ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

DEVELOPMENT OF IMPEDANCE DIFFERENTIAL METHOD FOR FAULT DETECTION AND LOCATION IN HYBRID TRANSMISSION LINES

M.Sc. THESIS

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

HİBRİD İLETİM HATLARINDA, ARIZA VE ARIZA YERİ TESBİTİ İÇİN EMPEDANCE DİFERANSİYEL METODUNUN GELİŞTİRİLMESİ

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HAZİRAN 2019

Saeed Asgarigovar, a M.Sc. student of İTU Graduate School of Science Engineering and Technology student ID 504161038, successfully defended the thesis entitled “DEVELOPMENT OF IMPEDANCE DIFFERENTIAL METHOD FOR FAULT DETECTION AND LOCATION IN HYBRID TRANSMISSION LINES”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 03 May 2019
Date of Defense : 12 June 2019

To my beloved mother and brother, and the best friend,

FOREWORD

First of all, I would like to appreciate my respected advisor, Prof. Dr. Ömer Usta for his support, providing me access to the Electrical Energy Systems Laboratory, and allocating his valuable time to improve this research.

Hereby, I would like to express my sincere appreciation to Dr. Heresh Seyedi from the University of Tabriz, Iran, for helping me over the recent years. He taught me the way of entering the research world.

I also thank Mr. Fatih Özveren, my laboratory colleague, for his collaboration.

Furthermore, my extremely grateful thanks go to my family and all my friends that support me to achieve my goals.

May 2019 Saeed ASGHARIGOVAR

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ABBREVIATIONS

ADVA	: Absolute Difference of Voltage Angle
ANFIS	: Adaptive Neuro-Fuzzy Inference System
ANN	: Artificial Neural Network
CB	: Circuit Breaker
CT	: Current Transformer
DC	: Direct Current
DFT	: Discrete Fourier Transform
DWT	: Discrete Wavelet Transform
EMTR	: Electromagnetic Time Reversal
FD	: Fault Detector
FI	: Fault Impedance
FIA	: Fault Inception Angle
FL	: Fault Location
FT	: Fault Type
GPS	: Global Positioning System
HTL	: Hybrid Transmission Line
LG	: Line to Ground fault
LL	: Line to Line fault
LLG	: Line to Line to Ground fault
LLLG	: Line to Line to Line to Ground fault
OHL	: Overhead Line
PLC	: Power Line Carrier
PMU	: Phasor Measurement Unit
PT	: Potential Transformer
SVM	: Support Vector Machine
SVR	: Support Vector Regression
UGC	: Underground Cable
WT	: Wavelet Transform

SYMBOLS

F, R_f, I_f	: Fault and its Impedance and Current
I_a, I_b, I_c	: Currents of phases A, B, and C
I_1, I_2, I_0	: Sequence Currents
U_a, U_b, U_c	: Voltages of Phases A, B, and C
U_1, U_2, U_0	: Sequence Voltages
R, X	: Resistance and Reactance
m	: Zero Sequence Compensation Factor
U_{jm}, U_{jn}	: Calculated Voltage of Junction Point From Buses M and N
I_{jm}, I_{jn}	: Calculated Current of Junction Point From Buses M and N
M, N	: Local and Remote Buses
U_{diff}, I_{diff}	: Differential Voltage and Current
t	: Time
D, d	: Line Length and Fault Distance From Bus M
Z_{ii}	: Internal Fault Detection Criterion
Δ ADVA	: Superimposed Value of the Absolute Difference of Voltage Angle
I_{bias}, I_{op}	: Bias and Operating Current
k	: Fault Location Coefficient
K_1, K_2	: First and Second Slopes of Differential Relay
Z_{diff}, Z'_{diff}	: Differential and Compensated Differential Impedances
Z_m, Z_n	: Source Impedances
I_m, I_n	: Local and Remote End Currents
U_m, U_n	: Local and Remote End Voltages
z	: Impedance Per Kilometer of Transmission Line
z_1,z_2,z_0	: Sequence impedances
Z_C	: Capacitive reactance
T	: Transfer Matrix
ℓ, γ	: Section Length and Propagation Constant

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DEVELOPMENT OF IMPEDANCE DIFFERENTIAL METHOD FOR FAULT DETECTION AND LOCATION IN HYBRID TRANSMISSION LINES

SUMMARY

Recently, utilizing high voltage underground cables (UGC) along with overhead lines (OHL) in transmission systems has been being developed. The main reasons of this development can be mentioned as enhancing power system reliability, connecting renewable energy resources specially off-shore wind farms to the grid, power system expansion, passing power transmission systems among dense urban areas, tourist attraction issues, and environmental concerns.

