THE UNIVERSITY OF TURKISH AERONAUTICAL ASSOCIATION
INSTITUTE OF SCIENCE AND TECHNOLOGY

EFFECT OF FLEXIBLE AC TRANSMISSION SYSTEM (FACTS) DEVICES ON DISTANCE RELAY PERFORMANCE IN A TRANSMISSION LINE

MASTER THESIS

NATHEER AHMED ALWAN

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER SCIENCE OF IN ELECTRICAL AND ELECTRONICS ENGINEERING

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Supervisor: Prof. Dr. Doğan ÇALIKOĞL

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I hereby declare that all information in the study I presented as my Master's Thesis, called; **EFFECT OF FLEXIBLE AC TRANSMISSION SYSTEM (FACTS) DEVICES ON DISTANCE RELAY PERFORMANCE IN A TRANSMISSION LINE** has been presented in accordance with the academic rules and ethical conduct. I also declare and clarify with my honour that I have fully cited and referenced all the sources I made use of in the present study.

29.11.2017

Natheer Ahmed ALWAN

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LIST OF ABBREVIATIONS

3Ph : Three Phase Fault
AC : Alternating Current
C.T : Current Transformer
DC : Direct Current
EHV : Extra High Voltage
GCSC : GTO Control Series Capacitor
GTO : Gate Turn Off Thyristor
IGBT : Insulated Gate Bipolar Transistor
IGCT : Integrated Gate-Commutated Thyristor
IPFC : Interline Power Flow Controller
L-L : Line to Line Fault
MI : Modulation Index
PWM : Pulse Width Modulation
RCA : Relay Characteristic Angle
S.I.R : Source Impedance Ratio
SC : Series Capacitor
S-L-G : Single Line to Ground Fault
SSSC : Static Synchronous Series Compensator
SVC : Static VAR Compensator
TCR : Thyristor Controlled Reactors
TCSC: Thyristor Controlled Static Compensator
TCSR: Thyristor Control Series Reactor
TSC : Thyristor Switched Capacitors
V.T : Voltage Transformer
VSC : Voltage Source Converter

ABSTRACT

Effect of Flexible AC Transmission System(FACTS) Devices on Distance Relay Performance in a Transmission line

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Based on the limited expansion and development of power transmission networks, the power system continuously works under a large load due to increase of the demand. It is therefore necessary to make full use of the power transmission system to meet the demand for electrical power as much as possible, hence, less need to build new transmission lines. The technology of FACTS (Flexible AC Transmission Systems) provides a way to take full advantage of transmission lines as well as new and updated transmission lines. However, the presence of such devices is associated with transmission line leads to changes that need to be addressed in order to protect the system from issues such as large changes of resistance, voltages and line currents.

This problem have been handled previously, so in this work we investigated Mho distance relay characteristics have been selected as characteristics for the phase element in the distance relay. The Iraqi protection sector uses these characteristics for all distance relays in the 400kV transmission lines of the Iraqi national grid.' Distance relay performance is defined in terms of reach accuracy and operating time. Reach accuracy is a comparison of the fault impedance reach of the relay under practical conditions with the distance relay setting impedance'. In this study we investigated the impact of mainly two FACTS devices: The Static Synchronous Compensator (STATCOM) and the Unified Power Flow Controller (UPFC) on the distance protection relaying system so as to recognize the important problems that protection engineers need to consider during the stages of design and operation of protection systems.

Simulation studies are carried out using MATLAB/SIMULINK. First, the distance relay has been modeled and validated with FACTS device models using test systems from the literature. Then, the distance relay performance is analyzed and the effects of various fault and loading conditions with FACTS devices are analyzed. Generally, the results show that the apparent impedance seen by a protection relay would vary from that of a system without FACTS devices. This may cause the relay sequence to be disrupted, resulting in an unreliable operation to protect the power system during faults. Furthermore, the results show clearly the dependency of the distance relay operation on many design and operational factors. These include the FACTS device type and its purpose, the FACTS device connection point or location, the fault type and fault point location along the line and the power flow.

Key words: Distance relay, Flexible AC Transmission System(FACTS)Devices, STATCOM, UPFC

ÖZET

İletim Hatlarındaki Esnek AC İletim Sistemleri Cihazlarının Mesafeli Röle Performansına Etkisi

ALWAN, Natheer Ahmed
Yüksek Lisans, Elektrik ve Elektronik Mühendisliği
Tez Danışmanı: Prof. Dr. Doğan ÇALIKOĞLU
Kasım 2017, 64 sayfa

Güç iletim hatlarındaki sınırlı gelişme ve büyüme temelinde artan talep yüzünden güç sistemi daima büyük bir yük altında çalışmaktadır. Bu nedenle, elektrik enerjisi talebini mümkün olduğunca karşılamak için güç iletim sisteminden tam olarak faydalanmak gerekir. Böylelikle yeni iletim hatları inşa etmek için daha az gereksinim duyulur. FACTS (Esnek AC İletim Sistemleri) teknolojisi iletim hatlarının yanı sıra yeni ve güncellenmiş iletim hatlarından tam olarak faydalanmak için olanak sağlamaktadır. Bununla birlikte, bu tür aygıtların varlığı, sistemin direncin, voltajların ve hat akımlarının büyük değişiklikleri gibi sorunlardan korunması için ele alınması gereken hat nakliye hatlarıyla ilgilidir.

Bu problem daha önce de işlenmiş olup, böylelikle bu çalışmada, mesafe rölesindeki faz elementleri için özellikler olarak Mho mesafe rölesi özelliklerini araştırmış bulunmaktayız. Irak güvenlik sektörü, Irak ulusal şebekesinin 400 kV iletim hatlarındaki tüm mesafe röleleri için bu özelliklerden istifade etmektedir. Mesafe rölesi performansı, kesinliğin elde edilmesi ve işletim süresi kapsamında açıklanmıştır. Kesinliği elde edilmesi, mesafe rölesi ayar empedansı ile pratik şartlar kapsamında rölenin hatalı bir empedans erişiminin mukayesesidir. Bu tez, iki farklı FACT cihazının sisteme başlıca etkisini belirlemek için uygulanan detaylı çalışmanın

sonuçlarını ortaya koymaktadır, Statik eş zamanlı kompansatör (STATCOM) ve birleştirilmiş güç akım denetleyici(UPFC) koruma mühendislerinin tasarlama ve koruma sistemleri işletimi aşamalarını göz önünde bulunduracağı önemli sorunları fark edebilmek için mesafe koruma rölesi sistemidir.

Simülasyon çalışmaları MATLAB/SIMULINK kullanılarak gerçekleştirilmiştir. İlk önce mesafe rölesi , literatürdeki test sistemleri kullanılarak FACTS araç modelleri ile modellendirilmiş ve doğrulanmıştır. Ardından mesafe rölesi performansı analiz edilmiş, ve çeşitli arıza ve yükleme koşullarının FACTS cihazları ile etkileri analiz edilmiştir. Genellikle koruma röle ile ortaya çıkan görünür empedans FACTS cihazları olmayan bir sistemindekinden farklı olacağı gösterebilmektedir. Röle sırasının bozulmasına neden olabilir, arıza boyunca güç sistemini korumak için güvenilmez bir işletim ile sonuçlanmasına neden olmaktadır. Buna ek olarak, sonuçlar mesafe rölesi işletiminin birçok tasarım ve işletim faktörlerine bağlılığını açıkça ortaya koymaktadır. Bunlar, FACTS cihaz çeşidini ve amacını, FACTS cihaz bağlantı noktası veya konumunu, arıza çeşidini ve hat ve güç akımı boyunca arıza nokta konumunu da kapsamaktadır.

Anahtar Kelimeler: Mesafe Röle, Esnek AC İletim Sistemleri(FACTS), STATCOM,UPFC.

CHAPTER ONE

Introduction and Literature Survey

1.1 Introduction

Electric power systems are consisting of generating, transmitting and distributing to deliver electrical energy to consumer by power transmission system. These power systems are the most complex and costly systems. Faults within these power systems are an unavoidable reality, electrical faults impose strain on all levels of this infrastructure, if left uncorrected, these faults would quickly destroy this infrastructure and lead to the breakdown of the power system. This fact identifies the need for an auxiliary system responsible for the protection of the infrastructure from faults and abnormal operation [1].

Distance relay is one of the most important protection elements in transmission line and it is flexible and economically that provide inexpensive protection, reliable and fast for power transmission lines with electrical fault circumstances [3]. Through observation the voltage and current for line as measured at the relaying point, the distance relay compares the system impedance with a pre-set reference stating the impedance of the protected line and decides if or not a fault condition occur on the line. when a fault is detected, the distance relay sends a trip signal to the circuit breaker to isolate and disconnect the faulted section. [4].

Distance relay models can be divided into two classes. The first class is the “Phasor-based models,” the input to relay model includes the fundamental frequency components of currents and voltages; therefore, there is no need for filters. The input signal differences are fed into the appropriate relay elements along with the settings in vector form.

The second category models the “Ground element model,” This model is very similar to the phase mho relay with two modifications. First, the compensated zero-sequence current (mI_0) is calculated and added to each phase current. Second, the phase voltages and compensated phase currents become the new operating quantities instead of the line values used in the phase relays. Otherwise, the functionality, settings and construction of the ground mho relay are identical to the phase mho relay [45].

FACTS devices are founded on the use of power electronics reliable high-speed, advanced control technology, high-power micro-computers and powerful analytical tools. [9].

This work illustrates the effect of FACTS compensators on the performance of distance relays with both analytic and simulation techniques. The effects of these devices and without presence of FACTS devices have seen on the relay by comparing R-X characteristics and the apparent impedance for various fault situations and different locations.

Table (1.1) shows a number of problems that can be corrected using suitable types of FACTS devices [6].

Table 1.1: Employment of FACTS devices

FACTS type	Voltage control	Transient stability	Oscillation damping	Q compensation	Power flow control
STATCOM, SVC	Yes	Yes	Yes	Yes	NO
SSSC, TCSC, TCSR	Yes	Yes	Yes	NO	Yes
UPFC	Yes	Yes	Yes	Yes	Yes
IPFC	Yes	Yes	Yes	NO	Yes

1.3 Literature Survey

The operation of transmission lines, including FACTS devices, has attracted wide spread interest as it improves the power transmit ability in long transmission lines [5, 6, 9, 11]. On the other hand, the introduction of FACTS brings new challenges as the apparent impedance of the lines is changed dynamically. Therefore, the reach setting of the distance relay is safely influenced based on the modes of operation of the FACTS device.

Several studies have been conducted to evaluate distance relay performance based on transmission systems with FACTS devices. The followings are some related articles:

The work employed a UPFC device to study its effect on the tripping outlines of a distance relay with different UPFC control parameters and SLG faults through different values of fault resistance. The limitations in the work were the disregarding of other types of fault along with limited operating conditions of the UPFC **[8].**

This study analyzed and investigated the effects of mid-point STATCOM compensation on the performance of resistance-based relays under normal operating situations and fault circumstances at various load angles. The changes in line loading and power flow direction, fault resistance and FACTS device location were among the parameters that were not addressed **[12]**.

The work analyzed and investigated the effects the Static Synchronous Series Compensator (SSSC) on the line and its locations; the simulation shows the impacts on the distance relay performance for various fault situations. The author also involved the impact of the operational mode of the SSSC **[13]**.

The authors clearly showed the impact of mid-point 48-pulse GTO STATCOM devices on distance relay performance with a system built in MATLAB/SIMULINK for two fault types at different locations. The simulation and analytical results show setting principles for distance relays with the impact of the STATCOM. It is to be noted that the setting strategy did not take into account the change of the STATCOM location and line loading **[7] [14]**.

The work investigated the three most important and applicable states of a UPFC, namely location, magnitude of voltage and phase angle. The apparent impedance measured through a distance relay in the presence of the UPFC was expressed by mathematical equations and the results were confirmed by a simulation in the PSCAD/EMTDC software environment to show how much a distance protection relay affects the UPFC on a transmission line **[10].**

They are presented a calculation procedure and simulation results of the apparent impedance for a series capacitor (SC) compensated transmission line. In [15], a single circuit transmission line was considered, while in [16], a double circuit line was considered for study. with different locations of the SC on the transmission line. The outcomes present the impact of series capacitors (SC) on a distance protection relay in various locations **[15]** [**16].**

They are investigated the effects of the STATCOM connected at the midpoint of a radial system on the apparent impedance that is seen by a distance protection relay as having been evaluated for various fault types using PSCAD software. For the work in **[17]**, two fault types were considered, namely SLG and L-L faults, while in **[18]**, SLG, L-L and 3Ph faults were treated. The results show an inverse effect of the STATCOM device on the distance protection relay with faults in one location only **[17] [18]**.

This work illustrated the direct effects of Static Var Compensator (SVC) devices, like a Thyristor Control Reactor (TCR) and Thyristor Switching Capacitor (TSC) insertion. Based on simulations and analytical procedures, the total impedance of a protected transmission line Z_{AB} and impedance seen by a mho distance relay shows the influence of various rates of thyristor firing angles. These angles injected different substances (B_{TCR} or B_{TSC}) which showed a direct effect on the total impedance of the protected line **[19].**

The work analyzed the impacts of the Interline Power Flow Controller (IPFC) on apparent impedance that is seen by the distance relay for diver's shunt faults. The author used IPFC of six pulses of VSC, investigated by two SSSCs at the DC link. The simulation results showed the combination of IPFC in the multiline system's impacts on the actual impedance of a fault seen by the distance relay, which is because of the injection/absorption of real/reactive power by the IPFC on the multiline system. As a result, the disturbance in the actual impedance fault drive of the relay mal-operates and so the relay under-reaches or over-reaches **[22].**

In this work, the effect of FACTS devices on distance relay performance has been investigated using two types of FACTS devices, namely the Static Synchronous Compensator (STATCOM) and the Unified Power Flow Controller (UPFC). The study was carried out with different fault types and positions, load conditions and FACTS locations using MATLAB/SIMULINK.

1.4 Aim of the Work

The objectives of this work can be enumerated as follows:

i. Execute an extensive study to research the effects of FACTS devices on distance protection relaying. Different FACTS devices and locations, different load conditions and fault types and positions are among the varying factors to be considered so as to recognize the significant matters that protection engineers need to observe when designing and developing a distance protection system.
ii. Develop a distance relay model using the MATLAB/SIMULINK software based on selected relay characteristics and apparent impedance equations for different fault types.
iii. Derive an equation for the apparent impedance measured through a distance protection relay for transmission lines including FACTS devices.
iv. Deduce a rule-of-thumb method to mitigate the effects of FACTS devices on distance relay settings based on the results obtained.
v. Verify the developed MATLAB/SIMULINK models via implementation of standard documented systems from the literature and from comparisons of results.

1.5 THESIS OUTLINE

This work is organized in five chapters involving the present chapter and one Appendix. The other chapters include:

Chapter Two: investigates power system faults and introduces distance protection fundamentals and characteristics.

Chapter Three: focuses on the operations of FACTS devices (STATCOM and UPFC) and the apparent impedance of distance relays in the case of transmission lines which include FACTS devices.

Chapter Four: presents modeling of the mho distance relay and provides information about the used FACTS models and studied systems in addition to the verification process of the model.

Chapter Five: Introduces the final conclusions in addition to suggestions for future work.

CHAPTER TWO

Power System Protection

2.1 Introduction

The main goal of protecting the power system is to isolate any damaged parts of the electrical system quickly so as to ensure continuity of current in other parts of the power system. Faults and equipment failures normally cause problem areas. A protection system is a group of devices, plots on a graph, and strategies joined to reveal faults, which disconnects the smallest possible faulty areas as quickly as possible. Due to the high probability of power system failures, a protection system must provide different schemes to detect and relieve such failures [2, 23].

2.2 Power System Faults

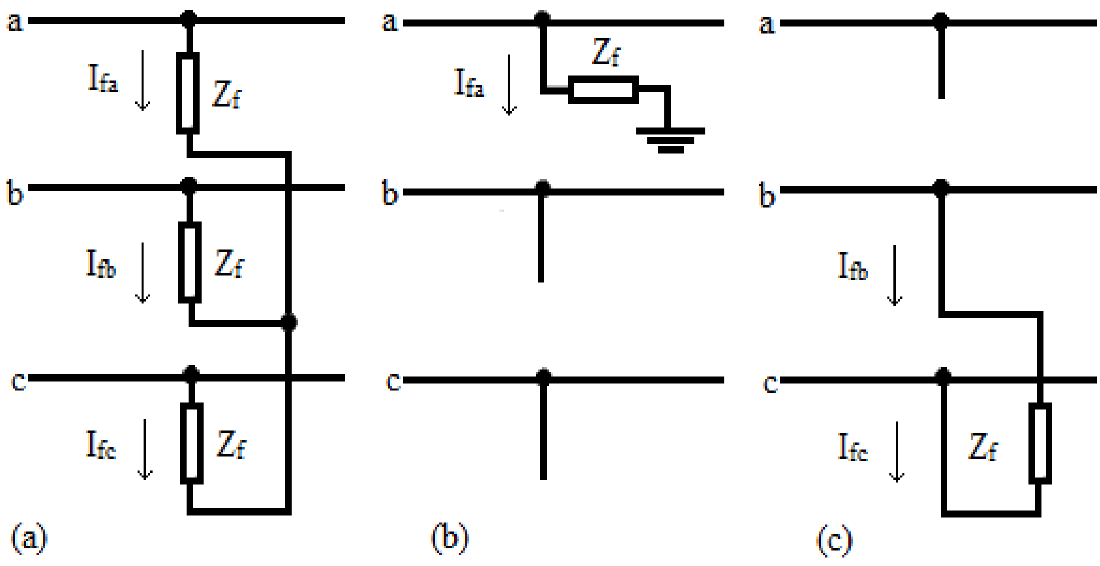
To study protection systems, it is important to develop an understanding of the types of fault that can be present in three-phase electrical systems. Each type of fault will create distinct voltage and current signals. To log the faults in any equipment and protect the equipment from each type of fault, it is necessary to recognize and use the proper signals. A three-phase system is subjected to the following types of fault [24]:

i. 3Ph (Three-Phase) ungrounded fault
ii. 3Ph-G (Three-Phase grounded) fault
iii. Ph-Ph (Phase-to-Phase) ungrounded fault

iv. Ph-Ph-G (Phase-to-Phase grounded) fault
v. Ph-G (Phase-to-Ground) fault

It is obvious that apart from faults i and ii above, the remainder may involve any one or two of the three phase faults. Those involving the three phases are termed as symmetrical faults while faults which un-equally affect the 3Ph are termed as unsymmetrical. Unsymmetrical faults are the most common. Typically, a 3Ph fault is the most dangerous task on the circuit breaker due to the high fault currents. However, there are cases where a Ph-G fault may produce higher fault current than a three-phase fault. This is the condition where the reactance of a zero-sequence at the point of fault is less than the reactance of the positive sequence.

