.89 | -117.5 | 12.1 | -36.12 | 17.62 | -105.5 | 6.783 | -139 | 5.943 | -105.1 | 28.52 | 144.9 | 53.15 | -32.2 | 12.74 | 158.1 |
| 100% | 21.86 | -116.6 | 0.001 | -104.8 | 21.55 | -106.8 | 8.013 | -134.7 | 7.283 | -106.5 | 34.87 | 143.6 | 50.26 | -32.36 | 15.61 | 156.7 |
| 110% | 5.879 | 112.6 | 2.766 | 0.5619 | 4.521 | 73.25 | 4.098 | 139.9 | 1.417 | 71.91 | 33.51 | 142.4 | 50.72 | -31.88 | 15.1 | 155.4 |
| 120% | 5.699 | 112.8 | 5.324 | 0.7231 | 4.342 | 71.96 | 4.051 | 140.3 | 1.372 | 70.52 | 32.22 | 141.1 | 51.11 | -31.43 | 14.67 | 154 |
| B10% | 6.252 | -124.2 | 47.27 | -37.17 | 6.464 | -90.24 | 3.645 | -166.3 | 2.153 | -89.11 | 10.49 | 160.2 | 61.53 | -32.01 | 4.636 | 174.2 |
| B20% | 5.929 | -124.7 | 48.29 | -37.22 | 6.119 | -88.92 | 3.579 | -167.6 | 2.065 | -87.78 | 9.938 | 161.5 | 61.75 | -32.02 | 4.452 | 175.6 |

# APPENDIX E

# The Output Data of ATP Simulation for SLG Fault for Compressed D-FACTS Implementation from Chapter 5

The tables of the output date of ATP simulation for SLG fault for compressed D-FACTS implementation

Table E.1: Bus 5 Data From ATP for SLG Faults With 0% Compensation

| SLGF Com 0% | The output data from ATP simulation (VTs and CTs at bus 5) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fault Location % | IA | | VA | | IN | | I1 | | I2 | | V0 | | V1 | | V2 | |
| | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° |
| **0** | 11.22 | -69.01 | 0.00 | -88.63 | 10.28 | -90.35 | 5.548 | -43.14 | 3.254 | -90.14 | 34.44 | 159.8 | 49.96 | -16.06 | 15.75 | 173.2 |
| **6** | 10.72 | -68.83 | 3.328 | 1.165 | 9.778 | -90.26 | 5.409 | -42.32 | 3.095 | -91.03 | 32.75 | 158.8 | 50.68 | -15.79 | 14.98 | 172.3 |
| **12** | 10.26 | -68.55 | 6.346 | 1.234 | 9.325 | -92.07 | 5.284 | -41.43 | 2.95 | -91.82 | 31.24 | 158 | 51.35 | -15.46 | 14.28 | 171.5 |
| **18** | 9.846 | -68.27 | 9.094 | 1.294 | 8.913 | -92.9 | 5.17 | -40.58 | 2.819 | -92.61 | 29.86 | 157.2 | 51.95 | -15.17 | 13.65 | 170.7 |
| **24** | 9.467 | -68.00 | 11.61 | 1.35 | 8.538 | -93.72 | 5.068 | -39.78 | 2.70 | -93.41 | 28.61 | 156.4 | 52.51 | -14.91 | 13.07 | 169.9 |
| **30** | 9.116 | -67.61 | 13.92 | 1.401 | 8.193 | -94.45 | 4.974 | -38.89 | 2.59 | -94.11 | 27.47 | 155.7 | 53.02 | -14.57 | 12.55 | 169.2 |
| **40** | 8.594 | -67.18 | 17.38 | 1.480 | 7.682 | -95.84 | 4.836 | -37.7 | 2.429 | -95.46 | 25.76 | 154.3 | 53.79 | -14.22 | 11.77 | 167.9 |
| **50** | 8.133 | -66.77 | 20.43 | 1.552 | 7.235 | -97.23 | 4.715 | -36.6 | 2.288 | -96.82 | 24.26 | 152.9 | 54.46 | -13.91 | 11.1 | 166.5 |
| **60** | 7.724 | -66.37 | 23.14 | 1.620 | 6.84 | -98.63 | 4.609 | -35.57 | 2.164 | -98.2 | 22.95 | 151.5 | 55.06 | -13.65 | 10.5 | 165.1 |
| **70** | 7.357 | -65.99 | 25.57 | 1.684 | 6.489 | -100 | 4.515 | -34.63 | 2.055 | -99.58 | 21.77 | 150.1 | 55.59 | -13.41 | 9.982 | 163.8 |
| **80** | 7.026 | -65.61 | 27.76 | 1.745 | 6.174 | -101.4 | 4.431 | -33.74 | 1.958 | -101 | 20.72 | 148.7 | 56.06 | -13.2 | 9.523 | 162.4 |
| **90** | 6.725 | -65.25 | 29.74 | 1.807 | 5.889 | -102.8 | 4.355 | -32.92 | 1.871 | -102.4 | 19.78 | 147.3 | 56.48 | -13 | 9.118 | 161 |
| **100** | 6.451 | -64.9 | 31.53 | 1.869 | 5.629 | -104.2 | 4.286 | -32.16 | 1.794 | -103.8 | 18.92 | 145.9 | 56.86 | -12.82 | 8.764 | 159.5 |
| **110** | 6.198 | -64.57 | 33.16 | 1.938 | 5.388 | -105.6 | 4.224 | -31.46 | 1.726 | -105.3 | 18.12 | 144.6 | 57.19 | -12.65 | 8.459 | 158.1 |
| **120** | 5.964 | -64.25 | 34.64 | 2.019 | 5.158 | -107 | 4.165 | -30.82 | 1.666 | -106.8 | 17.38 | 143.2 | 57.48 | -12.49 | 8.209 | 156.6 |
| **B10** | 7.474 | 59.3 | 4.067 | -35.03 | 6.597 | 92.2 | 4.385 | 24.86 | 2.384 | 91.87 | 32.3 | 161.1 | 50.84 | -16.3 | 14.93 | 174.6 |
| **B20** | 7.086 | 58.75 | 7.679 | -35.05 | 6.202 | 93.49 | 4.293 | 23.72 | 2.27 | 93.19 | 30.37 | 162.4 | 51.6 | -16.51 | 14.22 | 175.9 |