It is clear that electrical parameters (resistance, inductance, capacitance, etc.) of overhead lines are completely different from underground cables. Additionally, most of the protective relays and algorithms are sensitive to the line parameters. Hence, for reliable, secure and dependable protection of such a transmission system, its sections should have separate protective system with appropriate settings.

However, financial concerns prohibit power system engineers to establish a high voltage substation and employ high cost measurement and protection systems at the junction point of overhead line and underground cable. Therefore, hybrid transmission lines (HTL) are created.

In this situation, protection and fault location of hybrid power transmission lines become challenging problems for traditional protection systems. Distance relay, which is a well-known and highly employed relay for high voltage transmission lines, is incapable to detect and locate the fault, accurately, due to large differences between the characteristics of overhead line and underground cable.

In addition, the cable section has a high charging current, which is not considered by distance relay and makes the relay castrated in fault conditions. Thus, the topic of the thesis is one of the important and hot subjects of protection engineering.

To cope with the cited problem, in this thesis, impedance differential method, which has been proposed for unit protection of transmission lines, is explained and employed as fault detection and location algorithm. This technique utilizes voltage and current phasors at both end terminals of the line to calculate the fault impedance and, accordingly, determine the fault location on the line.

Nonetheless, impedance differential algorithm has been designed for homogeneous transmission lines and is not applicable to hybrid lines. Therefore, a transfer matrix-based method is developed and introduced to solve the problem of impedance differential algorithm in the case of hybrid transmission lines.

It means that, the proposed novel algorithm separates the sections of hybrid line and considers them as independent homogeneous lines by calculating the electrical

parameters of the junction point. Hereby, impedance differential method can be applied for protection and fault location of hybrid transmission lines.

In this regard, the algorithm computes the voltage and current phasor values of junction point of overhead line and underground cable from both ends using transfer matrix equations.

In no-fault and external faults conditions, the calculated voltage and current phasors are the same from both ends. However, owing to the nature of transfer matrix equations, calculations from the end that adjacent to the faulted section (OHL or UGC) are completely wrong, in internal fault conditions.

Thus, the proposed method should determine the end that performs correct calculations, using difference of the voltage angles of the reference buses with the junction point, as a criterion.

It is clear that voltage angle is not severely changed over the transmission system. However, incorrect calculation of the junction point voltage angle from the bus that is adjacent to the faulted section causes a large difference between the voltage angle of the bus and calculated voltage angle for the junction point from the same bus.

Indeed, correct calculation for the electrical parameters of the junction point is from the bus that difference of the measured voltage angle and calculated voltage angle for the junction point is lower. Therefore, the algorithm is capable to compute the voltage and current phasor values of the junction point, even in the internal fault conditions.

In fact, the proposed method is capable to divide an inhomogeneous hybrid line to the homogeneous line sections. Hence, impedance differential method is improved by transfer matrix algorithm to be applicable for hybrid transmission lines.

As a result, the novel proposed approach, which is a combination of impedance differential method and transfer matrix-based algorithm, is proposed as a unit protection method for fault detection and location in hybrid transmission lines.

To demonstrate satisfactory performance of the algorithm, different fault types (FT), fault locations (FL), fault inception angles (FIA), and fault impedances (FI) are applied to a test power system.

Consequently, robust performance of the proposed method is confirmed by numerous computer-based simulation studies. The algorithm is capable to protect the hybrid lines with various fault characteristics.

Chapters of the thesis are organized as follows:

Chapter 1 is allocated to introduction, which contains purpose of the thesis, literature review, and hypothesis.

Chapter 2 is related to transmission line protection survey. This chapter investigates conventional protection methods for power transmission systems.

Chapter 3 is assigned to the new method of fault detection and location in hybrid transmission lines.

Chapter 4 is about performance analysis of the proposed method using computer-based simulation studies.