An L-L fault is considered to be a minimum fault current having less severity on a power system than other fault types [25]. In 3Ph balanced faulty systems, it is adequate to calculate the currents and voltages in one phase and accept that the currents and voltages in the other two phases that are clearly equal in magnitude and phase displaced by an angle of ±120°. Fig. (2.1(a)) shows the connection diagram of such faults through fault impedance (Z_f). In unbalanced systems, this simplification is not valid.



(a) 3Ph fault, (b) SL-G fault, (c) L-L fault

Figure 2.1: Connection diagram for various faults through Z_f

Unbalance can occur in three-phase transmission systems due to faults, loads of single-phase, un-transposed transmission lines and non-equilateral conductor spacing [23]. Whenever an unbalanced faulty system is to be analyzed, the convenient and common method used is that of symmetrical components, developed firstly by C. L. Fortescue in 1918 [2]. Figs. (2.1(b) and (c)) show the connection diagrams of such faults.

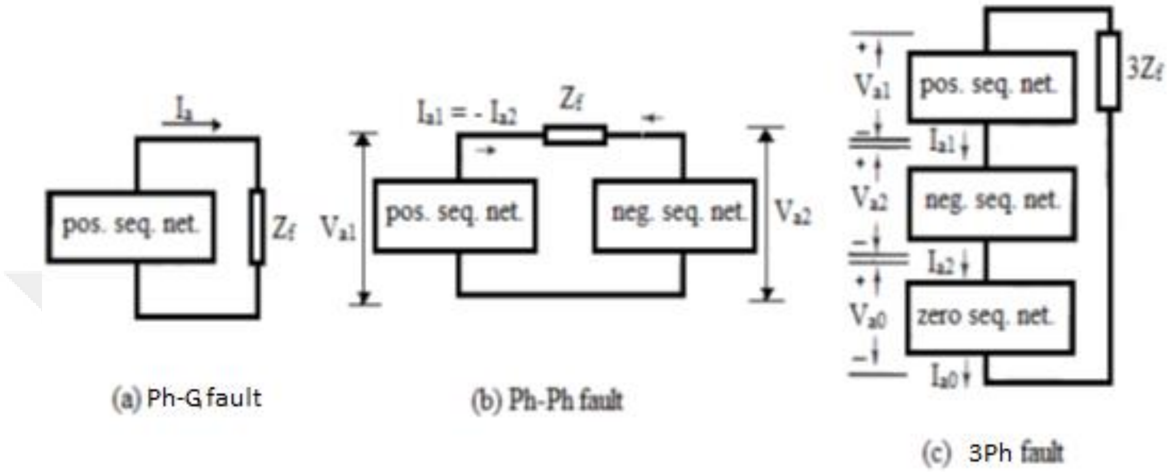


Figure 2.2: Fault system sequence network connection

Table 2.1: Sequence current voltage relations

Fault type (and phase)	Relation
Three – Phase (a - b - c)	$V_a = I_a Z_f$; $V_{a1} = I_{a1} Z_f = V_f - I_{a1} Z_1$ $I_{a1} = \frac{V_f}{Z_1 + Z_f}$
Phase – Phase (b - c)	$I_a = 0$, $I_b = - I_c$, $V_c = V_b - I_b Z_f$ $I_{a1} = - I_{a2}$; $\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_b - I_b Z_f \end{bmatrix}$ $3(V_{a1} - V_{a2}) = j\sqrt{3}\, I_b Z_f$; $I_b = -j\sqrt{3}\, I_{a1}$, $(V_{a1} - V_{a2}) = I_{a1} Z_f$
Phase – Ground (a)	$I_{a1} = I_{a2} = I_{a0} = \frac{V_f}{Z_1 + Z_2 + Z_0 + 3Z_f}$

In Fig. (2.2), the connection diagram of the system sequence networks is shown schematically for the three above mentioned fault states. Table 2.1 summarizes the necessary equations for the sequence current-voltage relations for the three fault types. The derivations of the shown relations are very well documented in standard power system text books [23-28]. In case a bolted or solid short circuit fault is to be considered, only $Z_f = 0$ is introduced in the above-mentioned relations. The analysis of unbalanced three-phase systems provides the foundation for deriving the apparent impedance which is seen by a distance relay under the mentioned fault types.

2.3 Protective Relays

A protective relay is the most important piece of equipment used in the protection of power systems. Relays use signals obtained from the power system (the signal can be, electrical, mechanical, heat, etc.) and process them resulting in an action output signal [24].

The advancement in science and engineering has led to the development of relays started electromechanically, followed by solid-state, digital and numerical relays. The primary concern of this work is to “simulate and use distance relays in a power transmission system incorporating FACTS devices.”

2.4 Distance Relay Protection

Distance relay devices are the most important among the protective devices used with power transmission lines especially at high voltages. This type of equipment has an important advantage compared to overcurrent relays. Distance relay devices eliminate long clearing times for the fault near the power sources required by an overcurrent relay if used for the purpose. [26].

2.5 Distance Relay Protection Principles

Distance relays measure the impedance between the relay location and the fault point. As the transmission line impedance/km remains relatively stable, those relays essentially react to the distance to the fault. This protection philosophy has found favor as the set-points are based on the impedance of the line that is relatively stable and easy to determine. As these set-points do not vary considerably with load currents or short circuit levels, distance relay settings can remain constant regardless of the many changes in the transmission network [24].

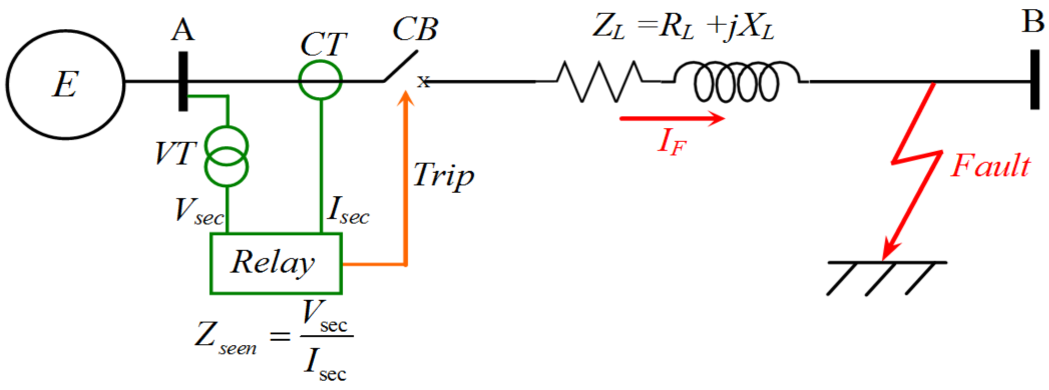


Figure 2.3: Distance relay principle operation

The basic principle of distance protection (figuratively shown in Figure 2.3) is that it follows the output of the voltage division measured by the relay on the current passing through it where the impedance is directly proportional to the distance of the fault. The distance of the fault can then be known by its impedance. If the measured impedance is less than the impedance of the reach point, a fault is assumed on the line between the relay and the reach point [27].

2.6 Distance relay Performance

'Distance relay performance is defined in terms of reach accuracy and operating time. Reach accuracy is a comparison of the actual ohmic reach of the relay under practical conditions with the relay setting value in ohms. Reach accuracy particularly depends on the level of voltage presented to the relay under fault conditions. The impedance measuring techniques employed in particular relay designs also have an impact. Operating times can vary with fault current, with fault position relative to the relay setting, and with the point on the voltage wave at which the fault occurs.

Depending on the measuring techniques employed in a particular relay design, measuring signal transient errors, such as those produced by Capacitor Voltage Transformers or saturating CT's, can also adversely delay relay operation for faults

close to the reach point. It is usual for electromechanical and static distance relays to claim both maximum and minimum operating times.
However, for modern digital or numerical distance relays, the variation between these is small over a wide range of system operating conditions and fault positions.'

2.7 Distance Relay Protection Zones

Carefully chosen distance relays vary the impedances in coupled links with various time delays related with those settings. Carefully chosen reach settings and shut-down times for different protection zones can be properly regulated between the power system and the distance relays. The distance relays have three protection zones. However, depending on the application, additional zones can be inserted in sequence [27, 28]. The following section provides ideal settings for three zones of a basic distance protection system. Fig. (2.4) shows the migration zones related to the time of their planning operation.

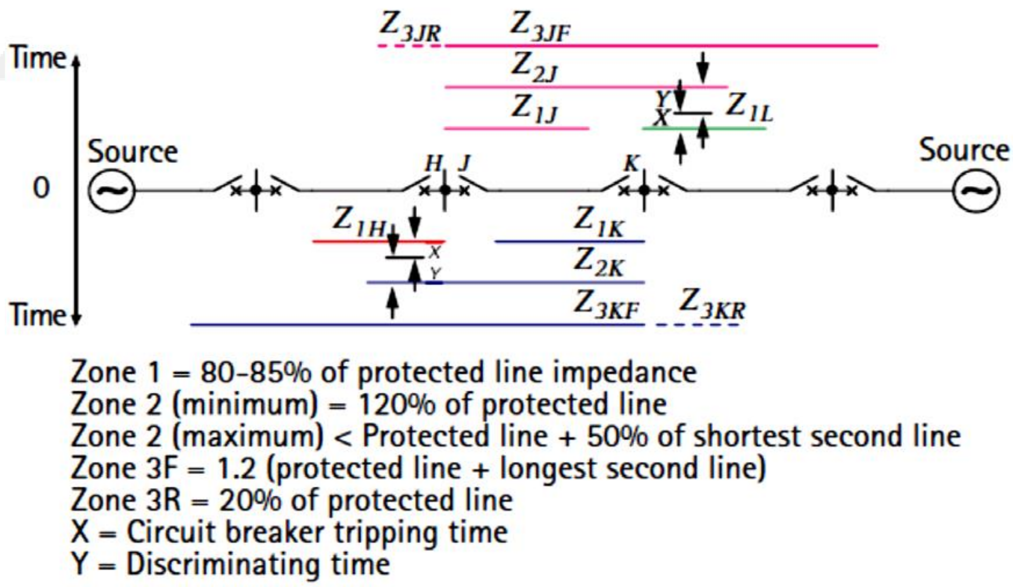


Figure 2.4: Three zone distance protection typical time/distance characteristics

2.7.1 Zone 1 setting

This is set between 80% and 85% of the length of transmission line impedance (depending on relay accuracy). The remaining 20-15% of the line impedance is a safety boundary to ensure that there is no hazard of the over-reaching Zone 1 protection on the protected line because of current and voltage transformer errors and the inexactness in the data of setting line impedance as well as relay setting errors and measurements. No intentional delay is provided to Zone 1 protection (i.e., instantaneous). The remaining 15-20% of the line will be covered by Zone 2 of the distance protection [26, 27].

2.7.2 Zone 2 setting

These are controlled in different ways along the next line of the line to be protected and the form of the network connected to it (especially when there is more than one line outside the same station). However, in all the areas, Zone 2 should cover the area not covered by Zone 1, which represents 15-20% of Zone 1. At the same time, Zone 2 is a backup safeguard. One of the most common control limits used is that Zone 2 is equal to the length of the line to be protected plus 20% (sometimes 50%) of the shortest length of the line to be protected. [26, 27].

2.7.3 Zone 3 setting

These are often covered so that the line to be fully protected and the next line are also complete (20% of the length of the third line may be added to this length) It is required that the impedance be less than the total impedance of the line plus the impedance of the transformer located in the next station because if the impedance of Zone 3 is greater than the total of these obstacles, it means that the protective device can be affected by the faults that can be on the secondary side of the transformer (i.e., in the distribution circuits), and this is called Load Encroachment. Fig. (2.5) shows a schematic of the mho characteristic and three zone characteristics. The third zone is shown offset to provide bus back up protection [26, 27].

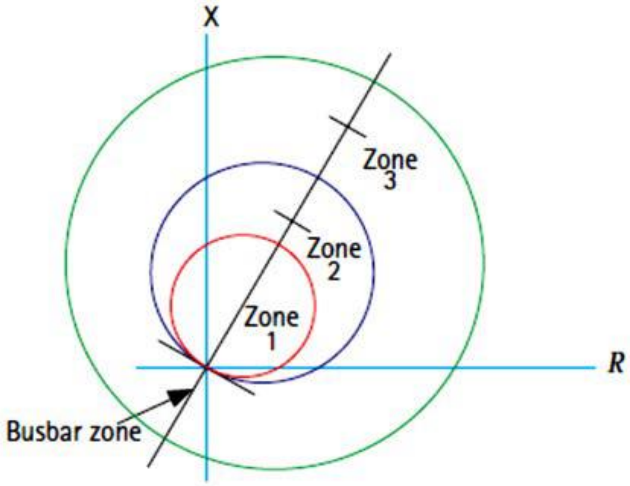
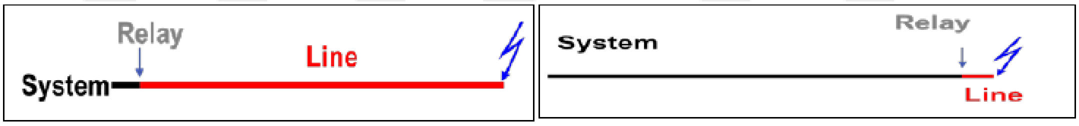


Figure 2.5: Busbar zone of an offset mho relay

2.8 Effect of Source Impedance on Distance Relay

The capability of a distance relay depends on the accurate measurement reach-point defect at the lower voltage at the relay position under these terms over the stated value. These voltages, with respect to relay design, may take in conditions of the maximum equivalent (Z_S/Z_L) which is the source to line impedance ratio (S.I.R.).



(a) Long line with low S.I.R (b) Short line with high S.I.R.

Figure 2.6: Source impedance and line impedance

A distance relay cannot be used for the protection of short lines because of the high S.I.R., as in Fig. (2.6) showing the voltage at a relay point for different types of fault that can be derived in terms of S.I.R. showing the effect of the source impedance on the performance of the distance relay. Fig. (2.7) shows the difference of the relay voltage point with the source to line impedance ratio (S.I.R.). A single line diagram of the circuit in Fig. (2.8) symbolizes any three-phase fault condition of the power system. The voltage V used in the impedance loop is the voltage of the open circuit of the power system and R is the relay location; I_R and V_R, respectively, are the current and voltage that are measured by the relay.

The impedances Z_S and Z_L respectively are the source and line impedances due to their respective locations with regard to the position of the relay. Z_S source impedance measures the fault level in the relaying point.

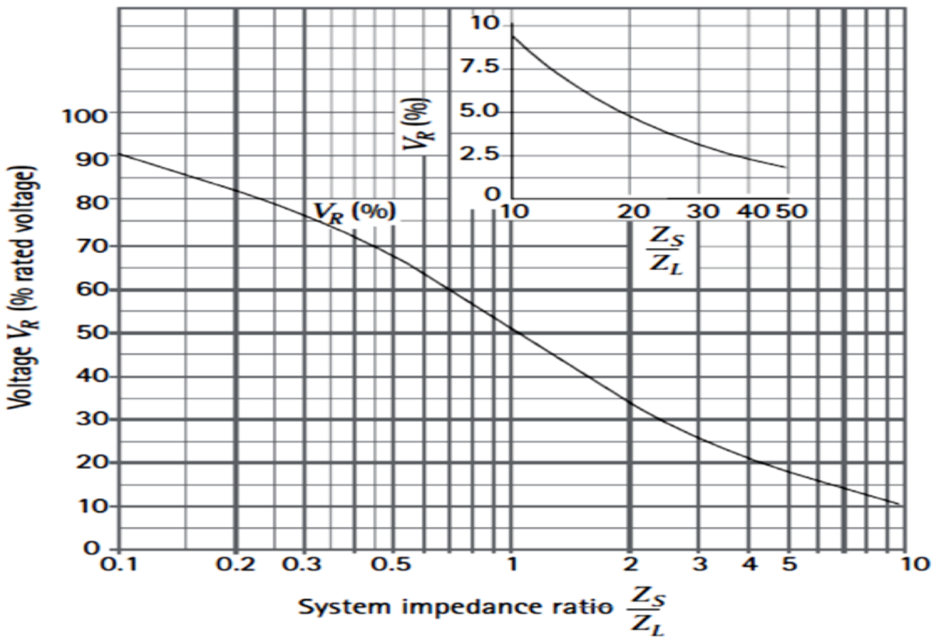


Figure 2.7: Voltage at relay point with S.I.R.

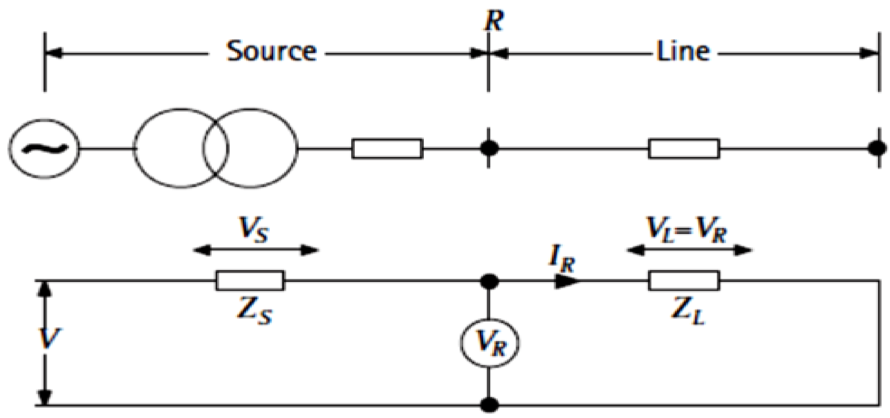


Figure 2.8: Power system configuration

$$V_R = I_R Z_L \text{ where } I_R = \frac{V}{Z_S + Z_L}$$

Therefore: ……………………………………………… (2.1)

$$V_R = \frac{Z_L}{Z_S + Z_L} V \quad \text{or } V_R = \frac{1}{(Z_S/Z_L)+1} V$$

The above relationships between V_R and Z_S/Z_L are proper for all types of short circuits according to the rules below [26]:

i. Phase fault, V_{ph-ph} is a represented source voltage and Z_S/Z_L represents the ratio of the positive sequence of the source impedance to the line impedance. V_R is the relay voltage phase-phase and I_R is the relay current phase-phase for the faulty phases.

$$V_{R(Ph-Ph)} = \frac{1}{\left(\frac{Z_{S1}}{Z_{L1}}\right)+1} V(Ph - Ph) \quad (2.2)$$

ii. Earth fault V Phase-Ground is the source voltage and Z_S/Z_L is the ratio of the composite of the positive and zero sequence impedances. V_R is the relay voltage phase-ground and I_R is the relay current for the phase faulted.

$$V_{R(SLG)} = \frac{1}{\left(\frac{Z_{S1}}{Z_{L1}}\right)\left(\frac{2+p}{2+q}\right)+1} V(SLG) \quad (2.3)$$

Where $Z_S = 2Z_{S1} + Z_{s0} = Z_{S1}(2 + p)$
and $Z_L = 2Z_{L1} + Z_{L0} = Z_{L1}(2 + q)$

$p = \frac{Z_{S0}}{Z_{S1}}$, $q = \frac{Z_{L0}}{Z_{L1}}$

2.9 Distance Relay Maloperation

Distance relay maloperation, concerning its settings, can be visualized considering relay under-reach and relay over-reach status. These are given in the following subsections.