Table E.2: Bus 6 Data From ATP for SLG Faults With 0% Compensation

| SLGF Com 0% | The output data from ATP simulation (VTs and CTs at bus 6) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fault Location % | IA | | VA | | IN | | I1 | | I2 | | V0 | | V1 | | V2 | |
| | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° |
| **0** | 7.593 | -120.1 | 43.32 | -35.18 | 7.565 | -90.67 | 4.041 | -159.6 | 2.636 | -89.79 | 12.27 | 159.8 | 60.49 | -29.54 | 5.668 | 173.5 |
| **6** | 7.905 | -119.8 | 42.35 | -35.18 | 7.881 | -91.57 | 4.11 | -158.6 | 2.732 | -90.71 | 12.77 | 158.8 | 60.27 | -29.64 | 5.866 | 172.6 |
| **12** | 8.241 | -119.5 | 41.31 | -35.18 | 8.218 | -92.36 | 4.187 | -157.5 | 2.835 | -91.51 | 13.32 | 158.1 | 60.03 | -29.64 | 6.086 | 171.7 |
| **18** | 8.607 | -119.1 | 40.18 | -35.19 | 8.584 | -93.15 | 4.272 | -156.3 | 2.949 | -92.33 | 13.91 | 157.3 | 59.78 | -29.65 | 6.328 | 170.9 |
| **24** | 9.007 | -118.8 | 38.95 | -35.19 | 8.983 | -93.94 | 4.368 | -155.1 | 3.074 | -93.15 | 14.55 | 156.5 | 59.49 | -29.65 | 6.594 | 170.1 |
| **30** | 9.444 | -118.3 | 37.6 | -35.2 | 9.416 | -94.63 | 4.474 | -153.7 | 3.212 | -93.86 | 15.26 | 155.8 | 59.19 | -29.55 | 6.891 | 169.4 |
| **40** | 10.28 | -117.7 | 35.04 | -35.21 | 10.25 | -95.96 | 4.683 | -151.5 | 3.477 | -95.23 | 16.6 | 154.4 | 58.5 | -29.56 | 7.459 | 168 |
| **50** | 11.28 | -117.2 | 31.99 | -35.24 | 11.23 | -97.3 | 4.941 | -149 | 3.797 | -96.62 | 18.19 | 153.1 | 57.89 | -29.58 | 8.142 | 166.6 |
| **60** | 12.48 | -116.6 | 28.3 | -35.26 | 12.43 | -98.64 | 5.266 | -146.3 | 4.187 | -98.02 | 20.13 | 151.8 | 57.03 | -29.6 | 8.978 | 165.2 |
| **70** | 13.98 | -116 | 23.74 | -35.3 | 13.91 | -99.99 | 5.681 | -143.4 | 4.674 | -99.43 | 22.53 | 150.4 | 55.96 | -29.62 | 10.02 | 163.7 |
| **80** | 15.88 | -115.5 | 17.95 | -35.36 | 15.8 | -101.4 | 6.227 | -140.3 | 5.295 | -100.9 | 25.58 | 149 | 54.6 | -29.66 | 11.35 | 162.3 |
| **90** | 18.38 | -114.9 | 10.37 | -35.43 | 18.28 | -102.7 | 6.967 | -137 | 6.113 | -102.3 | 29.58 | 147.7 | 52.82 | -29.7 | 13.11 | 160.9 |
| **100** | 21.79 | -114.4 | 0.00 | -102.1 | 21.68 | -104.1 | 8.011 | -133.6 | 7.239 | -103.8 | 35.08 | 146.3 | 50.38 | -29.75 | 15.52 | 159.4 |
| **110** | 6.428 | 114.1 | 3.03 | 2.69 | 4.805 | 76.88 | 4.377 | 140.8 | 1.595 | 75.3 | 33.59 | 144.9 | 50.88 | -29.23 | 14.96 | 157.9 |
| **120** | 6.211 | 114.3 | 5.813 | 2.791 | 4.599 | 75.48 | 4.318 | 141.3 | 1.539 | 73.81 | 32.18 | 143.5 | 51.32 | -28.75 | 14.48 | 156.5 |
| **B10** | 7.129 | -120.6 | 44.76 | -35.18 | 7.092 | -89.36 | 3.94 | -161.2 | 2.497 | -88.46 | 11.51 | 161.1 | 60.82 | -29.54 | 5.374 | 174.8 |
| **B20** | 6.721 | -121.2 | 46.05 | -35.18 | 6.667 | -88.06 | 3.854 | -162.6 | 2.378 | -87.15 | 10.83 | 162.4 | 61.09 | -29.54 | 5.125 | 176.2 |