The last but not the least chapter is dedicated to conclusion and recommendations.

HİBRİD İLETİM HATLARINDA, ARIZA VE ARIZA YERİ TESBİTİ İÇİN EMPEDANCE DİFERANSİYEL METODUNUN GELİŞTİRİLMESİ

ÖZET

Son zamanlarda, iletim sistemlerinde havai hatlar ile birlikte yüksek gerilim yeraltı kablolarının kullanılması da geliştirilmektedir.

Bu gelişmenin temel nedenleri, güç sistemi güvenilirliğini arttırmak, yenilenebilir enerji kaynaklarını özellikle kıyıdan uzak rüzgar çiftliklerini şebekeye bağlamak, güç sisteminin genişlemesi, enerji iletim sistemlerinin yoğun kentsel alanlar arasından geçmesi, turistik cazibe sorunları ve çevresel kaygılar olarak belirtilebilir.

Çok açıktır ki havai hatların elektriksel parametreleri (direnç, endüktans, kapasıtans, vb.) yer altı kablolarından tamamen farklı. Ek olarak, koruyucu rölelerin ve algoritmaların çoğu hat parametrelerine hassastır.

Bu nedenle, bu tür bir iletim sisteminin güvenilir, güvenli ve itimat edilir bir şekilde korunması için, her bölümü uygun ayarlarla ayrı bir koruma sistemine sahip olmalıdır.

Bununla birlikte, ekonomik kaygılar, güç sistemi mühendislerinin havai hat ve yeraltı kablosunun birleşme noktasında yüksek gerilim trafo merkezi ve yüksek maliyetli ölçüm ve koruma sistemleri kurmalarına engel teşkil etmektedir. Bu sebeple, hibrit iletim hatları oluşturuldu.

Bu şartlarda, hibrit güç iletim hatlarının koruma ve arıza yeri tesbiti, geleneksel koruma sistemleri için zorlayıcı ve karışık problemler haline geldi.

Havai hat ve yeraltı kablosunun özellikleri arasındaki büyük farklar olması nedeniyle, yüksek gerilim iletim hatları için iyi bilinen ve çok kullanılan mesafe koruma rölesi, arıza ve arıza yerini doğru tesbit edememektedir.

Ek olarak, kablo bölümü, yüksek bir şarj akımına sahiptir ve bu konu mesafe koruma rölesi tarafından dikkate alınmamakatdadır ve röleyi arıza koşullarında zayıflatmaktadır.

Dolayısıyla, tez konusu koruma mühendisliğinin önemli ve sıcak konularından biridir.

Belirtilen sorunla başa çıkmak için, bu tezde, empedans diferansiyel metodu iletim hatlarının birim koruması için önerilmiş ve arıza ve arıza yeri tesbit algorıtması olarak açıklanıp ve kullanılmıştır.

Bu teknik, arıza empedansını hesaplamak ve arızanın hat üzerindeki hata yerini belirlemek için hattın her iki üç terminalindeki gerilim ve akım fazlarını kullanır.

Bununla birlikte, empedans diferansiyel algorıtması homojen iletim hatları için tasarlanmıştır ve hibrit hatlar için uygulanabilir değildir.

Bu nedenle, hibrit iletim hatları durumunda empedans diferansiyel algorıtması problemini çözmek için transfer matris bazlı bir yöntem geliştirilip ve tanıtılmıştır.

Bu, önerilen yeni algoritmanın hibrid hattın bölümlerini ayırdığı ve birleşme noktasının elektriksel parametrelerini hesaplayarak bunları bağımsız homojen hatlar olarak kabul ettiği anlamına gelir.

Böylece, empedans diferansiyel metodu hibrit iletim hatlarının korunması ve arıza yeri tesbiti için uygulanabilir.

Bu bağlamda, algorıtma, transfer matrisi denklemlerini kullanarak, havai hat ve yeraltı kablosunun her iki ucundaki birleşme noktasının gerilim ve akım fazor değerlerini hesaplar.

Normal ve harici arıza koşullarında, her iki uçta hesaplanan gerilim ve akım fazerleri aynıdır. Bununla birlikte, transfer matris denklemlerinin doğası gereği, arızaya bitişik olan uçtan yapılan hesaplamalar, iç arıza koşullarında tamamen yanlıştır.