2.9.1 Distance relay under-reach

The distance protective relay can see a near-fault as if it is far away (if the fault is positive) in the sense that the relay sees a greater impedance than the real impedance, which is known as:

$$\textbf{\% Under-reach} = \frac{Z_R - Z_F}{Z_R} * 100\% \quad (2.4)$$

where ‘’Z_R = relay reach setting’’, and ‘’Z_F = effective reach’’.

One of the reasons for the under-reach is the high impedance fault, where the relay sees high impedance than real impedance and therefore cannot cover the full range of it [26]. Other causes for distance relay under-reach can be line series or shunt compensation [29].

2.9.2 Distance relay over-reach

The distance protective relay can see a distant fault as if it were nearby (if the fault is negative), meaning that the device sees an impedance less than the real impedance, which is defined as:

$$\textbf{\% Over-reach} = \frac{Z_F - Z_R}{Z_R} * 100\% \qquad (2.5)$$

where; ‘’Z_R = relay reach setting’’ and ‘’Z_F = effective reach’’.

The most common problem of over-reach is the exit of one of the parallel lines when it goes out of service for the survival of the other lines [26]. Series or shunt compensation in the transmission line can be among the causes of a relay to overreach [29].

2.10 Computation of the Apparent Impedance

In any case of fault type, the voltage and current of the relay point are used to activate the suitable relay element based on measured positive sequence signals. Therefore, the distance relay zone setting is depended on the line positive sequence impedance. Hence, appropriate voltage and current inputs and a processing algorithm are required to calculate the line positive sequence impedance seen at the relay point.

For normal balanced operations and/or symmetrical three-phase faults, only the phase voltage and current at the relay point may suffice to obtain the positive sequence impedance. On the other hand, under unbalance operations and/or unsymmetrical fault conditions, the other voltage and current sequences are also presented. The presence of the negative and zero sequence components prohibits direct use Ohm's Law to calculate the positive sequence phase of currents and voltages will be needed for measurements to be processed in order to facilitate the provision of the line positive sequence impedance under various fault conditions [25].

Appendix provides in detail the diagrams and necessary derivations of the measured positive sequence impedances to the faults for the various system fault conditions. The conclusion of the results of Appendix are presented in Tables 2.2 and 2.3.

Table 2.2: Apparent impedance equations for multi-phase faults

Apparent Impedance	Suitable for Faults
$\frac{V_a - V_b}{I_a - I_b} = \frac{V_1 - V_2}{I_1 - I_2} = Z_{1\_ab}$	'a'-'b' Ungrounded 'a'-'b' Grounded 3-Phase Ungrounded 3-Phase Grounded
$\frac{V_b - V_c}{I_b - I_c} = \frac{V_1 - V_2}{I_1 - I_2} = Z_{1\_bc}$	'b'-'c' Ungrounded 'b'-'c' Grounded 3-Phase Ungrounded 3-Phase Grounded
$\frac{V_c - V_a}{I_c - I_a} = \frac{V_1 - V_2}{I_1 - I_2} = Z_{1\_ca}$	'c'-'a' Ungrounded 'c'-'a' Grounded 3-Phase Ungrounded 3-Phase Grounded

Table 2.3: Apparent impedance equations for phase-to-ground faults

Apparent Impedance	Suitable for Faults
$\frac{V_a}{I_a + mI_0} = Z_{1\_a}$	'a' to Ground
$\frac{V_b}{I_b + mI_0} = Z_{1\_b}$	'b' to Ground
$\frac{V_c}{I_c + mI_0} = Z_{1\_c}$	'c' to Ground

2.11 Comparators for Distance Protection

It is possible to use the apparent impedance directly to implement distance protection by comparing the measured impedance with some type of impedance characteristic represented by a geometric shape, such as a circle or box. The performance of the apparent impedance approach, however, has been shown to suffer from many practical conditions of load flow and fault impedance [30]. Improved performance can be obtained by utilizing methods that are based on signal comparisons. Most modern microprocessor distance relays use methods similar to those detailed below.

The operating characteristics of distance relays can be obtained by either amplitude comparison or phase comparison of the sets of vectors derived from the signals of the current and voltage of the protected line. Equivalent performance is obtained in either case; however, phase comparison is more easily understood and more widely implemented in modern relays [31]. Hence, this study will focus only on the phase comparison implementation.

A general distance relay characteristic is derived by a two-input phase comparator of vectors S_1 and S_2, given by Equation (2.6) [32].

$$\left.\begin{aligned} S_1 &= I_r Z_R - K_1 V_r \\ S_2 &= K_2 V_r + K_3 I_r Z_R + K_4 V_{pol} \end{aligned}\right\} \quad \dots\dots\dots\dots\dots\dots (2.6)$$

where:

S_1 is the phasor of the operating voltage;

S_2 is the phasor of the polarization voltage;

I_r is the current of the particular fault loop;

V_r is the voltage of the particular impedance loop;

Z_R is the reach of the distance detector;

V_{POL} is the memory or cross-polarization voltage; and

K_1, K_2, K_3 and K_4 are complex constants defining the relay characteristics. The parameters V_r and I_r are the appropriate loop voltages and currents as calculated in Appendix A. Examples are listed below:

$V_r = V_a - V_b$ for the A - B element;

$I_r = I_a - I_b$ for the A - B element;

and/or,

$V_r = V_a$ for the A-Ground element;

$I_r = I_a + m\, I_0$ for the A-Ground element.

The angular displacement of vectors S_1 and S_2 if S_1 leads S_2 is considered positive. The phase comparator operates if the following condition is satisfied [33]:

$$\left.\begin{array}{c} -90° \leq \angle S_1 - \angle S_2 \leq 90° \\ \text{or} \\ |\angle S_1 - \angle S_2| \leq 90° \end{array}\right\} \quad \text{.......................(2.7)}$$

The use of this approach in the development of the distance relay characteristics will be presented in the following section.

2.12 Distance Protection Characteristics

The 'K' parameters of vectors S_1 and S_2 define the shape, size and position of the distance characteristic on the impedance plane [34]. These characteristics typically take the form of circles (e.g., impedance, mho and lens) and straight lines (e.g., reactance and quadrilateral). However, the numerical relays may be design operating characteristics of approximately any shape. The most commonly used operating characteristics by distance relays are impedance, mho self-polarized, mho cross-polarized, reactance, and quadrilateral characteristics [35].

The method used for the acquisition of different operating characteristics through the phase comparator is given in the following sections [33]. Special attention is given to the mho self-polarized characteristic because this has been selected as a characteristic for the distance relay that has been modeled in this study.

2.12.1 Impedance characteristics

The impedance relay characteristic is defined as a circle in the impedance plane with zero as its center. This characteristic is obtained by setting: K_1, K_2, $K_3 = 1$ and $K_4 = 0$. Hence, Equation (2.6) becomes:

$$\left.\begin{aligned} S_1 &= I_r\, ZR - V_r \\ S_2 &= V_r + I_r\, Z_R \end{aligned}\right\} \quad \ldots\ldots(2.8)$$

To represent the impedance relay characteristic, it is necessary to represent the voltage phasors S_1 and S_2 in the impedance plane. This is accomplished by dividing the above equations by the current (Ir), yielding:

$$\left.\begin{aligned} S'_1 &= Z_R - Z_r \\ S'_2 &= Z_r + Z_R \end{aligned}\right\} \quad \ldots\ldots(2.9)$$

where; Z_r is the apparent impedance seen by distance relay and Z_R is the reach of the distance detector.

Fig. (2.9(a)) demonstrates an example of the impedance relay with the operating conditions being met. It can be seen that with Z_r measured inside the characteristic circle, the angular variation between S'_1 and S'_2 will be less than 90°, which fulfils the operating condition. Fig. (2.9(b)) shows an example of the impedance relay with the operating conditions not being met. It can be seen that with Z_r measured outside of the characteristic circle, the angular variation between S'_1 and S'_2 will be greater than 90°, which does not fulfill the operating condition.

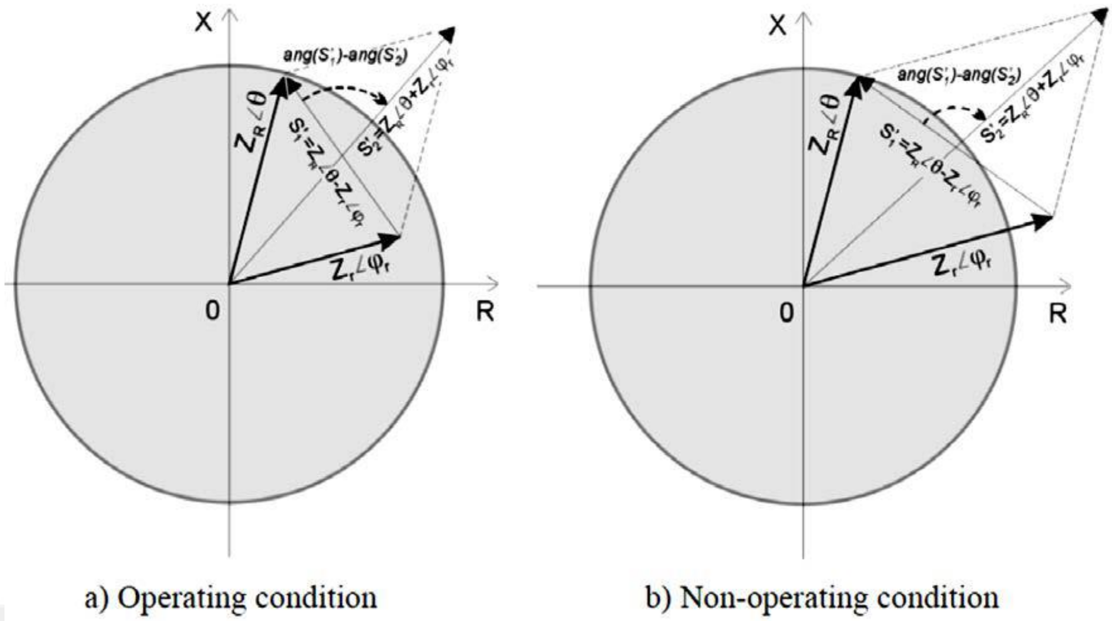


Figure 2.9: Impedance characteristics on R-X diagram

This simple geometric demonstration can be repeated for all points on the R-X plane to demonstrate that only points decline inside the characteristic circle centered on the origin with a radius of $|Z_R|$ that will cause the relay to operate. The impedance relay has three main disadvantages. These are not directional; therefore, it requires a directional element to have correct differentiation. It is affected by the fault arc resistance and is highly sensitive to oscillations in the power system as it covers a large area with its circular characteristic.

2.12.2 Mho self-polarized characteristics

The mho relay characteristic is defined as a circle in the impedance plane which passes through the origin. This characteristic is obtained by setting K_1, $K_2 = 1$ an K_3, $K_4 = 0$. Hence, Equation (2.6) becomes:

$$\left.\begin{aligned} S_1 &= I_r Z_R - V_r \\ S_2 &= V_r \end{aligned}\right\} \quad \text{.........................(2.10)}$$

These phasors represent the simplest of mho characteristics; they are self-polarized. They are referred to as self-polarized because the only phasor in the polarization vector (S_2) is the voltage of the impedance loop being measured.

To represent mho relay characteristic, it is necessary to represent the voltage phasors S_1 and S_2 in the impedance plane. Again, this is accomplished by dividing the above equations on the current (I_r), yielding:

$$\left.\begin{aligned} S'_1 &= Z_R - Z_r \\ S'_2 &= Z_r \end{aligned}\right\} \quad \text{...}(2.11)$$

Fig. (2.10a) presents an example of the mho relay with the operating conditions being met. It can be seen that with Z_r measured inside the characteristic circle, the angular variation between S'_1 and S'_2 will be less than 90 degrees, which fulfils the operating condition. Fig. (2.10(b)) shows an example of the mho relay with the operating conditions not being met. It can be seen that with Z_r measured outside of the characteristic circle, the angular variation between S'_1 and S''_2 will be greater than 90 degrees, which does not fulfill the operating condition.

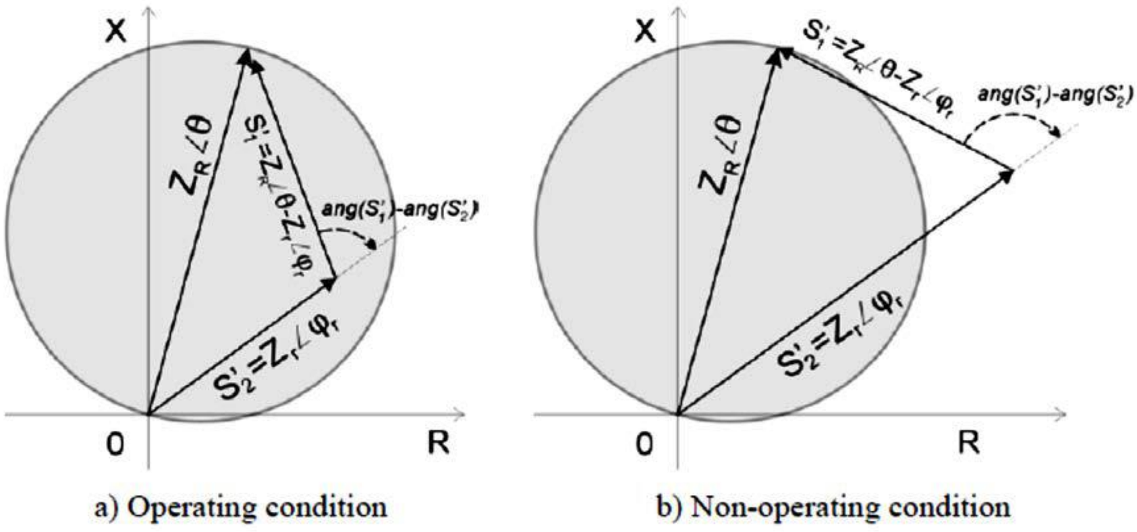


Figure 2.10: Diagram of Mho self-polarized characteristic on R-X

This simple geometric demonstration can be repeated for all points in the R-X plane to demonstrate that only points falling within the circle, centered at ($Z_R/2$) with a radius of $|Z_R|/2$ will cause the relay to operate. The mho characteristic, in general, is a popular design because it can be made from a single comparator, has well-defined reach, is firmly fixed directionally, and is made to allow fault resistance quite well without serious over-reaching faults because of the load [30].

2.13 Effect of Arc Resistance on Reach of Distance Relay

In cases of firm faults, the measured impedance by the relay is equal to the impedance until the fault point. However, the fault may not be firm, i.e., it might include an electric arc. With arc faults, it has been found that the drop fault voltages and the eventual current in phase, show that the impedance is completely resistive [33].

For the reactance characteristic, the setting of the reactance relay does not vary in the presence of arc resistance due to its being designed to measure only the reactance component of the line. It may be seen from the relay characteristics, shown in Fig. (2.11), that, theoretically, any rise in the resistance component of the fault impedance will not effect the relay reach as the relay will continue to measure the same value of the reactance (X) [33, 36].

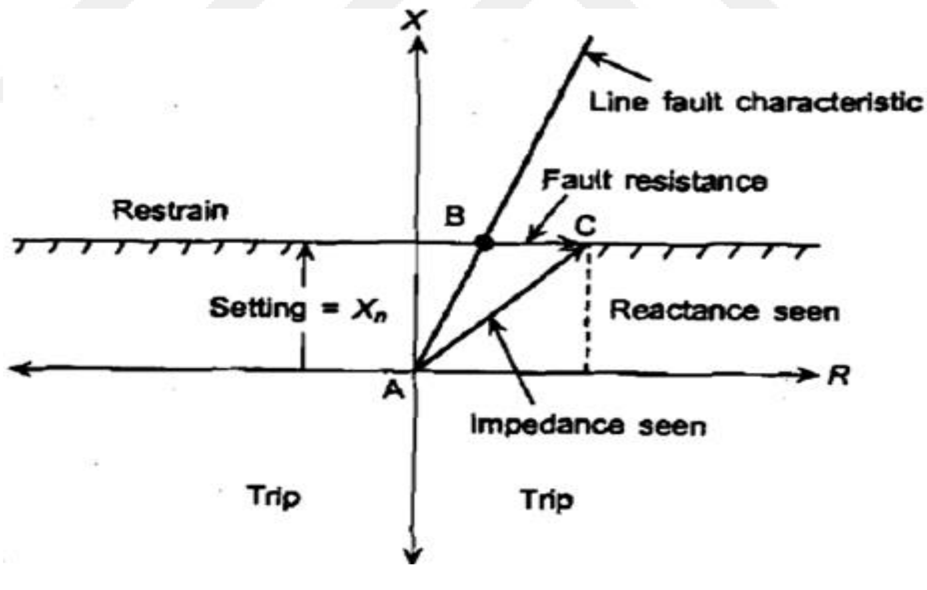


Figure 2.11: Effect of arc resistance on the reach of reactance relay

However, there is arc resistance (R_F) of the two currents in the system due to the fault current, fault resistance and impedance. Fig. (2.12(b)) shows the vector diagram for a reactance relay at G on the line having a leading source angle. From this, it can be seen that the reactance D presented to the relay is less than the actual line reactance to the fault X. Similarly, a relay at H on the line having a lagging source angle would under-reach [26]. This may appear as a complex impedance [30]. This is explained by reference to Fig. (2.12(a)), which shows a fault with high resistance R_F fed from both ends of the transmission line carrying load current. For simplicity, the power system has been reduced to an equivalent two-machine system. In the example shown, source voltage E_G is considered to be leading E_H due to the pre-fault load transfer. Under fault conditions, the fault current I_F is the vector sum I_G and I_H fed from each end of the I_F, which is not in phase with I_G and I_H measured by the relays at G and H. The I_F will appear to these relays as a complex I_G, and as a result, the relay over-reaches. Similarly, the relay at H on the line with a lagging source angle would under-reach [26].