Table E.3: Bus 5 Data From ATP for SLG Faults With 30% Compensation

| SLGF Com 30% | The output data from ATP simulation (VTs and CTs at bus 5) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fault | IA | | VA | | IN | | I1 | | I2 | | V0 | | V1 | | V2 | |
| Location % | Mag A | Ang ° | Mag V | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag V | Ang ° | Mag V | Ang ° | Mag V | Ang ° |
| **0** | 11.26 | -69.74 | 0.0008 | -88.43 | 10.01 | -89.74 | 5.509 | -45.42 | 3.308 | -89.66 | 33.54 | 160.4 | 49.31 | -15.37 | 16.01 | 173.7 |
| **6** | 10.4 | -69.94 | 5.551 | 8.813 | 9.278 | -91.84 | 5.249 | -44.28 | 3.018 | -91.66 | 31.08 | 158.3 | 50.5 | -14.69 | 14.6 | 171.7 |
| **12** | 9.662 | -69.94 | 10.28 | 8.522 | 8.68 | -93.77 | 5.02 | -42.92 | 2.776 | -93.49 | 29.08 | 156.3 | 51.62 | -14.07 | 13.43 | 169.9 |
| **18** | 9.021 | -69.88 | 14.37 | 8.274 | 8.181 | -95.65 | 4.826 | -41.58 | 2.566 | -95.27 | 27.41 | 154.5 | 52.62 | -13.58 | 12.42 | 168.1 |
| **24** | 8.461 | -69.76 | 17.93 | 8.064 | 7.761 | -97.48 | 4.659 | -40.26 | 2.381 | -96.99 | 26.01 | 152.6 | 53.5 | -13.18 | 11.53 | 166.3 |
| **30** | 7.965 | -69.59 | 21.06 | 7.888 | 7.41 | -99.26 | 4.515 | -38.95 | 2.216 | -98.68 | 24.83 | 150.9 | 54.31 | -12.85 | 10.73 | 164.7 |
| **40** | 7.566 | -69.09 | 23.71 | 6.696 | 7.003 | -100.5 | 4.416 | -37.86 | 2.094 | -99.87 | 23.47 | 149.6 | 54.9 | -12.66 | 10.15 | 163.5 |
| **50** | 7.209 | -68.61 | 26.08 | 5.867 | 6.642 | -101.7 | 4.329 | -36.86 | 1.986 | -101.1 | 22.27 | 148.4 | 55.43 | -12.48 | 9.633 | 162.2 |
| **60** | 6.887 | -68.16 | 28.22 | 5.266 | 6.319 | -103 | 4.251 | -35.93 | 1.89 | -102.3 | 21.19 | 147.1 | 55.91 | -12.32 | 9.176 | 161 |
| **70** | 6.596 | -67.72 | 30.17 | 4.817 | 6.029 | -104.3 | 4.181 | -35.07 | 1.805 | -103.6 | 20.22 | 145.9 | 56.34 | -12.18 | 8.771 | 159.7 |
| **80** | 6.33 | -67.3 | 31.93 | 4.473 | 5.765 | -105.5 | 4.117 | -34.27 | 1.728 | -104.8 | 19.34 | 144.6 | 56.72 | -12.04 | 8.412 | 158.5 |
| **90** | 6.086 | -66.9 | 33.55 | 4.208 | 5.524 | -106.8 | 4.06 | -33.52 | 1.66 | -106.1 | 18.55 | 143.3 | 57.07 | -11.91 | 8.093 | 157.2 |
| **100** | 5.842 | -66.32 | 35.12 | 4.067 | 5.305 | -108 | 3.995 | -32.45 | 1.599 | -107.3 | 17.83 | 142.2 | 57.5 | -11.69 | 7.823 | 156 |
| **110** | 5.634 | -65.95 | 36.48 | 3.913 | 5.096 | -109.3 | 3.946 | -31.8 | 1.544 | -108.7 | 17.14 | 140.9 | 57.78 | -11.57 | 7.581 | 154.7 |
| **120** | 5.438 | -65.6 | 37.72 | 3.807 | 4.895 | -110.6 | 3.899 | -31.22 | 1.495 | -110 | 16.49 | 139.7 | 58.01 | -11.45 | 7.387 | 153.4 |
| **B10** | 6.605 | 55.81 | 3.614 | -37.6 | 5.985 | 91.32 | 4.062 | 20.55 | 2.042 | 91.23 | 31.69 | 161.7 | 50.08 | -15.65 | 15.29 | 175.1 |
| **B20** | 6.302 | 55.35 | 6.864 | -37.54 | 5.665 | 92.63 | 3.992 | 19.62 | 1.958 | 92.56 | 30 | 163 | 50.76 | -15.9 | 14.66 | 176.4 |