Bu nedenle, önerilen yöntem, bitişik noktada olan referans baraların gelirim acılarının değişikliğini bir ölçüt olarak kullanarak doğru hesaplamalar yapan ucu belirlemelidir.

Gerilim açısının iletim sistemi üzerinde ciddi bir şekilde değişmediği açıktır. Bununla birlikte, arıza olan bölgeye bitişik olan baranın bağlantı noktasında gerilim açısının yanlış hesaplanması baradan olan gerilim açısı ile bağlantı noktasında hesaplanan gerilim açısı arasında büyük bir fark yaratır.

Aslında, birleşme noktasının elektriksel parametreleri için doğru hesaplama, ölçülen gerilim açısının ve birleşme noktası için hesaplanan gerilim açısının farklı olduğu baralarda daha düşük.

Bu nedenle, algoritma, birleşme noktasının gerilim ve akım fazör değerlerini iç arıza koşullarında bile hesaplayabilmektedir.

Aslında, önerilen yöntem homojen olmayan bir hibrit hattı homojen hat bölümlerine bölme yeteneğine sahiptir.

Dolayısıyla, empedans diferansiyel yöntemi, transfer matrisi algorıtması ile hibrit iletim hatlarına uygulanmak için geliştirilmiştir.

Sonuç olarak, empedans diferansiyel metodu ve transfer matrisi bazlı algoritmanın bir kombinasyonu olan önerilen yeni yaklaşım, hibrit iletim hatlarındaki arıza ve arıza yeri tespiti için bir birim koruma yöntemi olarak önerilmiştir.

Algoritmanın tatmin edici performansını göstermek için, bir test güç sistemine farklı arıza tipleri, arıza yerleri, arıza başlangıç acıları ve arıza empedansları uygulanır.

Sonuç olarak, önerilen yöntemin güçlü performansı bir sürü bilgisayar tabanlı simülasyon çalışmasıyla doğrulanmaktadır. Algorıtma, hibrit hatları çeşitli hata özellikleriyle koruma kabiliyetine şahptır.

Tezin bölümleri şu şekilde düzenlenmiştir:

1. Bölüm, tezin amacı, literatur taramasını ve hipotezi içeren giriş dersine ayrılmıştır.

Bölüm 2, iletim hattı koruma incelemesi ile ilgilidir. Bu bölüm, güç iletim sistemleri için geleneksel koruma yöntemlerini incelemektedir.

3. Bölüm, hibrid iletim hatlarındaki yeni arıza tespit ve konumlandırma yöntemine atanmıştır.

4. Bölüm, bilgisayar tabanlı simülasyon çalışmalarını kullanarak önerilen yöntemin performans analizi ile ilgilidir.

Sonuncu ama en önemli bölüm, sonuca ve tavsiyelere adanmıştır.

1. INTRODUCTION

High voltage power transmission systems are the largest system that are built by human. They are also the backbone of the electrical energy systems, since generation units deliver their generated power to the consumers through transmission lines. Due to their vastness in every geographical condition with numerous climates, they are highly exposed to fault occurrence in comparison to the other parts of a power system. Since, their installation and maintenance are very difficult and costly, protection of power transmission lines and preventing short circuit faults from dissipating them become more important than protection of the other components of the system. Furthermore, another challenging problem, which is only devoted to transmission lines, is identifying the exact fault location. Therefore, transmission line protection and fault location systems play vital roles among other protection systems. Distance relay can be mentioned as the most popular protective device that is employed for high voltage transmission lines.

High voltage transmission lines are generally utilized as homogeneous lines. In other words, power utilities install a specific overhead cable for all over a line, from sending bus to the receiving bus. Hence, fault location can be calculated by considering the line impedance. However, employing transmission lines consisting of different sections seems to be inevitable for power utilities, specially in the recent years. It is clear that underground cable is usually more reliable than overhead line. Thus, power utilities use underground cable in specific geographical conditions that the risk of power interruption for an overhead line is high. Additionally, transmission lines sometimes cross cities or tourist area. Therefore, installing large towers to carry overhead cable is not possible in these regions. Besides, with increasing tendency to establish more renewable distributed generation units specially off-shore wind farms, employing underground or marine cables for connecting them to the main overhead transmission system is certain. Hence, hybrid transmission lines including underground cable section and overhead line section are being developed.