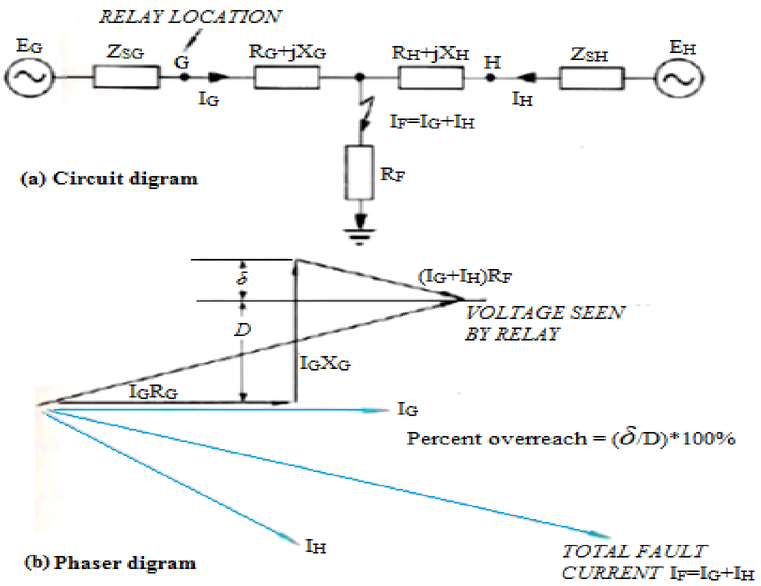


Figure 2.12: Apparent impedance with high arc resistance

For a mho characteristic distance relay, an arcing fault condition is changed at the fault angle due to the increase in value of the resistive component. For this reason, a mho relay is characteristic of having an angle equivalent to the line angle, under arcing conditions, and under-reaching. A mho relay is utilized with its relay characteristic angle (RCA) that is set lower than the line angle, so it can take a few values of arc resistance without leading to under-reach. Furthermore, when setting the relay, the variation between the line angle β and the relay angle ϕ must be recognized. The characteristic result is shown in Fig. (2.13), where AB identifies the length of the protected line.

Then the ϕ is set lower than β, the actual value of the protected line, and AB will equal the value of the relay setting. AQ is multiplied by cos(β – ϕ) [26]. The requirements of the AQ relay setting are as follows:

$$AQ = \frac{AB}{\cos(\beta - \phi)} \quad (2.12)$$

The RCA in general can be adjusted to be 45°, 60°, 75° and so on. This setting of 45° is used for high voltage (33 kV or 11 kV) distribution lines. The 60° setting is used for 66 kV or 132 kV lines while the 75° setting is used for 275 kV and 400 kV lines [36].

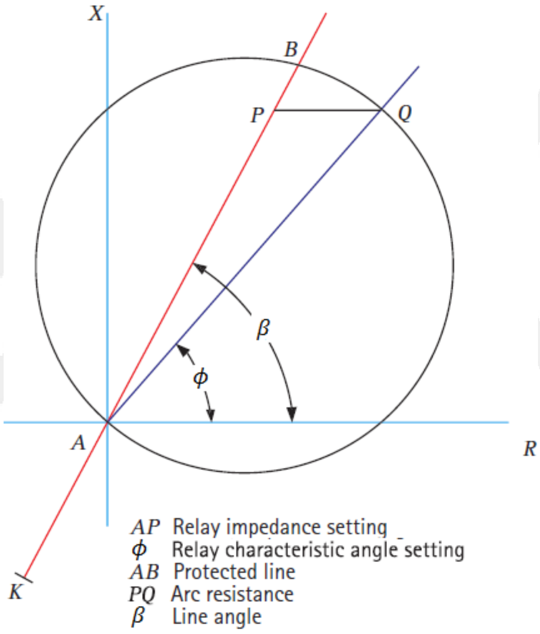


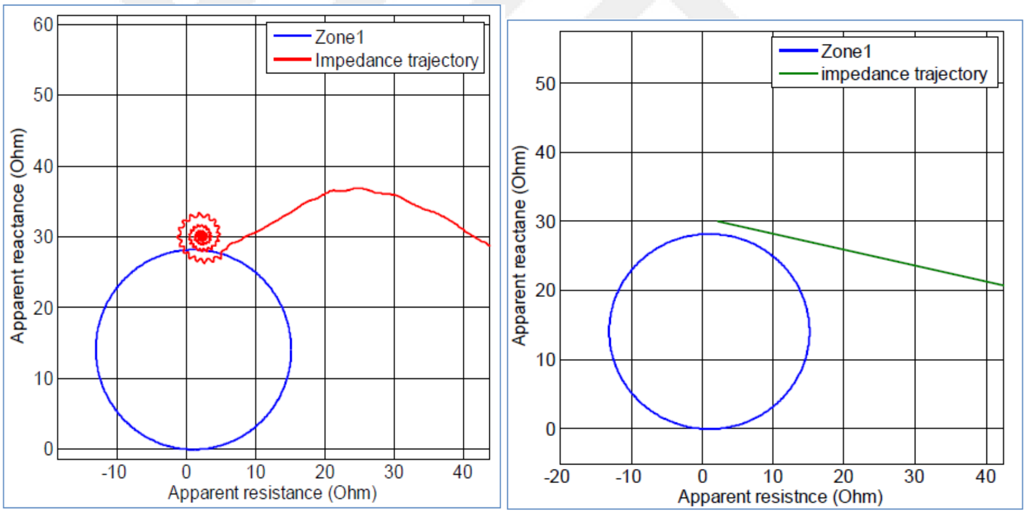
Figure 2.13: Mho distance relay with increased arc resistance coverage

2.14 Effect of DC Components on Distance Relay Performance

Generally, the fault current contains DC compensation in addition to the frequency component of the AC power. The proportion of DC to AC current component depends on the instantaneous voltage cycle which occurs as a fault and the value of degradation of the DC compensation depends on the X/R of the system.

To know how the presence of the DC component in the fault current affects the apparent impedance that is seen by the distance relay, we consider a 100-kilometer transmission line protected through a distance relay with Zone 1 covering the 80% of the length of the transmission line (i.e,80 km). If we assume a 3Ph fault with a maximum DC component at 85 km of distance relay locations (i.e., out of zone1), the apparent impedance route will be seen by the distance relay, shown in Fig. (2.14a). On the other hand, Fig. (2.14b) illustrates the route of the apparent impedance for the same fault, but here with no DC component (the DC component has been removed by using a phasor simulation in MATLAB/SIMULINK).

In Fig. (2.14(a)), the DC component causes transient oscillations in the apparent impedance which results in vortex-like shapes as the measured impedances approach the steady-state. As such, these oscillations may cause the relay to overreach (i.e., the Zone 2 fault may be treated as Zone 1). For correct performance of the distance relay, the DC component must be filtered out. Most commercially available microprocessor-based relays employ sophisticated filtering techniques. As an example, the GE Multiline D30 uses a modified MIMIC-type digital filter [37].



With maximum DC component　　　With DC component removed

Figure 2.14: Effect of DC component on apparent impedance

CHAPTER THREE

Flexible AC Transmission Systems

3.1 Introduction

FACTS devices have come into view in power systems due to the development of power electronics in their components for power and high voltage. In power systems, they provide higher controllability through power electronics devices. In different applications, we can insert FACTS devices worldwide, and modern types of FACTS devices are suitable for insertion in practice. This technology provides the best capability to operate in different circumstances and it improves the usage due to its presence [38, 39]. This chapter presents the possible types of FACTS devices and their advantages. We shed light on two types of second-generation FACTS devices, namely STATCOM and UPFC. The impact of these two devices is investigated regarding distance relay performance. Their description and bases of operations are briefly presented.

3.2 Types of FACTS

FACTS devices are power electronics devices based on the equipment in a system, which can quickly affect voltages, currents, impedances and/or phase angles in transmission systems. In a power system, the devices may improve security and flexibility. Generally, FACTS devices can be classified into four classes [6, 40]**:**

i. Series devices

Generally, these devices inject voltage in series with a line (Fig. 3.1(b)). The current is multiplied by the variable impedance flowing through it. It represents a series voltage that is injected into the line. As a phase quadrature of the voltage with the current of line, the series device provides or expends changeable reactive power. The purposes of the application of series controllers are to control the current, power flow and damp oscillations. The most widely used types of series of FACTS devices in the transmission grid are TCSC and SSSC.

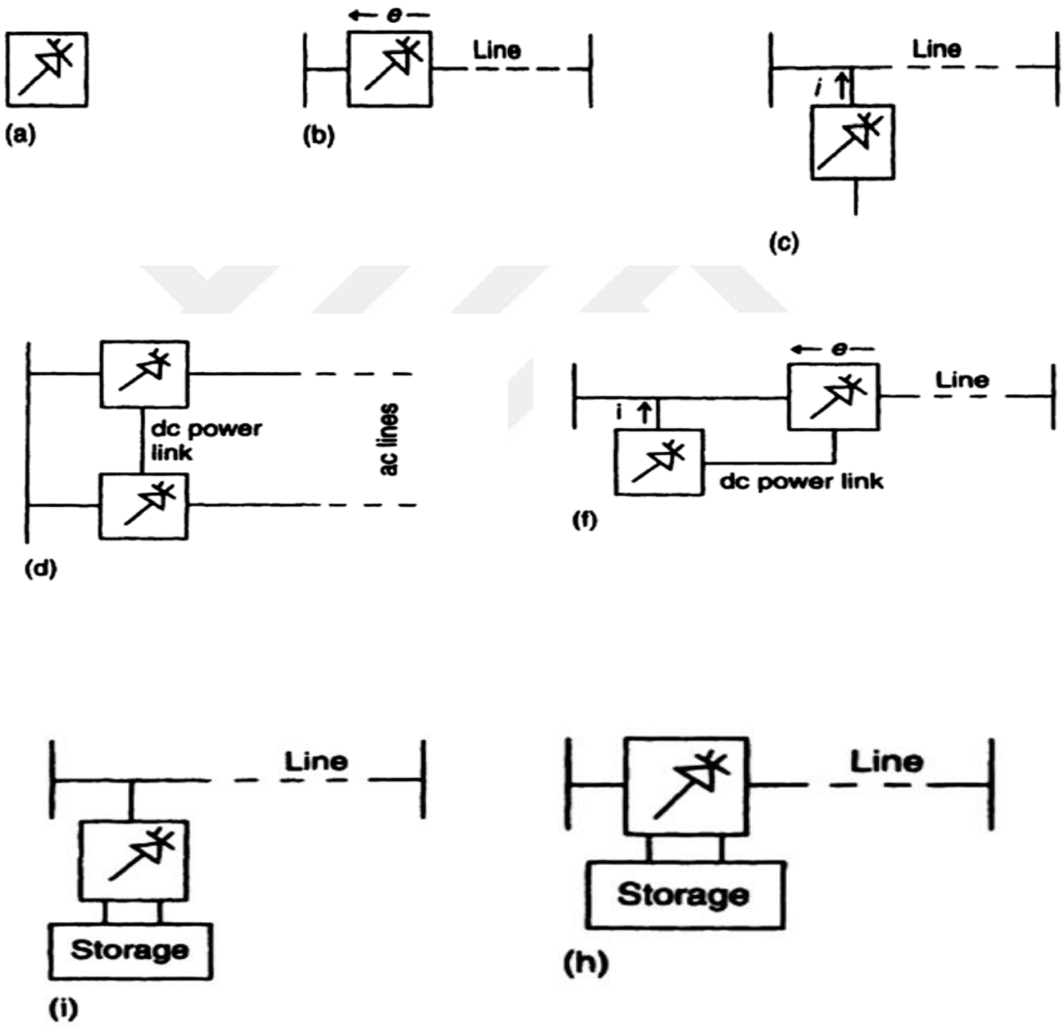


Figure 3.1: FACTS devices fundamental types:

(a) FACTS devices general symbols; (b) series device; (c) shunt device; (d) series-series device; (f) series-shunt device; (h) series with storage device; (i) shunt with storage device.

ii. **Shunt devices**:

Generally, these devices inject current into the system at the connection point (Fig. (3.1 (c)) where the line is connected to a variable shunt impedance and represents the current injected into the line that causes a changeable current flow. This device is a good way to control voltage around the connection point by injecting a reactive current (leading or lagging). The more utilized type of shunt FACTS in the transportation grid are the Static VR Compensation(SVC) and the STATCOM.

iii. **Combined device series-series**:

This device consists of a series of devices and separate circuits that are controlled in a regulated manner in a multi-line transportation system, as illustrated in Fig. (3.1(d)).

iv. **Combined device series-shunt**:

These consist of a shunt and a series of devices that are separated and controlled in a coordinated manner. A Unified Power Flow Controller (UPFC) consists of a series of shunt devices joined together via a DC link (Fig. (3.1(f)). In practice, shunt controllers inject current into the system and series controllers inject current into the line. However, when unifying the shunt and series devices, the real power can be interchanged between the series and shunt devices by the DC power link. Depending on the FACTS devices that are used in the control, it is categorized as:

- Variable impedance type (i.e., SVC, TCSR, etc.)
- Voltage Sourced -Converter (SC-based (i.e., STATCOM, UPFC, etc.)

FACTS devices based on VSC have many uses in addition to changeable impedance types. For instance, a shunt (STATCOM) is more precise than a Voltage Sourced- Converter (VSC) for the same value and it is technically outstanding. It may provide demanded reactive current and even bus voltages at low values and it may be designed to have an in structure short-term overload ability. Likewise, a shunt (STATCOM) may provide active power if its DC terminals have an energy source or large energy storage [41].

3.3 Voltage Source Converter

The Voltage-Source Converter (VSC) is the basic building block of many of the modern FACTS devices such as STATCOM, SSSC, and UPFC. The voltage-sourced converter generates AC voltage from a DC voltage, where the magnitude, the phase angle and the frequency of the AC output voltage can be controlled. The voltage-source converter DC voltage is supported by capacitor(s) large enough to at least handle a sustained charge/discharge current without a significant change in the DC voltage. Two VSC technologies can be used for the VSCs: [6]

- VSC using GTO-based square-wave inverters and special interconnection transformers. Typically, four three-level inverters are used to build a 48-step voltage waveform. Special interconnection transformers are used to neutralize harmonics contained in the square waves generated by individual inverters. In this type of VSC, the fundamental component of voltage is proportional to the voltage V_{DC}. Therefore, V_{DC} has to vary for controlling the injected voltage.
- VSC using IGBT-based PWM inverters. This type of inverter uses Pulse-Width Modulation (PWM) technique to synthesize a sinusoidal waveform from a DC voltage with a typical chopping frequency of a few kilohertz. Harmonics are cancelled by connecting filters at the AC side of the VSC. This type of VSC uses a fixed DC voltage V_{DC}. Voltage is varied by changing the modulation index ($MI=V_{ref} / V_{carrier}$) of the PWM modulator.

3.4 Static Synchronous Compensator (STATCOM)

The Static Synchronous Compensator (STATCOM) is a shunt compensation device that is able to provide and/or consume reactive power. It has numerous outputs to control nominated elements of an electrical power system (Fig. (3.2)). Specifically, the STATCOM is a converter of a voltage source from input DC voltage to AC outputs to provide a group of 3Ph, and in each phase two phases are doubled and are identical to the AC voltage system by a relatively small reactance (that is supplied through each interface reactor or the leakage inductance of a coupling transformer). The energy storage capacitor provides DC voltage [42].

3.4.1 Principle STATCOM operation

The shunt device regulates voltage in its terminals by controlling the amount of reactive power that is supplied into or consumed by the power system. If the system voltage is low (i.e., under the STATCOM reference voltage), the STATCOM supplies reactive power (STATCOM capacitive). If system voltage is high (i.e., above the STATCOM reference voltage), it consumes reactive power (STATCOM inductive). Reactive power differentiation is performed by a VSC that is linked on the secondary side of a coupling transformer. The VSC utilizes power electronic devices to assemble an AC voltage from a DC voltage source, such as a GTO, IGBT or IGCT.

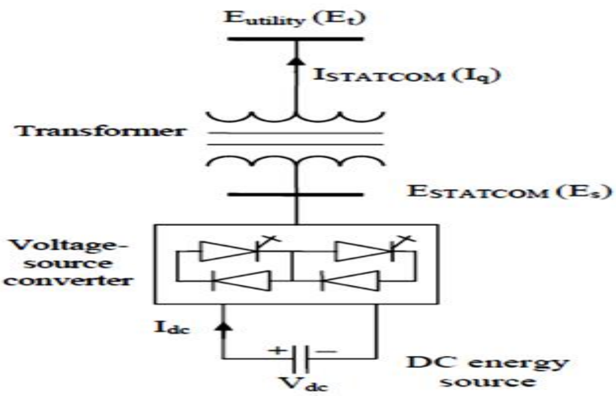
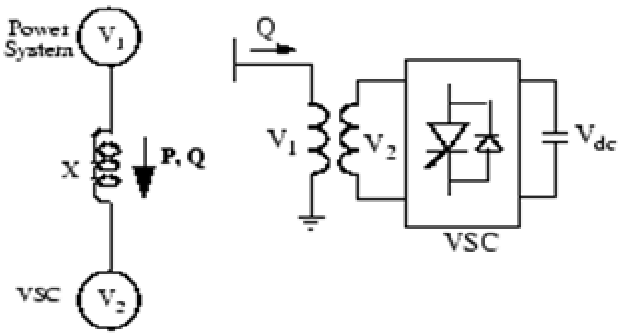


Figure 3.2: Single line of a STATCOM device



$$P = \frac{V_1 V_2 \sin \emptyset_{statcom}}{X}$$

$$Q = \frac{V_1 (V_1 - V_2 \cos \emptyset_{statcom})}{X}$$

where:

V_1 = line to line voltage of source

V_2 = line to line voltage STATCOM

X = Reactance of interconnection transformer and filters

$\emptyset_{statcom}$ = angle of V_1 with respect to V_2

Figure 3.3: The STATCOM principle

Fig. (3.3) illustrates the operating principle of the STATCOM showing the active and reactive power moving out between sources V_1 and V_2. In the above figure, V_1 symbolizes the voltage of the system to be controlled and V_2 is the voltage generated through the VSC. The generated voltage V_2 is in phase with V_1 ($\emptyset statcom$ = 0), only the reactive power flows (P = 0). When the generated voltage is lower than the voltage system, Q flows from the voltage system to the generated voltage (the STATCOM absorbs the reactive power). In an opposite manner, when the generated voltage is greater than the system voltage, Q flows from the generated voltage to the system voltage (the STATCOM generates reactive power). The value of the reactive power is shown in below equation:

$$Q = \frac{V_1(V_1 - V_2)}{X} \quad \text{...} (3.1)$$

The VSC on the DC side is the voltage source of the DC connected to the capacitor. The generated voltage is slightly phase shifted behind the system voltage to compensate for the VSC losses and the transformer maintains the capacitor charge [43].