Table E.4: Bus 6 Data From ATP for SLG Faults With 30% Compensation

| SLGF Com 30% | The output data from ATP simulation (VTs and CTs at bus 6) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fault | IA | | VA | | IN | | I1 | | I2 | | V0 | | V1 | | V2 | |
| Location % | Mag A | Ang ° | Mag V | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag A | Ang ° | Mag V | Ang ° | Mag V | Ang ° | Mag V | Ang ° |
| **0** | 6.614 | -123.7 | 46.12 | -37.12 | 6.842 | -91.58 | 3.721 | -165 | 2.256 | -90.47 | 11.1 | 158.9 | 61.29 | -32 | 4.851 | 172.9 |
| **6** | 7.039 | -123.2 | 44.88 | -37.2 | 7.18 | -93.01 | 3.802 | -163.3 | 2.411 | -92.04 | 11.64 | 157.4 | 60.98 | -32.13 | 5.177 | 171.3 |
| **12** | 7.545 | -122.5 | 43.41 | -37.2 | 7.578 | -94.28 | 3.92 | -161.2 | 2.586 | -93.45 | 12.28 | 156.1 | 60.59 | -32.15 | 5.548 | 169.8 |
| **18** | 8.117 | -121.8 | 41.74 | -37.24 | 8.044 | -95.51 | 4.095 | -159 | 2.783 | -94.81 | 13.03 | 154.9 | 60.15 | -32.17 | 5.968 | 168.4 |
| **24** | 8.771 | -121.1 | 39.82 | -37.31 | 8.592 | -96.69 | 4.222 | -156.7 | 3.01 | -96.11 | 13.92 | 153.7 | 59.65 | -32.2 | 6.451 | 167.1 |
| **30** | 9.526 | -120.3 | 37.6 | -37.46 | 9.241 | -97.8 | 4.416 | -154.1 | 3.272 | -97.34 | 14.97 | 152.6 | 59.07 | -32.24 | 7.011 | 165.9 |
| **40** | 10.36 | -119.8 | 35.04 | -37.48 | 10.08 | -99.08 | 4.629 | -152 | 3.536 | -98.61 | 16.32 | 151.3 | 58.48 | -32.25 | 7.574 | 164.6 |
| **50** | 11.35 | -119.2 | 31.99 | -37.5 | 11.08 | -100.4 | 4.892 | -149.6 | 3.854 | -99.9 | 17.94 | 150 | 57.78 | -32.27 | 8.255 | 163.3 |
| **60** | 12.56 | -118.7 | 28.3 | -37.53 | 12.29 | -101.6 | 5.222 | -147 | 4.243 | -101.2 | 19.89 | 148.8 | 56.92 | -32.29 | 9.088 | 162.0 |
| **70** | 14.05 | -118.2 | 23.74 | -37.57 | 13.78 | -102.9 | 5.643 | -144.3 | 4.728 | -102.5 | 22.3 | 147.5 | 55.86 | -32.32 | 10.13 | 160.7 |
| **80** | 15.95 | -117.6 | 17.95 | -37.62 | 15.68 | -104.2 | 6.196 | -141.3 | 5.348 | -103.8 | 25.36 | 146.2 | 54.51 | -32.36 | 11.46 | 159.3 |
| **90** | 18.44 | -117.1 | 10.37 | -37.69 | 18.16 | -105.5 | 6.943 | -138.2 | 6.167 | -105.2 | 29.38 | 144.9 | 52.73 | -32.41 | 13.21 | 158.0 |
| **100** | 21.86 | -116.6 | 0.001 | -104.8 | 21.55 | -106.8 | 8.013 | -134.7 | 7.283 | -106.5 | 34.87 | 143.6 | 50.26 | -32.36 | 15.61 | 156.7 |
| **110** | 5.879 | 112.6 | 2.766 | 0.5619 | 4.521 | 73.25 | 4.098 | 139.9 | 1.417 | 71.91 | 33.51 | 142.4 | 50.72 | -31.88 | 15.1 | 155.4 |
| **120** | 5.699 | 112.8 | 5.324 | 0.7231 | 4.342 | 71.96 | 4.051 | 140.3 | 1.372 | 70.52 | 32.22 | 141.1 | 51.11 | -31.43 | 14.67 | 154.0 |
| **B10** | 6.252 | -124.2 | 47.27 | -37.17 | 6.464 | -90.24 | 3.645 | -166.3 | 2.153 | -89.11 | 10.49 | 160.2 | 61.53 | -32.01 | 4.636 | 174.2 |
| **B20** | 5.929 | -124.7 | 48.29 | -37.22 | 6.119 | -88.92 | 3.579 | -167.6 | 2.065 | -87.78 | 9.938 | 161.5 | 61.75 | -32.02 | 4.452 | 175.6 |