Nevertheless, owing to large difference between characteristics (resistance, inductance, capacitance, etc.) of an overhead line and underground cable, the conventional protective devices (i.e. distance relay) are incapable to detect faults, reliably, and identify their locations, accurately, on a hybrid transmission line [1, 2]. Thus, lack of research in the case of introducing new methods for fault detection and location in hybrid transmission lines is sensible.

1.1 Purpose of Thesis

Power transmission line plays a significant role in power system operation. In this regard, a secure and dependable protection system is required to prevent from its degradation by faults. In addition, an accurate fault location algorithm is needed to identify fault location to send a crew and reenergize the line as soon as possible.

Hybrid transmission lines include at least two sections, an overhead line and an underground cable. Since their characteristics, such as impedance and capacitance, are entirely different, conventional protection and fault location methods are in capable to operate precisely, thus, they are not applicable to hybrid lines.

In this thesis, a novel approach is proposed for fault detection and location in hybrid transmission lines. The proposed method is based on transfer matrix equations and the calculated voltage phasor of the junction point from both ends. This method determines the faulted section and divides the hybrid line to a homogeneous line section to be appropriate for applying impedance differential method. Thereafter, impedance differential method can identify the fault location.

1.2 Literature Review

Hybrid transmission line protection becomes a challenging topic for researchers and protection engineers. In recent years, some researchers have focused on introducing new methods for fault detection, classification and location identification on hybrid lines. In [3], a method has been proposed to identify fault location and estimate the fault resistance. In this method, discrete Fourier transform (DFT), modal transformation theory, and distributed line model are utilized for fault location identification. Additionally, a two-part neuro-fuzzy based fault location approach has been presented for hybrid transmission lines in [4]. One of the parts is allocated to determine the faulted section by employing coefficients of DFT, whereas, the other part identifies the fault location. However, this approach has been only proposed for single line to ground faults. In [5], a technique based on adaptive network-based fuzzy inference system (ANFIS) has been suggested for protection of hybrid lines. In this technique, three phase and zero sequence currents has been applied to one ANFIS for fault type classification. The output of the first ANFIS is imported to the second one to determine the fault section (OHL or UGC). Furthermore, fundamental frequency of voltage and current, the angle between them, and current DC component has been utilized as attributes to eight ANFISs to locate the fault. In [6], wavelet transform (WT) has been utilized to locate faults in hybrid lines. In this paper, fault clearing transients on voltage signal, which are generated by circuit breaker of sending end, has been considered rather than fault transients. Furthermore, a single ended fault location method based on DWT coefficients of voltage signal and support vector machine (SVM) has been proposed in [7]. In this method, which is based on travelling wave technique, SVM classifiers determine faulted section and the faulted half of each section. In [8], characteristics of hyperbolic tangent function-based fault location approach has been suggested for extra high voltage hybrid transmission line. In [9], a travelling wave-based fault location algorithm has been presented for multi terminal hybrid transmission lines. The algorithm measures voltage samples at all the receiving ends and employs GPS for time synchronization and DWT for decomposing the voltage signal. In addition, another method based on fast discrete orthogonal S-transform and entropy principle has been proposed for fault detection, location, and classification in hybrid lines [10]. These techniques have been employed for feature extraction. Furthermore, support vector regression (SVR) and SVM have been utilized for identifying fault type and location in hybrid lines. In [11, 12], fault location approaches for multi-section hybrid lines have been proposed. These approaches utilize phasor measurement units (PMU) at all ends to measure the electrical data and also GPS for synchronizing the measured values. In [12], the method transforms a three-terminal line into a two-terminal line by identifying the faulted branch, initially. In [13], a three-terminal multi-section hybrid transmission line with an off-service branch has been considered to apply a fault location algorithm. This protective algorithm requires synchronized phasor measurements at the in-service buses. If a fault exists on the off-service branch, the algorithm utilizes apparent reactance and sequence networks to locate the fault. In addition, electromagnetic time reversal (EMTR) technique has been applied to fault location on hybrid transmission lines in [14, 15].