3.4.2 STATCOM V-I characteristic

Fig. (3.4) illustrates the ideal STATCOM V-I characteristics. This device may be operated above its total output current zone until the voltage levels become very low in the system. Moreover, we can say that the STATCOM can maintain the maximum capacitive or inductive of output current of the AC system voltage independently. In addition, the STATCOM generates or absorbs the maximum VAR that changes linearly with the AC voltage system [6].

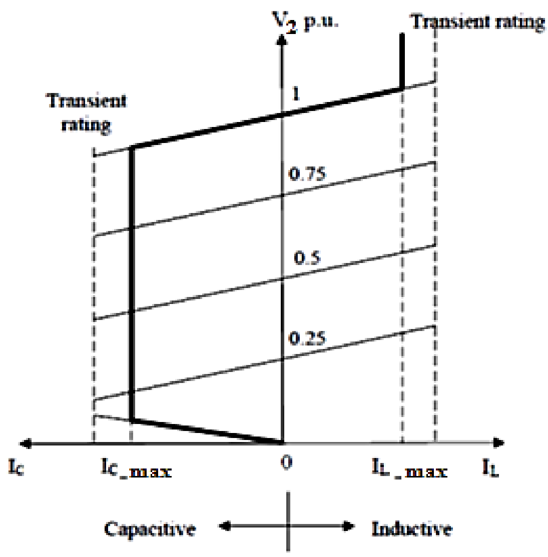


Figure 3.4: The STATCOM V-I characteristics

3.5 Unified Power Flow Controller (UPF)

The Unified Power Flow Controller (UPF) is a combined FACTS device consisting of a shunt (STATCOM) device and a series (SSSC) device, as shown in Fig. (3.5), which are connected through a common DC link to permit the power to flow bi-directionally between the output of the series (SSSC) and the shunt (STATCOM) devices. The UPFC controls the flow of the active and reactive power through the line without an external electric source of energy, and it controls the amount of reactive power that is supplied to the line at the point of installation [43, 44]. The fundamental function of the STATCOM device at the UPFC is to provide or consume the real power required by the SSSC device at the UPFC and at the mutual DC link to support the real power exchange of voltage injections into the SSSC [6].

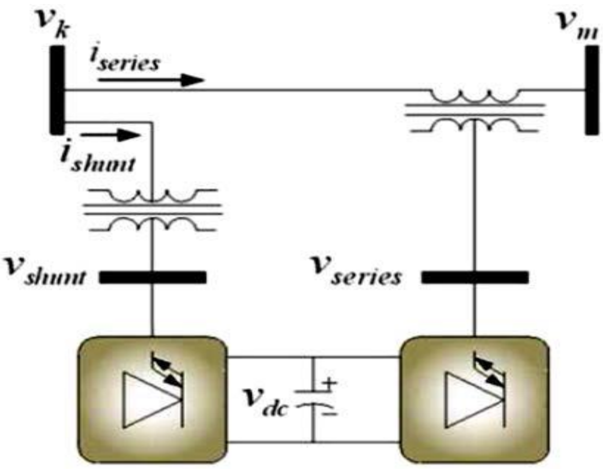


Figure 3.5: The UPFC device

In Fig. (3.6), when the value of the V_s injected voltage stays constant and when the V_1 phase angle for bus voltage sending varies from 0 to 360 degrees, the position described by the terminal point of vector V_2 which is the UPFC bus voltage ($V_2 = V_1 + V_s$), as shown in the phasor diagram being a circle of the format in Fig. (3.6). As the phase angle (θ) is a variation of the injected voltage of the series, the two-line ends of the phase shift (δ) between voltages V_2 and V_3 are also varied. This leads to the ability to control both the active power (P) and the reactive power (Q) being transmitted at one-line end [41].

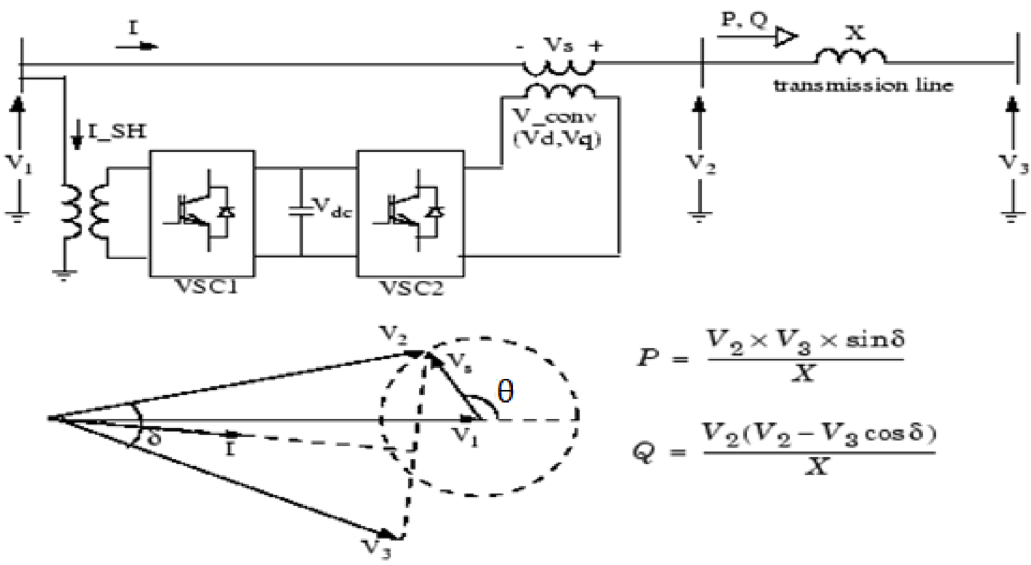


Figure 3.6: UPFC single-line diagram and voltages and currents phasor diagram

3.6 Summary of FACTS devices

Economically, more energy can be transferred through existing or new transport networks with unobstructed availability at lower investment costs, or in situations that are far less costly than larger networks. The use of FACTS in existing lines and substations is to achieve the following:

1. Increased synchronous stability.
2. Increased power transmission capability.
3. Increased voltage stability in the grid.
4. Improved load sharing capability.
5. Decreased system transmission losses.

The selection of FACTS may not be clear in each case, but the subject of the system studies, taking into account all the basic requirements and requirements of the system, may need to be clear in order to arrive at the optimal technical and economic solutions.

3.7 Apparent Impedance Analysis

This section presents a mathematical analysis of the influence of the two types of FACTS devices on the apparent impedance seen by the distance protection relay for compensation installed at the midpoint the transmission lines. The same procedure can be applied to other locations of FACTS devices.

3.7.1 Apparent impedance equation in the presence of a STATCOM

The simplified network of a power system is obvious in Fig. (3.7). In the second section of compensated line, there is a fault (i.e., after the STATCOM position) since for a fault before the STATCOM, the apparent impedance of the distance relay is calculated by using the conventional equation. From the previous sections, the STATCOM device presents a shunt branch containing a voltage source with impedance in series, shown in the Fig. (3.7). The apparent impedance is derived from the phenomenon seen by relaying the phase-to-ground and three phases in the next sub-sections (the same procedure can be used for other types of fault) [17].

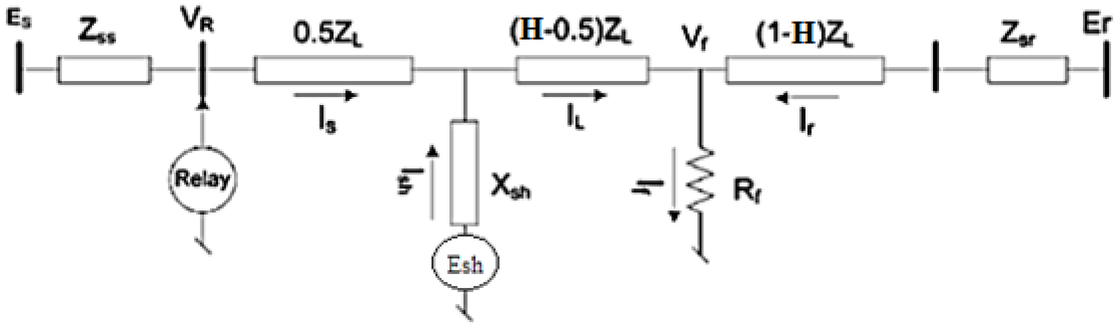


Figure 3.7: Simplified faulted network for a power system with a STATCOM device

A-SLG fault (Phase to ground):

In the relay point, the voltage sequences for the L-L fault after the shunt compensator device (fault location, H≥ 0.5) can be shown as:

$$V_{Rx} = 0.5\, Z_{Lx}\, I_{sx} + (H - 0.5)Z_{Lx}\,(I_{shx} + I_{sx}) + I_{fx}R_f \quad (3.2)$$

where:

x = 1, 2, or 0; a affix indicate the sequence component;

$V_{R\,x}$ = in the relay location voltage sequence (V_{R1}, V_{R2}, V_{R0});

H = fault location from the relay to the fault point in per unit of the total line length;

$I_{sh\,x}$ = the shunt device current sequence;

$I_{s\,x}$ = in the relay location currents sequence;

$I_{f\,x}$ = in the fault resistance current sequence;

R_f = fault resistance;

$Z_L\, x$ = the line impedance sequence components.

The voltage is obtained at the relay location by adding the three sequence components:

$$V_R = V_{R1} + V_{R2} + V_{R0} \qquad (3.3)$$

After simplification we get:

$$V_R = H\, Z_{L1}\, I_s + T1 + T2 + T3 \qquad (3.4)$$

where:

$I_s = I_{s1} + I_{s2} + I_{s0}$; $T1 = H\, I_{s0}(Z_{L0} - Z_{L1})$;

$I_{sh} = I_{sh1} + I_{sh2} + I_{sh0}$; $T2 = (H - 0.5) Z_{L1} I_{sh0} (Z_{L0} - Z_{L1})$;

$I_f = I_s + I_r + I_{sh}$; $T3 = (H - 0.5) Z_{L1} I_{sh} + I_f R_f$;

$Z_{L1} = Z_{L2}$ (The line impedances are assumed equal for positive and negative sequence.)

The shunt compensation device and the current of the zero sequence can be rejected because there will not be a current injection of zero sequence due to the utilization of the delta connection at one side of the coupling transformer for the STATCOM. Therefore, Equation (3.4) can be reduced to Equation (3.5) and with simplification we get:

$$VR = H\, Z_{L1} (I_s + mI_{s0}) + (H - 0.5) Z_{L1} I_{sh} + I_f R_f \qquad (3.5)$$

where:

$m = (Z_{L0} - Z_{L1})/Z_{L1}$ which is the zero-sequence current compensation factor.

The ground unit measuring in the distance relay utilizes the phase voltage at the relay location (V_R) and the identical phase current appropriately compensated by the current of zero-sequence (I_R) so that it correctly measures the impedance of the positive sequence of the line. As a result, the apparent impedance seen by the ground unit distance is given as:

$$Z_{relay} = \frac{V_{relay}}{I_{relay}} = \frac{V_R}{I_R} \qquad (3.6)$$

where $I_R = (I_s + m\, I_{s0})$

Substituting Equation (3.5) into Equation (3.6), the apparent impedance seen by the ground distance unit of the relay is specified by:

$$Z = H\, Z_{L1} + (H - 0.5) Z_{L1}\, (I_{sh}/I_R) + R_f (I_f/I_R) \quad (3.7)$$

When the fault resistance is negligible, Equation (3.7) becomes:

$$Z = H\, Z_{L1} + (H - 0.5) Z_{L1} (I_{sh}/I_R) \quad (3.8)$$

B-3Ph fault (Three phase):

The apparent impedance seen by the relay for a 3Ph fault can be derived; only the final equation (Equation (3.8)) is given as a summary:

$$Z_{relay} = \frac{V_{relay}}{I_{relay}} = H\, Z_{L1} + (H - 0.5) Z_{L1} (I_{sh}/I_s) \quad (3.9)$$

where V_{relay} is the line voltage and I_{relay} is the identical line current.

From Equations (3.8) and (3.9), the first term ($H\, Z_{L1}$) symbolizes the line impedance to the fault point for a firm fault without shunt compensation at the midpoint. Therefore, the error in the apparent impedance appears due to the shunt compensation, which is given as:

$$Z_{error} = (H - 0.5) Z_{L1} (I_{sh}/I_R) \quad (3.10)$$

This inexactitude because of the shunt device is proportional to the location of the fault (H) and the ratio of the current in the shunt device on the current of the relay (I_{sh}/I_R).

The positive quantity of this current ratio, related to the FACTS device of injected current, will drive to a higher impedance seen by the relay, which may result in relay under-reach. Furthermore, the negative quantity of the current ratio may result in the relay experiencing a fault at a location nearer than the actual fault location hence leading to an overreaching effect. This may occur if the shunt FACTS absorb the reactive current instead of the injecting current.

3.7.2 Apparent impedance equation in the presence of the UPFC

This section shows the mathematical analysis of the effect of the series-shunt compensation (i.e., the UPFC) on the apparent impedance observed by the distance relay. The impedance computations are derived for the midpoint compensation of the transmission line with the UPFC. Fig. (3.8) shows the schematic diagram of the compensated line for a distance protection study.

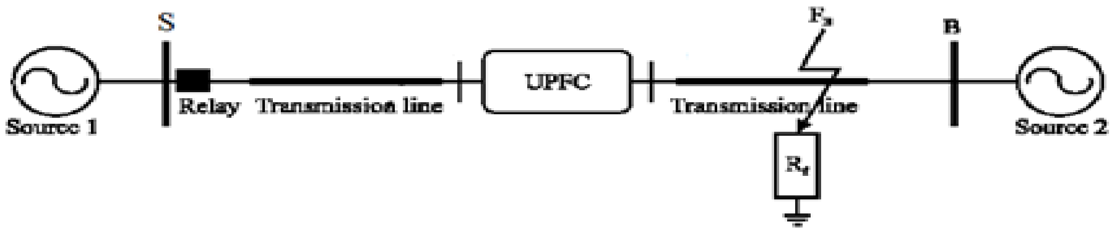


Figure 3.8: Sample power network with UPFC

The operation of the distance relay is analyzed with an existing UPFC, as shown in Fig. (3.8). A fault occurs after the UPFC device. For the fault to occur before the UPFC (or without UPFC), the apparent impedance seen by the distance relay may be calculated using conventional equations. Fig. (3.9) illustrates the sequence network of the system from the relay position [10].

A-SLG fault (phase to ground):

When an SLG fault occurs on the right side of the UPFC and the distance is (n*L) from the relay point, the positive, negative and zero sequence networks of the system during the fault are illustrated in Fig. (3.9). The mathematical analysis starts as follows:

$V_{1s} = I_{1s}\ 0.5\ Z1 + V1_{pq} + I_{1line}(n - 0.5)Z_1 + R_f I_{1f}$ .... (3.11)

$V_{2s} = I_{2s}\ 0.5\ Z_2 + V_{2pq} + I_{2line}(n - 0.5)Z_2 + R_f I_{2f}$ .... (3.12)

$V_{0s} = I_{0s}\ 0.5\ Z_0 + V_{0pq} + I_{0line}(n - 0.5)Z_0 + R_f I_{0f}$ .... (3.13)

where:

$I_{1line} = I_{1s} + I_{1sh}$ $I_{2line} = I_{2s} + I_{2sh}$

$I_{0line} = I_0s + I_{0sh}$, and

V_{1s}, V_{2s}, V_{0s} are at the relay location of the sequence phase voltages;

V_{1pq}, V_{2pq}, V_{0pq} are the series sequence phase voltages injected by the UPFC;

I_{1s}, I_{2s}, I_{0s} are at the relay location of the sequence phase currents;

I_{1line}, I_{2line}, I_{0line} are in the transmission line of the sequence phase currents;

I_{1f}, I_{2f}, I_{0f} are in the faults of the sequence phase currents;

I_{1sh}, I_{2sh}, I_{0sh} are the shunt sequence phase currents injected by the UPFC;

Z_1, Z_0 are the transmission line sequence impedances; and

n is the per-unit distance of the fault from the relay location.

From above, the voltage at the relay point can be derived as:

$$V_s = n\, Is\, Z_1 + V_{pq} + U_1 + U_2 + U_3 + R_f I_1 f \quad (3.14)$$

where:

$V_s = V_{1s} + V_{2s} + V_{0s}$; $U_1 = n\, I_{0s}(Z_0 - Z_1)$

$I_s = I_{1s} + I_{2s} + I_{0s}$; $U_2 = I_{sh}(n - 0.5)Z_1$

$I_{sh} = I_{1sh} + I_{2sh} + I_{0sh}$; $U_3 = (n-0.5)\, I_{0sh}\, (Z_0 - Z_1)$

$V_{pq} = V_{1pq} + V_{2pq} + V_{0pq}$;

In practice, one side of the shunt transformer is always delta connected and there is no zero-sequence current provided by the UPFC, which is to say $I_{0sh} = 0$. Then, Equation (3.14) can be reformulated as:

$$V_s = n\, I_s\, Z_1 + V_{pq} + n\, I_{0s}(Z_0 - Z_1) + I_{sh}(n - 0.5)Z_1 + R_f I_f \quad (3.15)$$

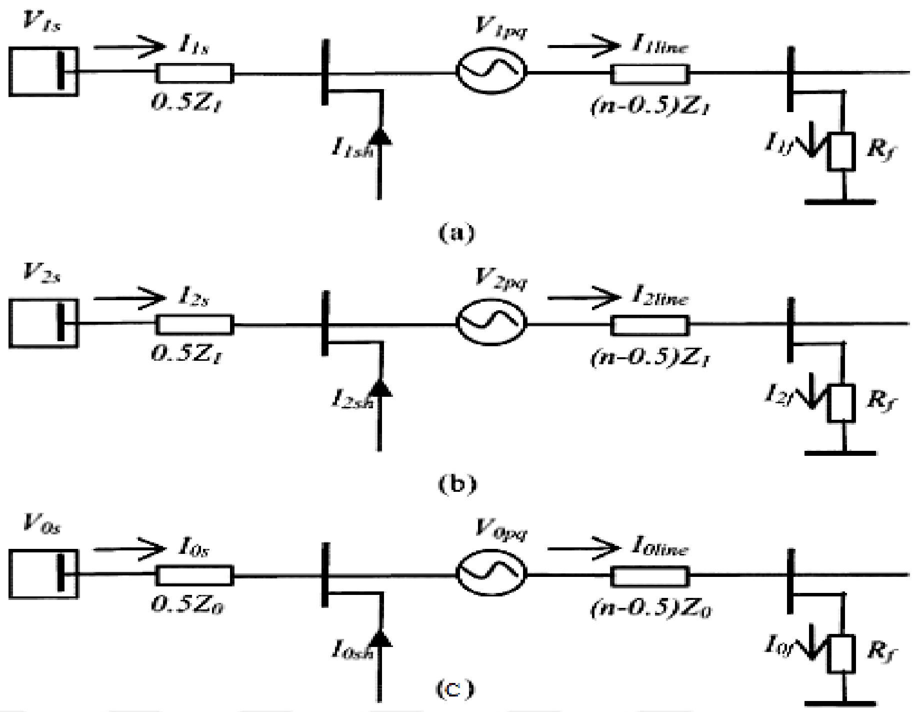


Figure 3.9: The system from the relay location to fault sequence networks
(a) Positive (b) Negative (c) Zero

In transmission systems without a UPFC, for an SLG fault, the apparent impedance of the distance relay can be computed by using the following equation:

$$Z = \frac{V_R}{I_R + \frac{Z_0 - Z_1}{Z_1} I_R} = \frac{V_R}{I_{relay}} \text{...} (3.16)$$

where:

V_R and I_R are the phase voltage and phase current at the relay point, respectively I_{R0} is the zero- sequence phase current I_{relay} is the relaying current

The apparent impedance in the presence of a UPFC can be obtained by substituting Equation (3.15) into (3.16), as follows:

$$Z = n\,Z_1 + (V_{pq}/I_{relay}) + (I_{sh}/I_{relay})(n - 0.5)Z1 + R_f(I_f/I_{relay}) \text{......................} (3.17)$$

When the fault resistance is negligible, Equation (3.17) becomes:

$$Z = n\,Z_1 + (V_{pq}/I_{relay}) + (I_{sh}/I_{relay})(n - 0.5)Z_1 \text{..} (3.18)$$

B-3 Ph fault (Three phase):

The apparent impedance, observed by the relay for the 3Ph fault can be derived by using only the last equation (Equation 3.18), given in summary:

$$Z_{relay} = \frac{V_{relay}}{I_{relay}} = n\,Z_1 + (V_{pq}/Is) + (I_{sh}/Is)(n - 0.5)Z_1 \quad \text{.............................(3.19)}$$

where V_{relay} is the line voltage and I_{relay} is the corresponding line current.