# APPENDIX F

## Protection Element Responses for Commercial Relays for SLG Fault for Dispersed D-FACTS Implementation from Chapter 5

Table F.1: The Response of Protection Elements for SLG Faults With 0% Compensation

| SLGF 0% Com | Conventional Elements | | | | POTT Scheme | | Differential Scheme | | Fault Location % | | Observation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Relay 1 | | Relay 2 | | | | | | | | |
| Fault Location % | Zone1 | Zone2T | Zone 1 | Zone 2T | Relay 1 | Relay 2 | Relay 1 | Relay 2 | Relay1 | Relay 2 | |
| 0 | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 0.00 | 101.01 | |
| 10 | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 10.07 | 90.65 | |
| 20 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 20.13 | 80.35 | |
| 30 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 30.27 | 70.46 | |
| 40 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 40.39 | 60.28 | |
| 50 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 50.46 | 50.18 | |
| 60 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 60.6 | 39.98 | |
| 70 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 70.70 | 30.05 | |
| 80 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 81.11 | 20 | |
| 90 | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 91.47 | 10 | |
| 100 | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 101.62 | 0.00 | |
| 110 | 0 | 1 | - | - | Z2T | - | - | - | 111.83 | - | |
| 120 | 0 | 1 | - | - | Z2T | - | - | - | 122.32 | - | |
| B10 | - | - | 0 | 1 | - | Z2T | - | - | - | 111.03 | |
| B20 | - | - | 0 | 1 | - | Z2T | - | - | - | 121.79 | |

Table F.2: The Response of Protection Elements for SLG Faults With 30% Compensation

| SLGF 30% Com | Conventional Elements | | | | POTT Scheme | | Differential Scheme | | Fault Location % | | Observation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Relay 1 | | Relay 2 | | | | | | | | |
| Fault Location % | Zone1 | Zone2T | Zone1 | Zone2T | Relay 1 | Relay 2 | Relay 1 | Relay 2 | Relay 1 | Relay 2 | |
| 0 | 1 | 0 | 0 | NT | NT | NT | 87L | 87L | 0.00 | 123.33 | |
| 10 | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 12.16 | 110.37 | |
| 20 | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 24.37 | 98.40 | |
| 30 | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 36.53 | 85.92 | |
| 40 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 48.68 | 73.43 | |
| 50 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 60.77 | 61.10 | |
| 60 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 72.82 | 48.86 | |
| 70 | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 85.10 | 36.62 | |
| 80 | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 96.95 | 24.34 | |
| 90 | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 109.45 | 12.19 | |
| 100 | 0 | NT | 1 | 0 | NT | NT | 87L | 87L | 121.48 | 0.00 | |
| 110 | 0 | NT | - | - | 51T | - | - | - | 131.88 | - | |
| 120 | 0 | NT | - | - | 51T | - | - | - | 142.04 | - | |
| B10 | - | - | 0 | NT | - | 51T | - | - | - | 133.73 | |
| B20 | - | - | 0 | NT | - | 51T | - | - | - | 143.94 | |

# APPENDIX G

## Protection Element Responses for SLG Fault for Compressed D-FACTS Implementation from Chapter 5

The tables of the protection elements response of SEL-311L for SLG faults for compressed implementation

Table G.1: The Response of Protection Elements for SLG Faults With 0% Compensation

| SLGF Com 0% | Conventional Elements | | | | POTT Scheme | | Differential Scheme | | Fault Location % | | Observation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Relay 1 | | Relay 2 | | | | | | | | |
| Fault Location % | Zone1 | Zone2T | Zone 1 | Zone 2T | Relay 1 | Relay 2 | Relay 1 | Relay 2 | Relay1 | Relay 2 | |
| 0 | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 0.00 | 101.02 | |
| 6 | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 6.05 | 94.91 | |
| 12 | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 12.10 | 88.44 | |
| 18 | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 18.15 | 82.6 | |
| 24 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 24.19 | 76.36 | |
| 30 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 30.19 | 70.18 | |
| 40 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 40.37 | 60.21 | |
| 50 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 50.36 | 50.14 | |
| 60 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 60.66 | 39.99 | |
| 70 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 70.74 | 30.04 | |
| 80 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 80.98 | 20.01 | |
| 90 | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 91.43 | 10 | |
| 100 | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 101.55 | 0.00 | |
| 110 | 0 | 1 | - | - | Z2T | - | - | - | 111.69 | - | |
| 120 | 0 | 1 | - | - | Z2T | - | - | - | 122.11 | - | |
| B10 | - | - | 0 | 1 | - | Z2T | - | - | - | 110.98 | |
| B20 | - | - | 0 | 1 | - | Z2T | - | - | - | 121.67 | |