In the two equations (3.18 and 3.19), it can be observed that if the traditional distance relay is used in the transportation system using UPFC during the fault, the apparent impedance observed by the relay has two sections: first, a positive sequence impedance from the relay point to fault point, that is what the distance relay is set to measure; the second is, because of the effect of UPFC on the apparent impedance, it could be classified even further into two sections; one results from the shunt current (I_{sh}) injected by the shunt part and the other effect of the series voltage (V_{pq}) is provided by the series part. Therefore, the distance relay will undergo overreach or under-reach depending on the operational conditions of the UPFC.

CHAPTER FOUR

Modeling and Studied Systems

4.1 Introduction

The effect of the STATCOM and UPFC involving their related controls on the performance of distance relay are studied using the MATLAB/SIMULINK block set. This chapter presents the Simulink models that have been developed for the simulation of the power system, FACTS device and distance relay along with the particular faults under study. The preparatory calculations of the distance relay zone settings are also presented.

4.2 Distance Relay Modeling

The MATLAB/SIMULINK library does not contain a model for distance relays; therefore, it is necessary to build a model for the distance relay and verify it. Software models have been used in the form of equations representing the operational characteristics of relays for a long time by researchers, manufacturers and consultants to design relays and verify their performances. These paradigms portray characteristics that are introduced in different methods, such as interaction versus resistance. The information on which these models are established is either obtainable from manufacturers' publications and patents, or from technical papers describing the performance of the relay [32].

Numerical relay models can be divided into two classes. The first class is the "Phasor-based models," which regards only the basic frequency component of voltages and currents and were the first to be the most utilized by manufactures and researchers to design relays and check their performance. The second category models the "Transient relay model," which takes into account the high frequency and disintegrating DC component of voltages and currents in addition to the fundamental frequency components. This type is rarely used as it needs sophisticated filters to remove the DC and high frequency components [45]. Due to the troublesome effect of the DC components on distance relay performance and since this work is not primarily concerned with signal analysis techniques, the phasor-based model of the distance relay is selected here.

4.3 Distance Relay Phasor Model

The most commonly used input to the relay model is the basic frequency components of currents and voltages. Initially, the models of this kind are used to check whether the performances of the relays are acceptable. In the following paragraphs, models of the phase and ground element are presented in MATLAB/SIMULINK for the phasor-based distance relay.

4.3.1 Phase element model

Mho characteristics were selected as characteristics for the phase element in the distance relay. The Iraqi protection sector uses these characteristics for all distance relays in 400 kV transmission lines in the Iraqi national grid. To implement the basic mho characteristic (i.e. the self-polarized mho characteristic), a circle is drawn crossing through the origin and the desired zone reach limit along the line impedance phasor. The center of the circle will fall at 1/2 of the zone reaching along the line impedance phasor. Fig. (4.1) shows a simple mho characteristic for Zone 1, Zone 2 and Zone 3. The mho characteristic is inherently directional without the need for directional elements. The relay model was developed to implement the mho characteristic relay algorithms is shown in Fig. (4.2). The input to relay model includes the fundamental frequency components of currents and voltages; therefore, there is no need for filters. The input signal differences are fed into the appropriate relay elements along with the settings in vector form.

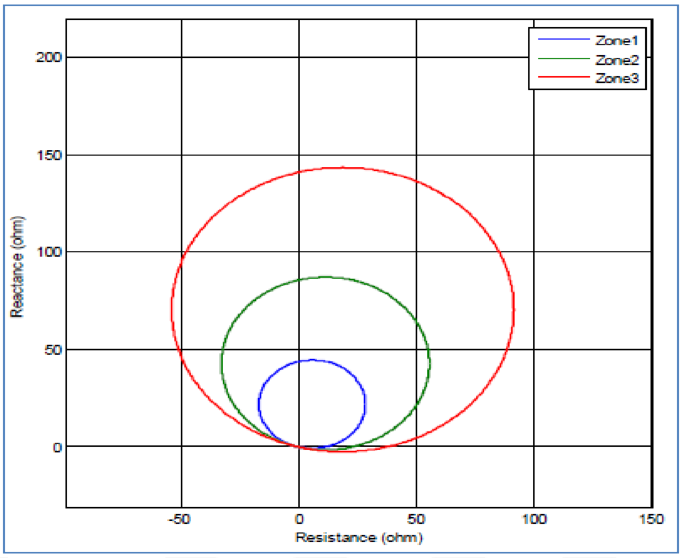


Figure 4.1: Sample of 3 zones with self-polarized mho distance relay characteristic

The contents of each element are shown in Fig. (4.3). Each element contains two parts. Fig. (4.3(a)) is for the apparent positive sequence impedance calculations. Fig. (4.3(b)) is for the generation of trip signals. If the angular criterion of the mho characteristic is met, an 'on-delay' timer will activate and trip the breaker after an appropriate delay.

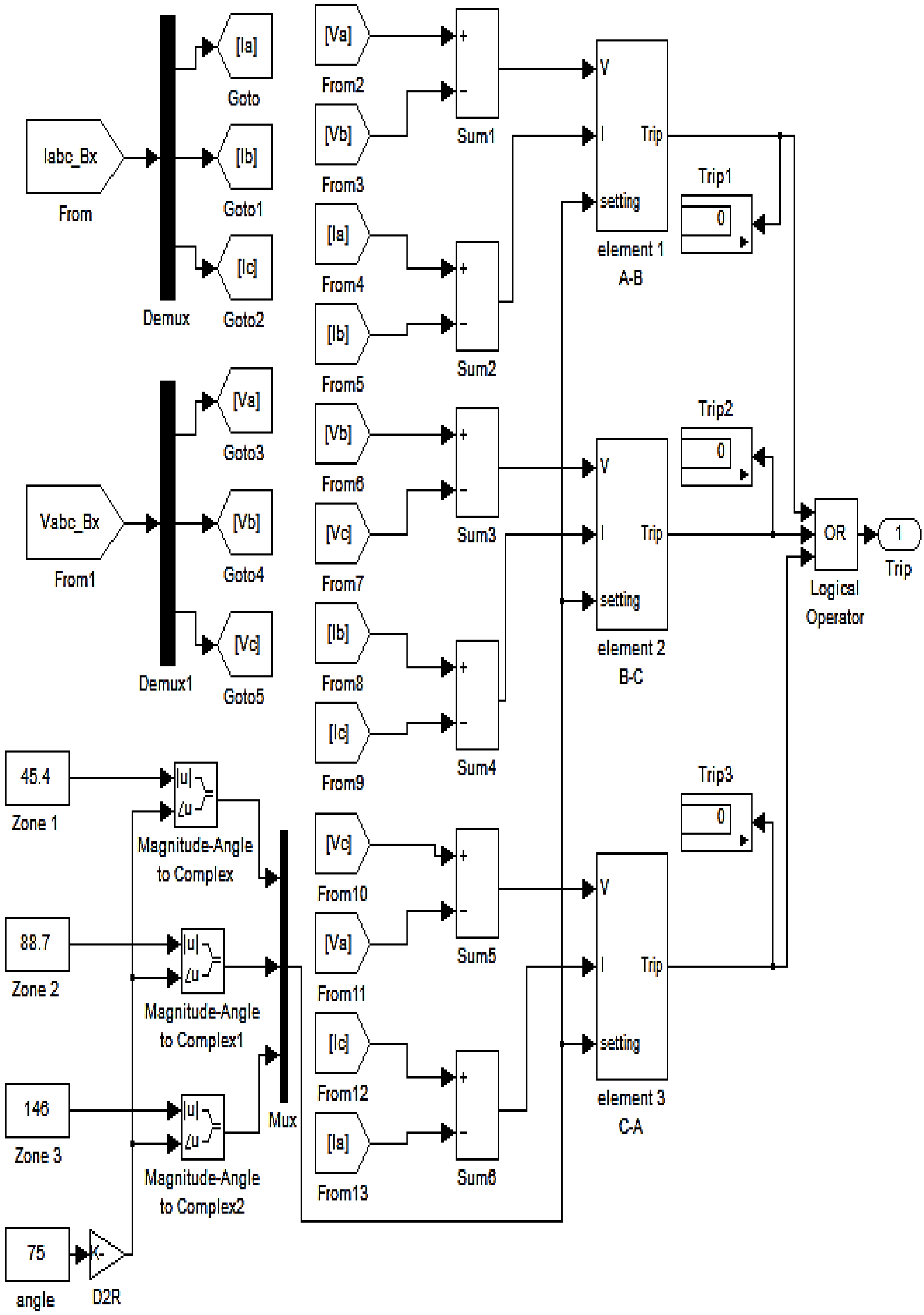
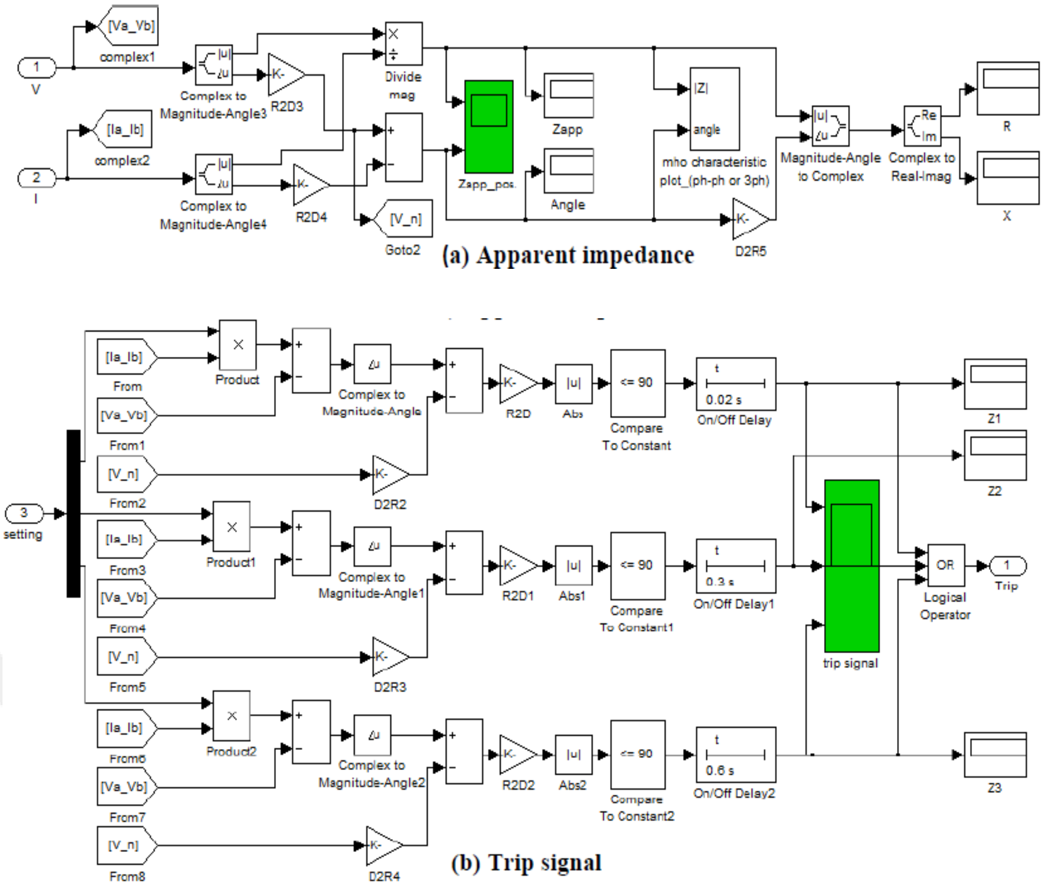


Figure 4.2: Distance relay Mho model for phases fault



(a) Apparent impedance and (b) Trip signal

Figure 4.3: Fault detection and classification for phases fault

4.3.2 Ground element model

The mho characteristic for the ground distance relay is identical to the mho characteristics of the phase distance relay. The modeled R-X diagram for the mho ground element is identical to the phase element one and similar to that shown in Fig. (4.1).

Fig. (4.4) illustrates the ground element model developed to implement the ground mho relay algorithms. This model is very similar to the phase mho relay with two modifications. First, the compensated zero-sequence current (mI_0) is calculated and added to each phase current. Second, the phase voltages and compensated phase currents become the new operating quantities instead of the line values used in the phase relays.

Otherwise, the functionality, settings and construction of the ground mho relay are identical to the phase mho relay.

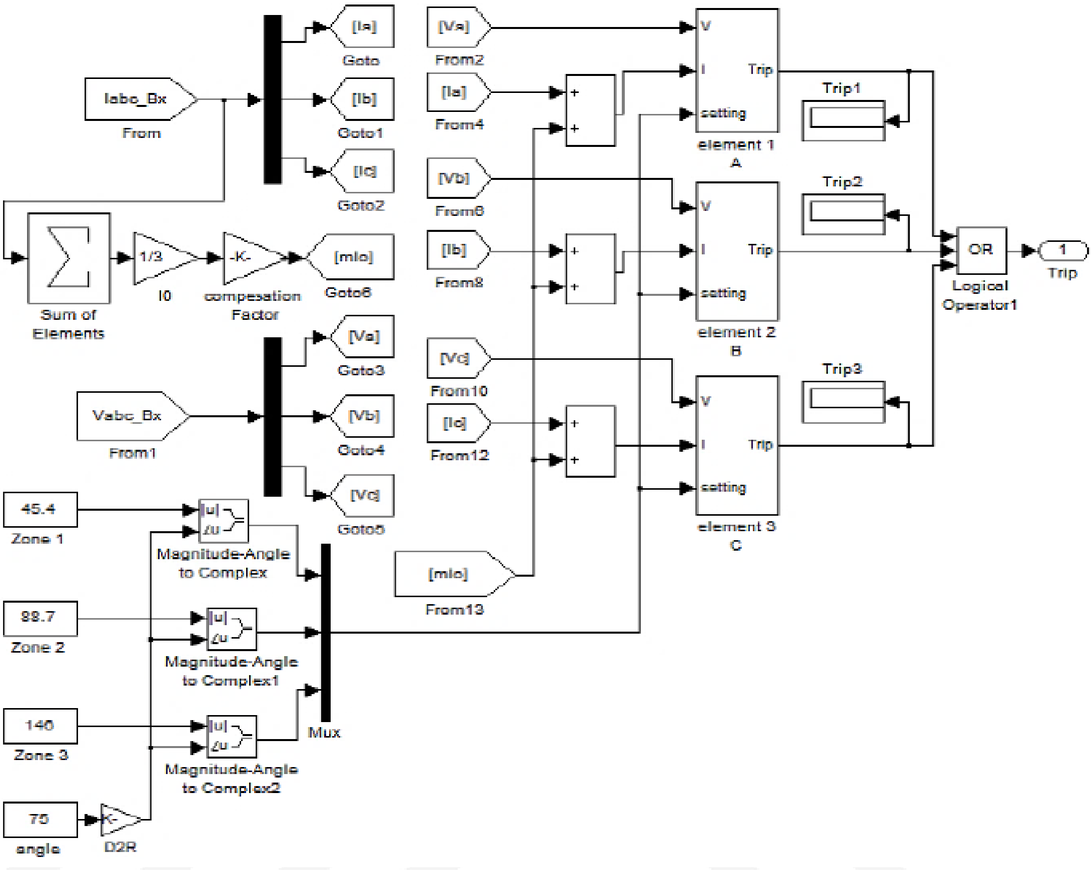


Figure 4.4: Distance relay Mho model for phases to ground fault

4.4 FACTS Devices Model

In this work, only the STATCOM and the UPFC are considered. The MATLAB/SIMULINK library contains models for these two FACTS devices; therefore, there is no need to model these devices and their models can be directly used with modifications for input parameters to become suitable for use in the particular systems studied. The following sections briefly present the necessary requirements for each model.

4.4.1 STATCOM device model

The STATCOM block, shown in Fig. (4.5), is a phasor-based model. It does not contain a detailed representation of the power electronics involved. This block models an IGBT-based on the STATCOM.

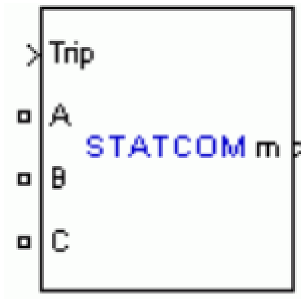


Figure 4.5: STATCOM phasor model

The STATCOM model parameters are: [46].

- The nominal line-to-line system voltage in Vrms and the nominal system frequency in Hertz
- The nominal power of the converter in VA
- The positive-sequence resistance and inductance of the converter
- The nominal voltage of the DC link in Volts
- The total capacitance of the DC link in Farads

The value of all the above parameters can be changed as desired, and in this work, the STATCOM device is used as a voltage regulator.

4.4.2 UPFC device model

The UPFC block, shown in Fig. (4.6), is a phasor model which does not contain detailed representation of the power electronics involved. The UPFC block models an IGBT-based UPFC.

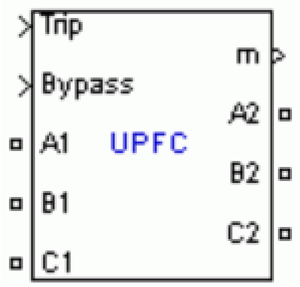


Figure 4.6: UPFC phasor model

The UPFC model parameters are [47]:

- The nominal line-to-line voltage in Vrms and the nominal system frequency in hertz.
- The nominal rating of the shunt converter in VA.
- The positive-sequence resistance R and inductance L of the shunt converter.
- The rating of the series converter in VA and the maximum value of the injected voltage V_conv.
- The positive-sequence resistance and inductance of the series converter.
- The nominal voltage of the DC link in volts.
- The total capacitance of the DC link in farads.

The value of all the above parameters can be changed as desired, and in this work the UPFC device is used as a power flow controller and as a voltage regulator.

4.5 The Systems studied

As mentioned earlier, the MATLAB/SIMULINK block set has been used for all simulations of performance throughout this work. In order to verify the models built for the STATCOM and UPFC devices, two test systems (system-1 and system-2) from literature were considered [7]. Section 4.6 below demonstrates the verification process of the model with system parameters given in Table 4.1.

Table 4.1: System Parameters

Power System	Parameters
Equiv. Source Generator A	6500 MVA, 500 kV, 50 Hz
Equiv. Source Generator B	9000 MVA, 500 kV, 50 Hz
Line Length	100 km
Positive Sequence Line Resistance (R_1)	0.0255 Ω/km
Zero Sequence Line Resistance (R_0)	0.3864 Ω/km
Positive Sequence Line Inductance (L_1)	0.9341e–3 H/km
Zero Sequence Line Inductance (L_0)	4.1284e–3 H/km
Positive Sequence Line Capacitance (C_1)	12.74e–9 F/km
Zero Sequence Line Capacitance (C_0)	7.751e–9 F/km

4.6 The Verification Process

The two systems considered here are to be used in order to verify the models built for the distance relay, the STATCOM and UPFC. All necessary data are results comparisons, which are also shown.

4.6.1 System-1 study (STATCOM)

This test system is considered here for the verification of the performance of the distance relay model with a STATCOM device in operation. The system is a 500-kilovolt transmission with a mid-point connected STATCOM. The distance relay is considered to be situated at position Ra, as shown in Fig. (4.7).

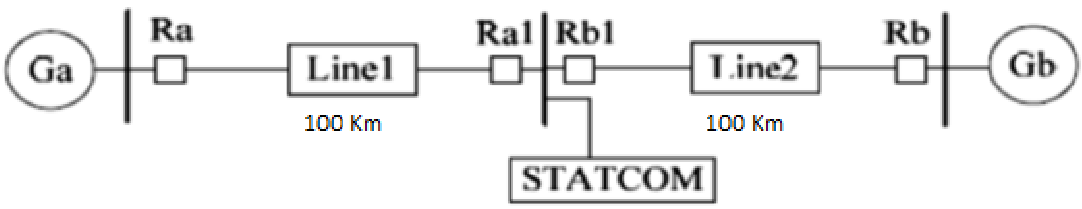


Figure 4.7: System-1 diagram(STATCOM)

The STATCOM model used in reference [7] was a GTO-based model with interconnection transformers for harmonics elimination. Table 4.1 shows the system data and Fig. (4.8) illustrates the Simulink model of system-1 incorporating the STATCOM. The distance relay is connected on the bus-B1 side. The STATCOM used here is of the IGBT-phasor type.

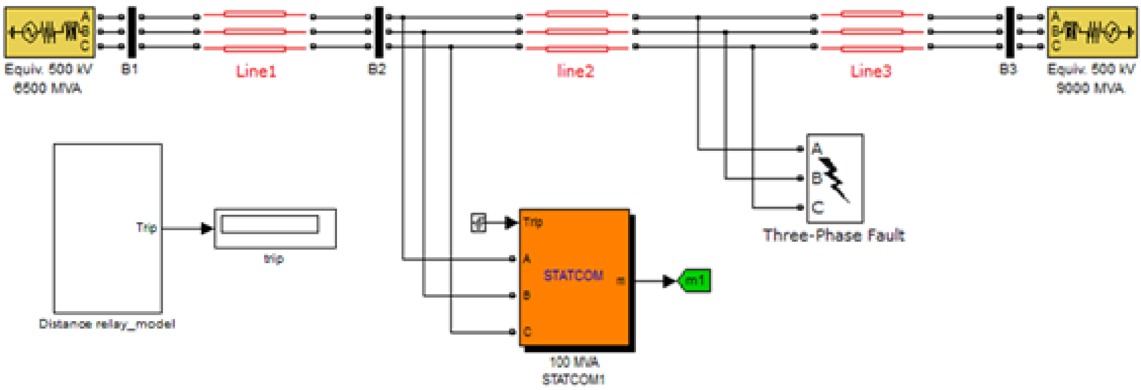


Figure 4.8: Simulink model for STATCOM

An extensive series of simulation studies were conducted on the system-1 model and under as close conditions as possible to those of reference [7]. The simulation faults considered were 3Ph-G and SLG with a STATCOM device connected at the mid-point.

4.6.2 Effect of Fault Location

The apparent and actual impedance we obtained from simulating the power system when the STATCOM is at the mid-point is shown in Table (4.2), from which we observe that the faults in the three phases without the STATCOM and the apparent impedance of the protection relay are approximately the same with some values that are slightly higher than the actual impedance.

Table 4.2: Comparison of the actual Impedances with the STATCOM and without the STATCOM

Fault Location (Km)	Actual Impedance without STATCOM	Relay response		Apparent Impedance with STATCOM	Relay response	
		Z1	Z2		Z1	Z2
110	2.9 + j39.0	Trip	Trip	2.9 + j39.1	Trip	Trip
120	3.1 + j42.6	Trip	Trip	3.2 + j42.8	Trip	Trip
130	3.4 + j46.2	-	Trip	3.5+ j46.5	-	Trip
140	3.7 + j49.9	-	Trip	3.8 + j50.2	-	Trip
150	4.0 + j53.5	-	Trip	4.1+ j54.0	-	Trip
160	4.2 + j57.2	-	Trip	4.3 + j57.8	-	Trip
170	4.5 + j60.9	-	Trip	4.6 + j61.6	-	Trip
180	4.8 + j64.6	-	Trip	5.0 + j65.4	-	Trip
190	5.0 + j68.3	-	Trip	5.3 + j69.3	-	Trip

Fig. (4.9) and Fig. (4.10) shows the differences of resistance and reactance when the STATCOM is installed at the mid-point as well as without the STATCOM.

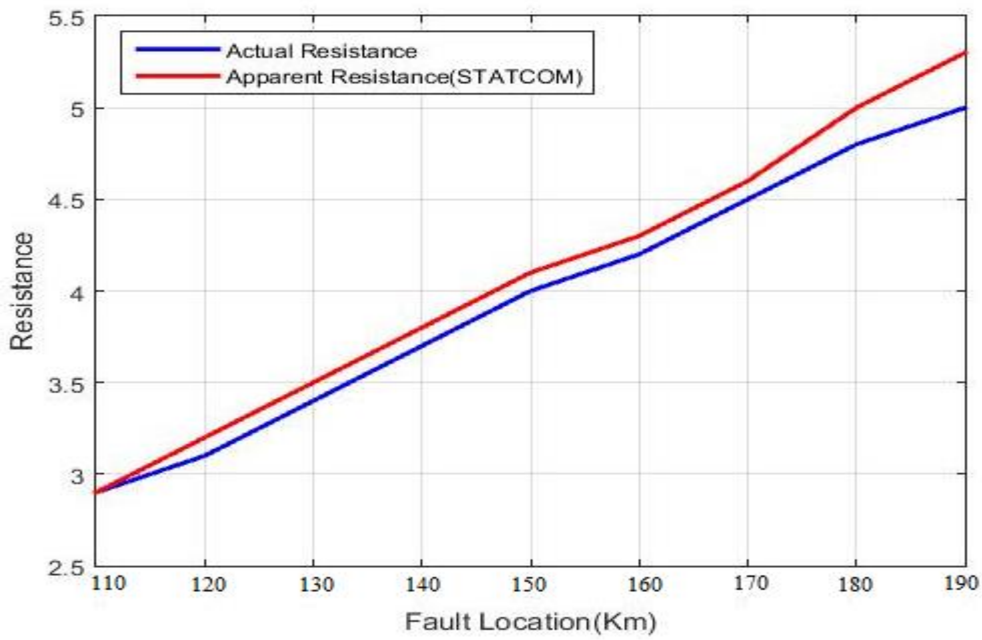


Figure 4.9: Comparison of Apparent Resistance with Actual Resistance

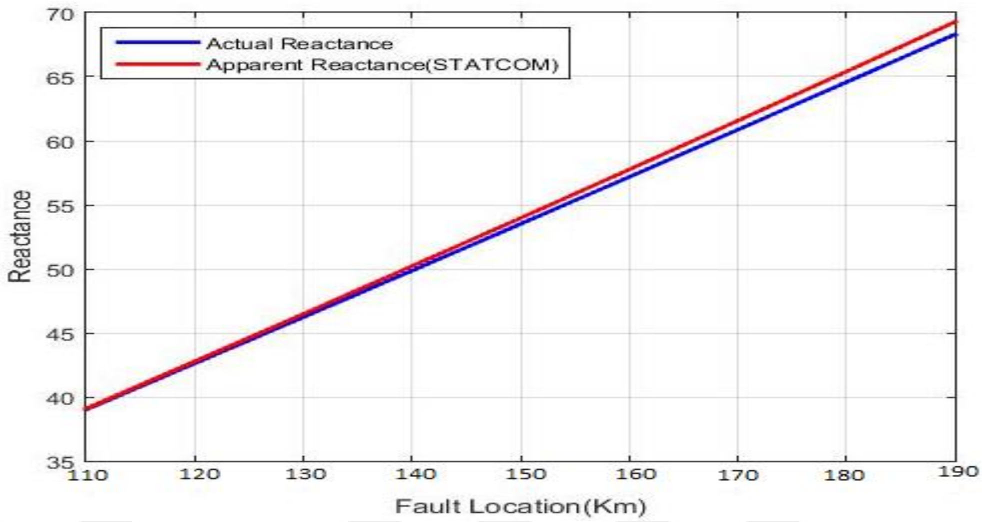


Figure 4.10: Comparison of Apparent reactance with Actual reactance

Fault locations illustrate that faults occur without a STATCOM, and as we know, that when a fault occurs without a STATCOM, it does not affect the performance of the distance relay. Moreover, both curves have similar slopes to that point. However, the fault location for resistance and reactance with the STATCOM has a higher amount than without a STATCOM, which is due to the STATCOM being within the fault loop and generating reactive power to the system, which probably includes that relay under- reaching in the case with a STATCOM.

4.6.3 Effect of STATCOM Location

The location of the STATCOM is also important in analyzing the performance of the protection relay and it impacts on the impedance measured by the protection relay. In order to analyze its effects, we put the STATCOM at the beginning of the line at a distance of 40 km away from the source of the generation with a fault on the three phases at 190 km the measured impedance will be 5.5+ j70.7, this is the largest comparison of the value of the STATCOM at the midpoint of 5.3 + j69.3 while the real impedance measured by the distance relay is 5.0 + j68.3. Therefore, the

STATCOM has a greater effect on the performance of the protection relay if it is connected at the beginning of the line.

Table 4.3: Comparison of the apparent impedance with respect to fault location in the STATCOM case

Fault location (Km)	Apparent impedance without STATCOM	Apparent impedance with STATCOM
45	1.2+j15.9	1.2+j15.7
55	1.4+j19.4	1.4+j19.5
65	1.7+j23.0	1.7+j23.2
75	1.2+j26.5	1.2+j26.8
85	2.2+j30.0	2.3+j30.5
95	2.5+j33.7	2.6+j34.2

4.7 System-2 study (UPFC)

This test system is considered here for the verification of the performance of the distance relay model with a UPFC device in operation. The system is a 500-kilovolt transmission with a mid-point connected UPFC. The distance relay is considered to be situated at position Ra, as shown in Fig. (4.11).

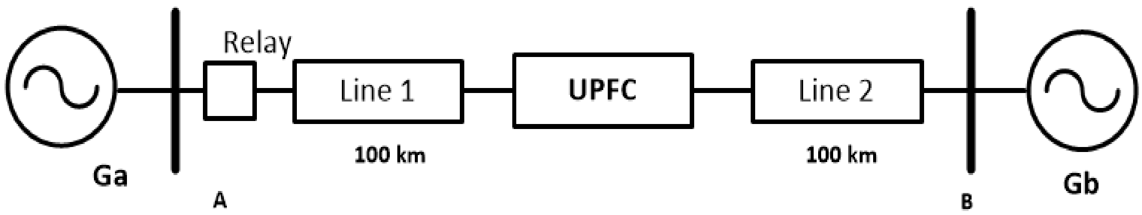


Figure 4.11: System-2 diagram(UPFC)

The UPFC model used in Table 4.1 shows the system data. Fig. (4.12) shows the Simulink model of system-1 incorporating the UPFC. The distance relay is connected at the bus-B1 side. The UPFC used here is of the IGBT-phasor type.

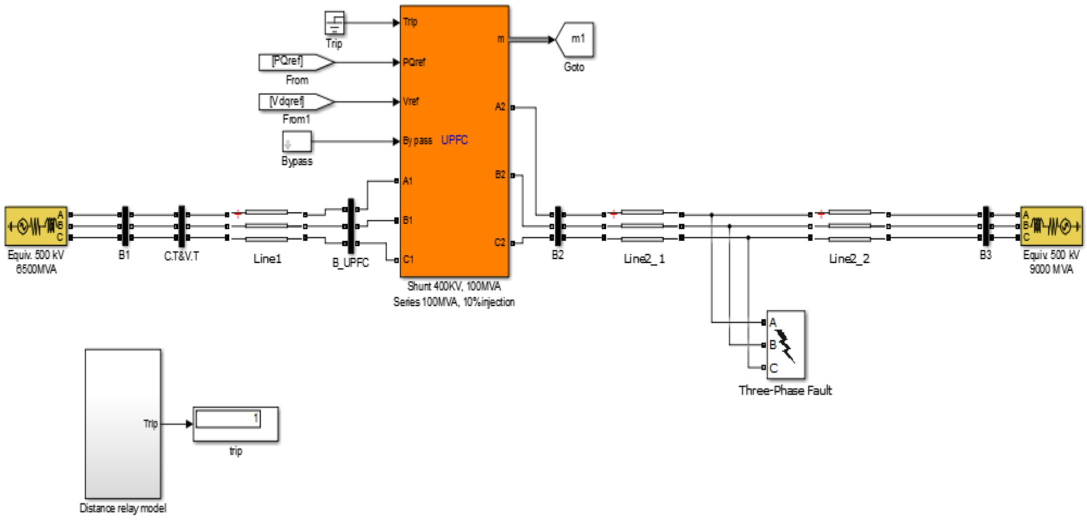


Figure 4.12: Simulink model for UPFC

Extensive series of simulation studies were conducted on the system-2 model and under as close conditions as possible to those of reference [7]. The simulation faults considered were 3Ph-G and SLG with a UPFC device connected at the mid-point.

4.7.1 Effect of Fault Location

The apparent and actual impedance we obtained from simulating the power system when the UPFC was at the mid-point is shown in Table (4.3) below, which illustrates that faults in the three phases without the UPFC and the apparent impedance of the protection relay are approximately the same with some values that are slightly higher than the actual impedance of the STATCOM.

Table 4.4: Comparison of actual Impedances with UPFC and without UPFC

Fault Location (km)	Actual Impedance Without UPFC	Relay response		Apparent Impedance With UPFC	Relay response	
		Z1	Z2		Z1	Z2
110	2.9 + j39.0	Trip	Trip	3.0 + j39.0	Trip	Trip
120	3.1 + j42.6	Trip	Trip	3.3 + j42.8	Trip	Trip
130	3.4 + j46.2	-	Trip	3.6 + j46.6	-	Trip
140	3.7 + j49.9	-	Trip	3.9+ j50.3	-	Trip
150	4.0 + j53.5	-	Trip	4.2 + j54.2	-	Trip
160	4.2 + j57.2	-	Trip	4.5 + j58.0	-	Trip
170	4.5 + j60.9	-	Trip	4.8 + j61.9	-	Trip
180	4.8 + j64.6	-	Trip	5.2 + j65.8	-	Trip
190	5.0 + j68.3	-	Trip	5.5 + j69.7	-	Trip

Fig. 4.14 and Fig. 4.15illustrates the difference of resistance and reactance with the fault location.