Table G.2: The Response of Protection Elements for SLG Faults With 30% Compensation

| SLGF Com 30% | Conventional Elements | | | | POTT Scheme | | Differential Scheme | | Fault Location % | | Observation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Relay 1 | | Relay 2 | | | | | | | | |
| Fault Location % | Zone1 | Zone2T | Zone1 | Zone2T | Relay 1 | Relay 2 | Relay 1 | Relay 2 | Relay1 | Relay 2 | |
| 0 | 1 | 0 | 0 | NT | NT | NT | 87L | 87L | 0.00 | 123.81 | |
| 6 | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 10.25 | 113.18 | |
| 12 | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 20.42 | 102.42 | |
| 18 | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 30.54 | 91.74 | |
| 24 | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 40.06 | 81.02 | |
| 30 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 50.47 | 70.14 | |
| 40 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 60.48 | 60.12 | |
| 50 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 70.19 | 50.08 | |
| 60 | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 80.55 | 40.09 | |
| 70 | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 90.37 | 30.05 | |
| 80 | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 100.20 | 20.02 | |
| 90 | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 110.64 | 10.01 | |
| 100 | 0 | NT | 1 | 0 | NT | NT | 87L | 87L | 121.48 | 0.00 | |
| 110 | 0 | NT | - | - | 51T | - | - | - | 131.88 | - | |
| 120 | 0 | NT | - | - | 51T | - | - | - | 142.04 | - | |
| B10 | - | - | 0 | NT | - | 51T | - | - | - | 133.73 | |
| B20 | - | - | 0 | NT | - | 51T | - | - | - | 143.94 | |

# APPENDIX H

## Protection Element Responses for Commercial Relays for SLG Faults on Line 2 for Mutually Coupled Parallel Lines That are Electrically Isolated from Chapter 6

Table H.1: The Response of Protection Elements for SLG Faults With 0% Compensation

| SLGF Com 0% | Conventional Elements | | | | POTT Scheme | | Differential Scheme | | Fault Location % | | Observation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Relay 1 | | Relay 2 | | | | | | | | |
| Fault Location % | Zone1 | Zone2T | Zone1 | Zone2T | Relay 1 | Relay 2 | Relay 1 | Relay 2 | Relay 1 | Relay 2 | |
| 0 | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 0.00 | 90.29 | |
| 10 | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 9.72 | 81.84 | |
| 20 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 19.38 | 73.10 | |
| 30 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 29.03 | 64.28 | |
| 40 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 38.60 | 55.42 | |
| 50 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 48.15 | 46.25 | |
| 60 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 57.54 | 37.16 | |
| 70 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 66.74 | 27.95 | |
| 80 | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 75.89 | 18.75 | |
| 90 | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 84.86 | 9.41 | |
| 100 | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 93.10 | 0.00 | |
| 110 | 0 | 1 | - | - | Z2T | - | - | - | 103.00 | - | |
| 120 | 0 | 1 | - | - | Z2T | - | - | - | 113.06 | - | |
| B10 | - | - | 0 | 1 | - | Z2T | - | - | - | 99.83 | |
| B20 | - | - | 0 | 1 | - | Z2T | - | - | - | 110.3 | |

Table H.2: The Response of Protection Elements for SLG Faults With 30% Compensation

| SLGF Com 30% | Conventional Elements | | | | POTT Scheme | | Differential Scheme | | Fault Location % | | Observation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Relay 1 | | Relay 2 | | | | | | | | |
| Fault Location % | Zone1 | Zone2T | Zone1 | Zone2T | Relay 1 | Relay 2 | Relay 1 | Relay 2 | Relay 1 | Relay 2 | |
| 0 | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 0.00 | 110.95 | |
| **10** | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 11.86 | 100.59 | |
| **20** | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 23.63 | 89.99 | |
| **30** | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 35.39 | 79.26 | |
| **40** | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 46.95 | 68.30 | |
| **50** | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 58.26 | 57.25 | |
| **60** | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 69.60 | 46.01 | |
| **70** | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 80.95 | 34.65 | |
| **80** | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 91.51 | 23.12 | |
| **90** | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 101.95 | 11.59 | |
| **100** | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 111.78 | 000 | |
| **110** | NT | NT | - | - | 51T | - | - | - | 121.27 | - | |
| **120** | NT | NT | - | - | 51T | - | - | - | 131.23 | - | |
| **B10** | - | - | NT | NT | - | 51T | - | - | - | 120.54 | |
| **B20** | - | - | NT | NT | - | 51T | - | - | - | 130.88 | |

# APPENDIX I

## Protection Element Responses for Commercial Relays for SLG Faults on Line 8 for Mutually Coupled Parallel Lines That are Electrically Isolated from Chapter 6

Table I.1: The Response of Protection Elements for SLG Faults With 0% Compensation

| SLGF Com 0% | Conventional Elements | | | | POTT Scheme | | Differential Scheme | | Fault Location % | | Observation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Relay 1 | | Relay 2 | | | | | | | | |
| Fault Location % | Zone1 | Zone2T | Zone1 | Zone2T | Relay 1 | Relay 2 | Relay 1 | Relay 2 | Relay 1 | Relay 2 | |
| **0** | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 0.00 | 92.16 | |
| **10** | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 9.50 | 83.58 | |
| **20** | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 18.93 | 74.73 | |
| **30** | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 28.28 | 65.65 | |
| **40** | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 37.50 | 56.38 | |
| **50** | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 46.66 | 47.19 | |
| **60** | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 55.74 | 37.89 | |
| **70** | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 64.44 | 28.43 | |
| **80** | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 73.30 | 19.02 | |
| **90** | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 81.67 | 9.54 | |
| **100** | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 89.74 | 0.00 | |
| **110** | 0 | 1 | - | - | Z2T | - | - | - | 99.10 | - | |
| **120** | 0 | 1 | - | - | Z2T | - | - | - | 109.10 | - | |
| **B10** | - | - | 0 | 1 | - | Z2T | - | - | - | 102.19 | |
| **B20** | - | - | 0 | 1 | - | Z2T | - | - | - | 112.82 | |

Table I.2: The Response of Protection Elements for SLG Faults With 30% Compensation

| SLGF Com 30% | Conventional Elements | | | | POTT Scheme | | Differential Scheme | | Fault Location % | | Observation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Relay 1 | | Relay 2 | | | | | | | | |
| Fault Location % | Zone1 | Zone2T | Zone1 | Zone2T | Relay 1 | Relay 2 | Relay 1 | Relay 2 | Relay 1 | Relay 2 | |
| **0** | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 0.00 | 92.29 | |
| **10** | 1 | 0 | 0 | 1 | Com | Com | 87L | 87L | 9.53 | 83.75 | |
| **20** | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 18.98 | 74.71 | |
| **30** | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 28.34 | 65.56 | |
| **40** | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 37.63 | 56.41 | |
| **50** | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 46.59 | 47.23 | |
| **60** | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 55.82 | 37.87 | |
| **70** | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 64.61 | 28.45 | |
| **80** | 1 | 0 | 1 | 0 | Com | Com | 87L | 87L | 73.28 | 19.02 | |
| **90** | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 81.79 | 9.53 | |
| **100** | 0 | 1 | 1 | 0 | Com | Com | 87L | 87L | 89.74 | 000 | |
| **110** | 0 | 1 | - | - | Z2T | - | - | - | 99.76 | - | |
| **120** | 0 | 1 | - | - | Z2T | - | - | - | 109.88 | - | |
| **B10** | - | - | 0 | 1 | - | Z2T | - | - | - | 102.32 | |
| **B20** | - | - | 0 | 1 | - | Z2T | - | - | - | 112.41 | |

# APPENDIX J

## Protection Element Responses of the Commercial Relays for SLG Faults With Fault Resistance in Presence of D-FACTS Devices from Chapter 6

Table J.1: The Response of Protection Elements for SLG Faults With 0% Compensation and $R_f = 0\ \Omega$

| Response of Relays Elements (SEL-311L) with 0% D-FACTS Compensation | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $R_f$ = 0 Ω | | | | | | | | | | |
| Fault Location % | Conventional Elements | | | | POTT Scheme | | Diff Scheme | | Location Element | | Observation |
| | Relay 1 | | Relay 2 | | Relay 1 | Relay 2 | Relay 1 | Relay 2 | Relay 1 % | Relay 2 % | |
| | Zone 1 | Zone 2 | Zone 1 | Zone 2 | | | | | | | |
| 0 (100% for R2) | 1 | 0 | 0 | 1 | COM | COM | 87L | 87L | 0.00 | 100.84 | |
| 30 (70% for R2) | 1 | 0 | 1 | 0 | COM | COM | 87L | 87L | 30.21 | 70.15 | |
| 70 | 1 | 0 | 1 | 0 | COM | COM | 87L | 87L | 70.68 | 30.01 | |
| 100 | 0 | 1 | 1 | 0 | COM | COM | 87L | 87L | 101.54 | 0.00 | |

Table J.2: The Response of Protection Elements for SLG Faults With 0% Compensation and $R_f = 4\ \Omega$

| Response of Relays Elements (SEL-311L) with 0% D-FACTS Compensation | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $R_f$ = 4 Ω | | | | | | | | | | |
| Fault Location % | Conventional Elements | | | | POTT Scheme | | Diff Scheme | | Location Element | | Observation |
| | Relay 1 | | Relay 2 | | Relay 1 | Relay 2 | Relay 1 | Relay 2 | Relay 1 % | Relay 2 % | |
| | Zone 1 | Zone 2 | Zone 1 | Zone 2 | | | | | | | |
| 0 (100% for R2) | 1 | 0 | 0 | 1 | COM | COM | 87L | 87L | 0.06 | 101.32 | |
| 30 (70% for R2) | 1 | 0 | 1 | 0 | COM | COM | 87L | 87L | 30.33 | 70.39 | |
| 70 | 1 | 0 | 1 | 0 | COM | COM | 87L | 87L | 70.88 | 30.13 | |
| 100 | 0 | 1 | 1 | 0 | COM | COM | 87L | 87L | 101.89 | 0.06 | |