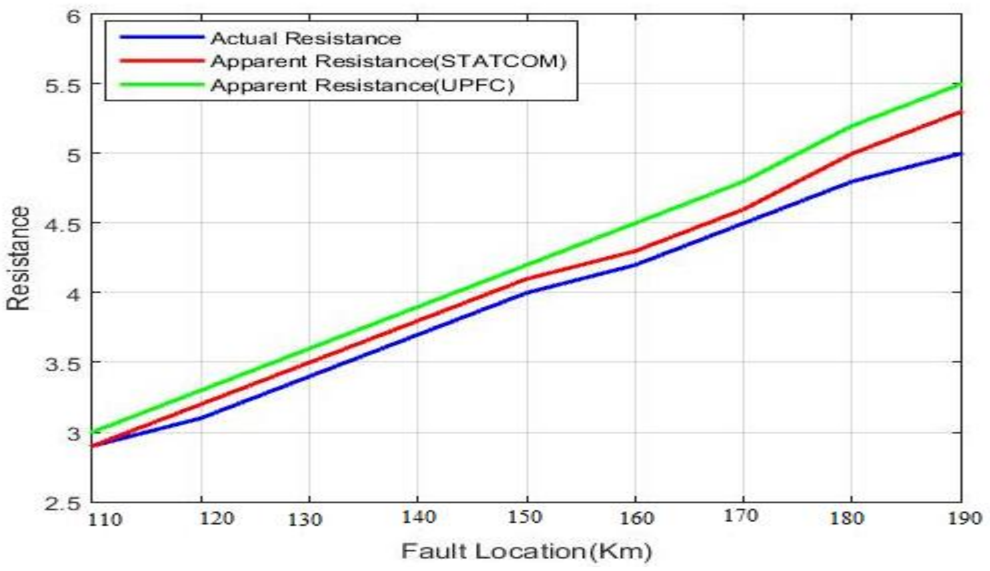


Figure 4.14: Comparison of Apparent Resistance with Actual Resistance

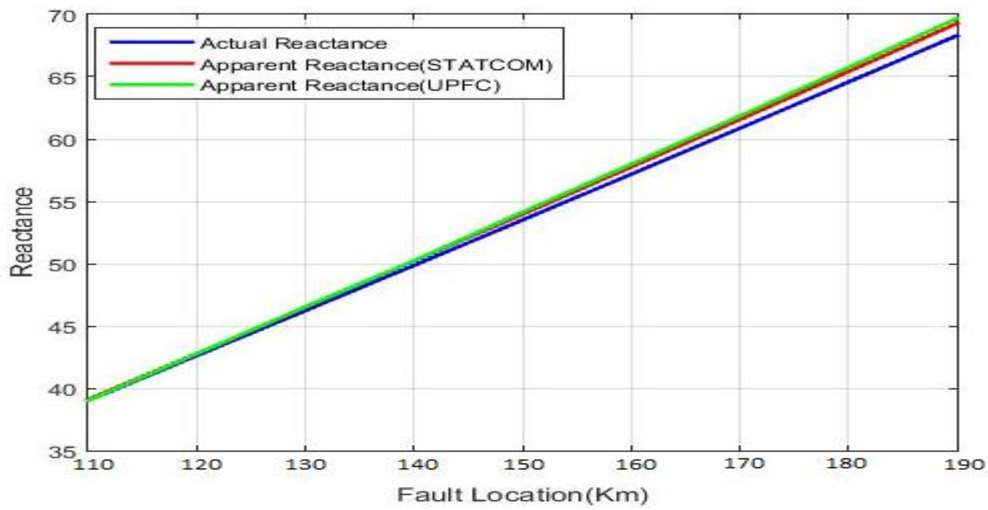


Figure 4.15: Comparison of apparent reactance with actual reactance

When a UPFC is installed at the mid-point of the line, it can be compared with the influence of the STATCOM on a relay in a similar scheme. The fault location illustrates that a fault occurs without the UPFC as we know that if a fault occurs without the UPFC, it will not impact the performance of the relay. Additionally, both curves have similar slopes to that point. However, resistance and reactance increase for the system with the UPFC with an increase in the number of fault locations. As stated previously, the impact of the UPFC is greater than that of the STATCOM for faults in the line.

4.7.2 Effect of UPFC Location

The location of the UPFC is also important in analyzing the performance of the protection relay and its effect on the impedance measured by the protection relay. In order to analyze its effect, we put the UPFC at the beginning of the line and at a distance of 40 km away from the source of the generation with a fault on the three phases at 190 km the measured impedance will be 5.6+j70.7, this is the largest comparison of the value of the UPFC at the midpoint of 5.5+ j69.7, while the real impedance measured by the protection relay is 5.0 + j68.3. We can therefore say that the UPFC has a greater influence on the performance of the protection relay when compared with the STATCOM, which was 5.3 + j69.3at the midpoint of the line.

Table 4.5: Comparison of the apparent impedance with respect to fault location in the UPFC case

Fault location (Km)	Apparent impedance without UPFC	Apparent impedance with UPFC
45	1.2+j15.9	1.2+j15.9
55	1.4+j19.4	1.5+j19.4
65	1.7+j23.0	1.9+j23.1
75	1.9+j26.5	2.2+j26.8
85	2.12+j30.1	2.4+j30.5
95	2.5+j33.7	2.7+j34.2

4.8 Recommendations to reduce the effect of FACTS devices

Observation of the apparent impedance results in case of FACTS compensated transmission line, give rise to propose a new setting boundary for distance relay zones, to mitigate the impact of FACTS on distance relay performance. The zones setting must be changed as following:

i) STATCOM compensated transmission line:

For the STATCOM at mid-point of transmission lines, the results show that the biggest increment in apparent impedance was with 3-ph fault, since the apparent impedance amounts to 95% of the line when the fault happens at 80% of the line, **therefore Zone1 of the distance relay must be set to 95% of the line in order to prevent the probability of underreach with STATCOM device, same case with Zone2 and Zone3.**

ii) UPFC compensated transmission line:

The above actions cannot be used in the presence of the UPFC on the transmission line due to the complex variations of the apparent impedance, since the apparent impedance increases or decreases causing over or under reach of the distance relay, the solution is by using Artificial Neural Network (ANN) method to change the fault boundaries during the operation of distance relay.

CHAPTER FIVE

Conclusions and Suggestions for Future Work

5.1 Conclusions

The studies performed in this work give the following conclusions:

i. The proposed distance relay is tested without connecting FACTS controllers under different fault types and locations. The simulation results have shown the ability to detect and classify any fault type with a high level of accuracy to determine a fault location.

ii. In the event of a fault, the apparent impedance will increase when the STATCOM provides reactive power to the system, which will lead the distance relay under-reach.

iii. The impact of the STATCOM was clear on the apparent impedance. That impact depends on fault type and location. Higher deviations in apparent impedance were noticed under 3Ph faults.

iv. In normal system operations, the STATCOM has no impact on the distance relay for different line loading, whereas the apparent impedance remains outside the zones trip boundaries.

v. When examining the influence of the STATCOM on the performance of the distance relay, we found that the measured impedance value is greater than the value of the real resistance, i.e., the relay in the case of over-reach.

vi. In the case of UPFC, the situation is more complex as it relates to the influence of both the SSSC and STATCOM compensators. If the SSSC effect is greater, the relay will be in the case of under-reach; however, if the greatest influence is the STATCOM, the relay will be in the case over-reach. Compared with the STATCOM, the effect of the UPFC on the apparent impedance is the most important and complicated since the UPFC has a larger effect on the apparent resistance. This is due to the active power being supplied and absorbed by both the SSSC and STATCOM.
vii. Adaptive settings of the distance relay tripping boundaries instead of the fixed type relay settings are necessary to enhance the ability of the classical distance relay to follow up with the dynamic difference in the line impedance with the FACTS devices.

5.2 Suggestions for Future Work

Finishing the work in this dissertation, many ideas for extending this work became apparent to us. These include the following:

i. The important part in a future work is to research the adaptive reach setting of distance relays for correct performance in the presence of FACTS device. The adaptive algorithm may be built with the aid of artificial intelligence packages to predict the trip boundaries of the distance relay using real time system data through communication links. These data may include the latest pre-fault data obtainable at the relay location along with the apparent impedance measured by the relay and state of the FACTS devices.
ii. Use of the developed models to study and analyze various system component variation impacts on distance relays at the 132-kilovolt level.
iii. Parallel double-circuit lines equipped with distance relays and other types of faults can make a further extension to the study.
iv. Faults represented by nonlinear impedance can be a challenging field for such performance studies.
v. Other distance relay characteristics can be used; for instance, quadrilateral and reactance characteristics.
vi. The study can be extended to comprise other FACTS devices.

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Appendix: Apparent Impedance Equations

The following sections will examine the possible fault types, in a simple power system consisting of two power sources coupled by a transmission line (assumes $Z_1 = Z_2$), and develop the appropriate algorithm to measure the positive sequence impedance to the fault in each case [25].

A.1 L-L ungrounded fault:

For the purposes of this calculation, the phase to phase "b-c" fault can be represented by the sequence network shown in figure (A.1). The positive and negative sequence voltages at the faulted bus are similar and presented by:

$V_{1F}=V_{2F}=V_1-Z_1 I_1=V_2-Z_1 I_2 \; V_1-V_2 I_1-I_2=Z_1$

We have: $V_b-V_c=(a_2-a)(V_1-V_2)$

Same as for the current: $I_b-I_c=(a_2-a)(I_1-I_2)$

After making the necessary substitutions, the following result develops:

$V_b-V_c I_b-I_c=V_1-V_2 I_1-I_2=Z_{1\_bc}$ ....(A.1)

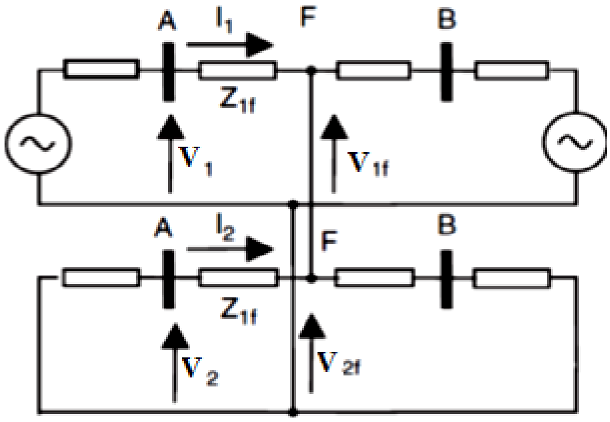

Figure A.1: phase b and c fault symmetrical component circuit

So, a distance relay, reading the L-L Voltage between phases 'b' and 'c' and the variation between the currents in the two phases, shall measure the positive sequence impedance between the phases if a b-c fault occurs. Similar analysis will show this to be true for other two kinds of phase to phase faults.

$V_a - V_b I_a - I_b = V_1 - V_2 I_1 - I_2 = Z_{1\_ab}$ ....(A.2)

$V_c - V_a I_c - I_a = V_1 - V_2 I_1 - I_2 = Z_{1\_ca}$ ....(A.3)

A.2 SLG fault:

For the purposes of this calculation, the phase 'a' to ground fault can be represented by the sequence network shown in figure (A.2). The voltages and currents in the three sequence networks at the relay location can be given as:

$V_{1F} = V_1 - Z_1 I_1$ $V_{2F} = V_2 - Z_1 I_2$ $V_{0F} = V_0 - Z_0 I_0$

At the fault point (F), the voltage of phase ‘a’ equal zero (i.e. $V_{1F} = V_{2F} = V_{0F} = 0$)

Therefore: $V_1 = Z_1 I_1$

$V_2 = Z_1 I_2$

$V_0 = Z_0 I_0$

Thus, the voltage of phase 'a' at the relay location A is given by:

$V_a = V_1 + V_2 + V_0 = Z_1(I_1 + I_2) + Z_0 I_0$

$V_a = Z_1(I_1 + I_2 + I_0) + (Z_0 - Z1)\ I0$

$V_a = Z1(Ia) + (Z0 - Z1)I0$

$V_a = Z_1[Ia + \frac{Z_0 - Z_1}{Z_1}\ I0]$ define: $m = \frac{Z_0 - Z_1}{Z_1}$

$V_a = Z1[Ia + m\ I0]$

Therefore: $VaIa + mI0 = Z1\_a$ ……………………………………..(A.4)

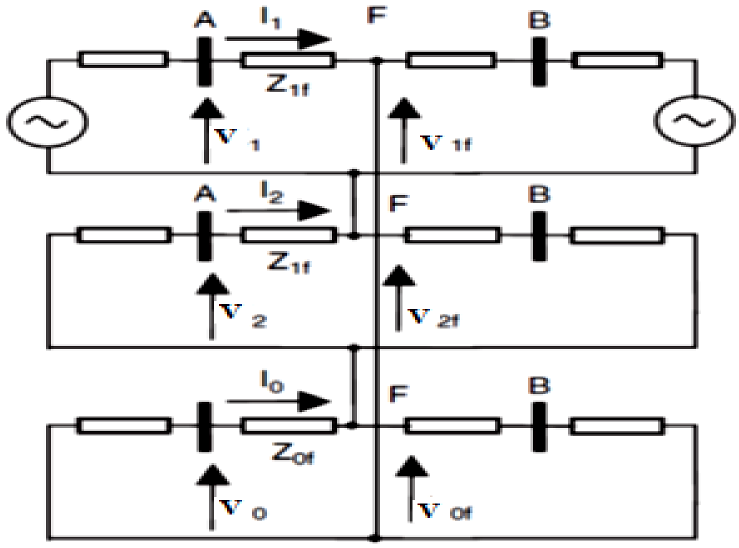

Figure A.2: Symmetrical component circuit for phase 'a' to ground fault

The factor 'm' introduced is commonly referred to as the compensation factor. Thus, a distance relay reading the phase 'a' voltage, phase 'a' current and the compensated zero sequence current, shall measure the positive sequence impedance to ground if a phase 'a' to ground fault occurs. Similar analysis can be employed to show this to be true for the other two types of phase to ground faults.

$\frac{V_b}{I_b+mI_0} = Z_{1-b}$ ……………………………………..(A.5)

$\frac{V_c}{I_c+mI_0} = Z_{1-c}$ ……………………………………...(A.6)

A.3 3Ph fault (ungrounded and grounded):

The purposes of this calculation, the three-phase fault will be assumed to be a balanced fault. Regardless of grounding, the positive sequence network becomes shorted to itself resulting in no current flowing in the negative and zero sequence networks. Thus, the sequence network for grounded and ungrounded three phase faults can be simplified as shown in figure (A.3). The positive sequence voltage at the relay location 'A' is presented by:

$V1=Va=Z_1 I_1=Z_1 Ia$

$\frac{V_1}{I_1}=\frac{V_a}{I_a}=Z1$ …………………………(A.7)

The result in the equation (A.7) is valid for 3ph fault; however, the computation of the positive sequence impedance in case of 3ph fault is more preferred in form of pervious equations (A.1 and A.4).

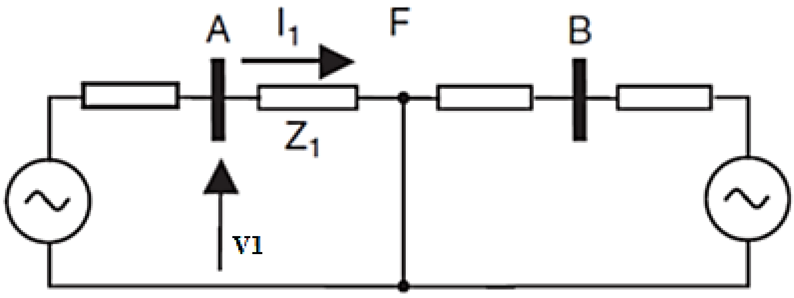

Figure A.3: Symmetrical component circuit for three-phase fault

It can be observed that equation (A.1) and equation (A.7) are equivalent during a three-phase fault as V_2 and I_2 equal zero. Hence:

$$\frac{V_b - V_c}{I_b - I_c} = Z1\_bc \qquad * \text{ Valid for } 3-\text{ph fault}$$

It can also be observed that equation (A.4) and equation (A.7) are equivalent during a three-phase fault, as I_0 equals zero. Hence:

$$\frac{V_a}{I_a + mI_0} = Z1\_a \qquad * \text{ Valid for } 3-\text{ph fault}$$

A.4 LL-G fault:

The purposes of this calculation, the double phase "b-c" to ground fault can be represented by the sequence network shown in figure (A.4). The positive and negative sequence voltages at the faulted bus are similar and presented by :

$V_{1F} = V_{2F} = V_1 - Z_1 I_1 = V_2 - Z_1 I_2$

$$\frac{V_1 - V_2}{I_1 - I_2} = Z1$$

We have: $V_b - V_c = (a2 - a)(V_1 - V_2)$

Same as for the current: $I_b - I_c = (a2 - a)(I_1 - I_2)$

After making the necessary substitutions, the following result develops:

$\frac{V_b - V_c}{I_b - I_c} = \frac{V_1 - V_2}{I_1 - I_2}$= Z1_bcg ………………………………(A.8)

From the above equation, it can be concluded that the computation of the apparent impedance for double phase to ground fault is same as for phase to phase fault. Similar analysis can be used for the other two types of double phase to ground faults.

$\frac{V_a - V_b}{I_a - I_b} = \frac{V_1 - V_2}{I_1 - I_2}$ = Z1_abg …………………………(A.9)

$\frac{V_c - V_a}{I_c - I_a} = \frac{V_1 - V_2}{I_1 - I_2}$ = Z1_cag …………………………(A.10)

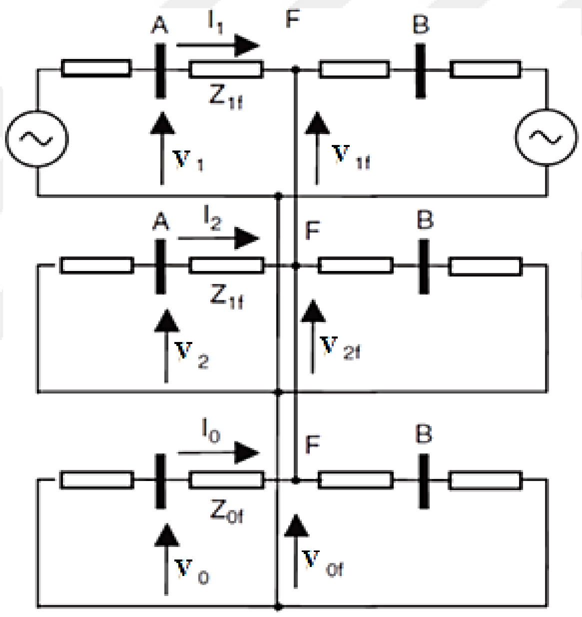

Figure A.4: Symmetrical component circuit for phase b and c to ground fault

The previous analysis has shown, for all faults involving two or more phases, equations (A.1, A.2 and A.3) can accurately measure the positive sequence impedance to the fault. These three equations form the basis of what is familiar as the apparent impedance measurements for multi-phase faults. These equations are summarized in table A.1.

Table A.1: Apparent impedance equations for multi-phase faults

Equation		Suitable for Faults
A.1	$\frac{V_a - V_b}{I_a - I_b} = \frac{V_1 - V_2}{I_1 - I_2} = Z_{1\_ab}$	'a'-'b' Ungrounded 'a'-'b' Grounded 3-Phase Ungrounded 3-Phase Grounded
A.2	$\frac{V_b - V_c}{I_b - I_c} = \frac{V_1 - V_2}{I_1 - I_2} = Z_{1\_bc}$	'b'-'c' Ungrounded 'b'-'c' Grounded 3-Phase Ungrounded 3-Phase Grounded
A.3	$\frac{V_c - V_a}{I_c - I_a} = \frac{V_1 - V_2}{I_1 - I_2} = Z_{1\_ca}$	'c'-'a' Ungrounded 'c'-'a' Grounded 3-Phase Ungrounded 3-Phase Grounded

Similarly, for faults involving a single phase and ground, equations (A.4, A.5 and A.6) can accurately measure the positive sequence impedance to the fault. These three equations form the basis of what is familiar as the apparent impedance measurements for phase to ground faults. These equations are outlined in table A.2.

Table A.2: Apparent impedance equations for phase -to-ground faults

Equation		Suitable for Faults
A.4	$\frac{V_a}{\boldsymbol{I_a + mI_0}} = Z_{1\_a}$	'a' to Ground
A.5	$\frac{V_b}{\boldsymbol{I_b + mI_0}} = Z_{1\_b}$	'b' to Ground
A.6	$\frac{V_c}{\boldsymbol{I_c + mI_0}} = Z_{1\_c}$	'c' to Ground

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