Table J.3: The Response of Protection Elements for SLG Faults With 30% Compensation and $R_f = 0\ \Omega$

| Response of Relays Elements (SEL-311L) with 30% D-FACTS Compensation | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $R_f$ = 0 Ω | | | | | | | | | | |
| Fault Location % | Conventional Elements | | | | POTT Scheme | | Diff Scheme | | Location Element | | Observation |
| | Relay 1 | | Relay 2 | | Relay 1 | Relay 2 | Relay 1 | Relay 2 | Relay 1 % | Relay 2 % | |
| | Zone 1 | Zone 2 | Zone 1 | Zone 2 | | | | | | | |
| 0 (100% for R2) | 1 | 0 | 0 | 1 | COM | COM | 87L | 87L | 0.00 | 123.29 | R2 trip in zone 2 |
| 30 (70% for R2) | 1 | 0 | 1 | 0 | COM | COM | 87L | 87L | 36.47 | 85.96 | R2 trip in zone 1 |
| 70 | 0 | 1 | 1 | 0 | COM | COM | 87L | 87L | 84.95 | 36.58 | R1 trip in zone 1 |

Table J.4: The Response of Protection Elements for SLG Faults With 30% Compensation and $R_f = 4\ \Omega$

| Response of Relays Elements (SEL-311L) with 30% D-FACTS Compensation | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $R_f$ = 4 Ω | | | | | | | | | | |
| Fault Location % | Conventional Elements | | | | POTT Scheme | | Diff Scheme | | Location Element | | Observation |
| | Relay 1 | | Relay 2 | | Relay 1 | Relay 2 | Relay 1 | Relay 2 | Relay 1 % | Relay 2 % | |
| | Zone 1 | Zone 2 | Zone 1 | Zone 2 | | | | | | | |
| 0 (100% for R2) | 1 | 0 | NT | NT | NT | NT | 87L | 87L | 0.03 | 123.53 | Move up out of Zone 2 |
| 30 (70%for R2) | 1 | 0 | 0 | 1 | COM | COM | 87L | 87L | 36.64 | 85.80 | Move up to trip zone 2 |
| 70 | 0 | 1 | 1 | 0 | COM | COM | 87L | 87L | 85.45 | 36.59 | |
| 100 | 0 | 1 | 1 | 0 | COM | COM | 87L | 87L | 122.24 | 0.04 | Move down to trip in Zone 2 |

# APPENDIX K

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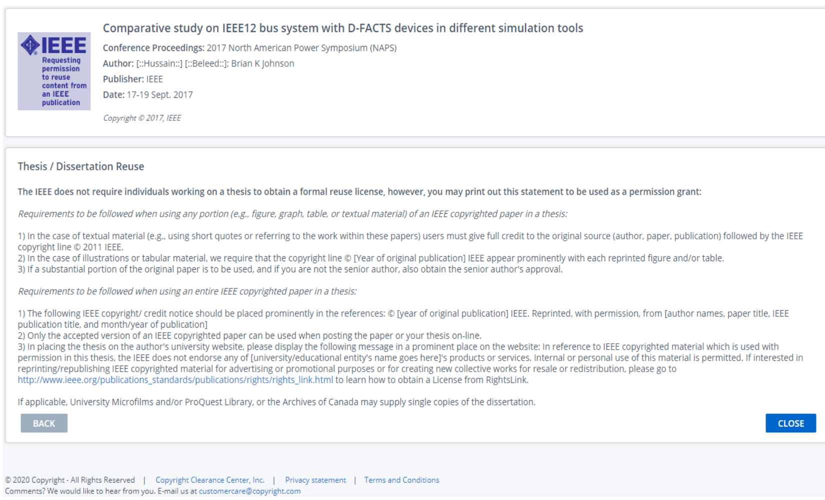

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**Conference Proceedings:** 2017 North American Power Symposium (NAPS)
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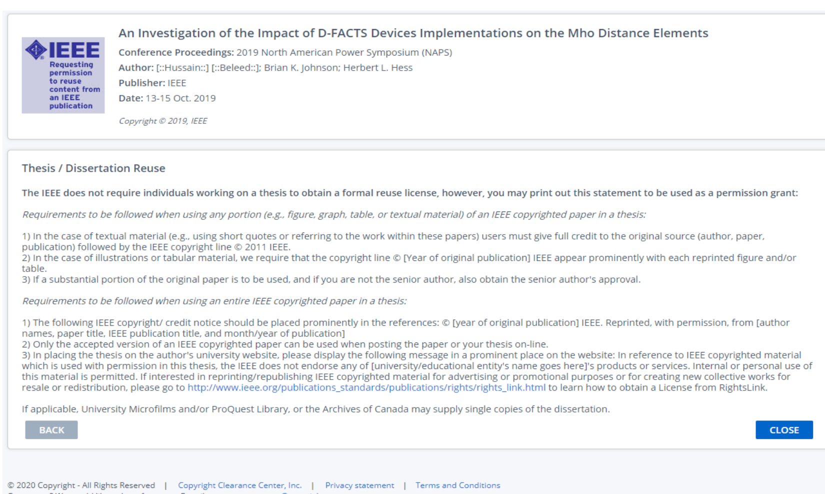

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**Conference Proceedings:** 2019 North American Power Symposium (NAPS)
**Author:** [::Hussain::] [::Beleed::]; Brian K. Johnson; Herbert L. Hess
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