It is obvious that every protection system with high security must take no action in external fault condition. However, effect of external fault has not been considered in the proposed methods in [3-6, 8]. Furthermore, undoubtedly, power system is a completely dynamic system. It means that its topology is changing by several reasons such as maintenance a transformer, tripping a transmission line or disconnecting a generating unit. Hence, the impact of changing strengths of the equivalent sources at both ends of the studied line must be investigated. Nevertheless, this issue has not been investigated in [3-6, 9]. Moreover, artificial neural network-based approaches [4, 5, 7, 10] need large datasets to train the network. However, there is no available recorded dataset in most of the cases. In addition to the mentioned bottlenecks of the papers published in this topic, methods of [3, 4, 6, 7, 9, 10] are based on high frequency components. Hence, high sampling rate is required for these methods. This issue exposes the methods to be vulnerable to noise.

1.3 Hypothesis

Hypothesis of the thesis can be mentioned as follows:

The result of transfer matrix equations is correlated with fault location. When a fault occurs between a reference bus and a desired point, which its electrical parameters are required to calculate, transfer matrix equations result in wrong values. Therefore, the incorrect results can be utilized as a criterion to determine that whether the fault has occurred in overhead line section or underground cable section. This can be used by impedance differential method to focus on the faulted section, which is homogeneous, rather than inhomogeneous hybrid line.

2. TRANSMISSION LINE PROTECTION SURVEY

In this section of the thesis, initially, two main categories of transmission line protection methods, which are unit and non-unit protection methods, are introduced. Afterwards, conventional protection methods of transmission lines that belong to each category are investigated and their advantages and disadvantages are discussed.

2.1 Non-Unit Protection

Non-unit protection methods, which are called single-ended protection methods, utilize measured electrical signals, such as voltage or current, at one of the end terminals of transmission line. In these methods, there is no communication channel between upstream and downstream relays [16]. Hence, they must be coordinated by time delay to act as backup to their downstream relays. It means that, if a fault occurs close to the remote end, the protection system will not detect the fault, instantaneously. Furthermore, there is a constraint in determining zone limits in non-unit protection techniques. Distance protection, which is the most well-known system for protection of transmission lines, is in this category.

2.1.1 Distance protection

Distance relay is widely employed for protection of transmission lines. It calculates the impedance between the relay, which installed in substation, and a desired reach point on the line. Since the impedance per kilometer of the line is constant, it is capable to locate the fault on its protective zone. It means that if a fault, which connects the energized conductor to the ground, occurs within the protective zone of the relay, the impedance that seen by the relay is decreased from the zone impedance. Hence, the relay can detect the fault. The relay utilizes three-phase voltage and current signals that are measured by potential transformer (PT) and current transformer (CT) in the substation to compute the line impedance. The *R*-*X* (real and imaginary parts of the measured impedance by the relay) coordinate plane is used to determine the protective zone range and separate the operation zone from the restrain zone. Figure 2.1 depicts an example power system and the relay location and connections with CT, PT and circuit breaker (CB). Furthermore, R-X diagram of the power system is shown in Figure 2.2.

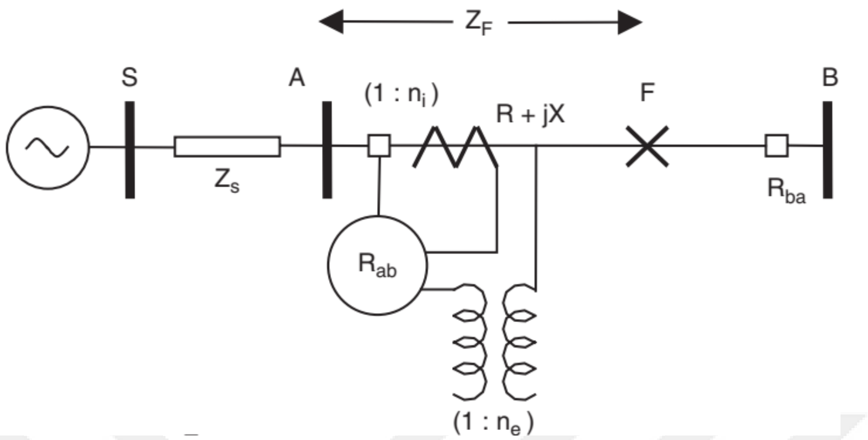

Figure 2.1 : An example power system and distance relay connections.

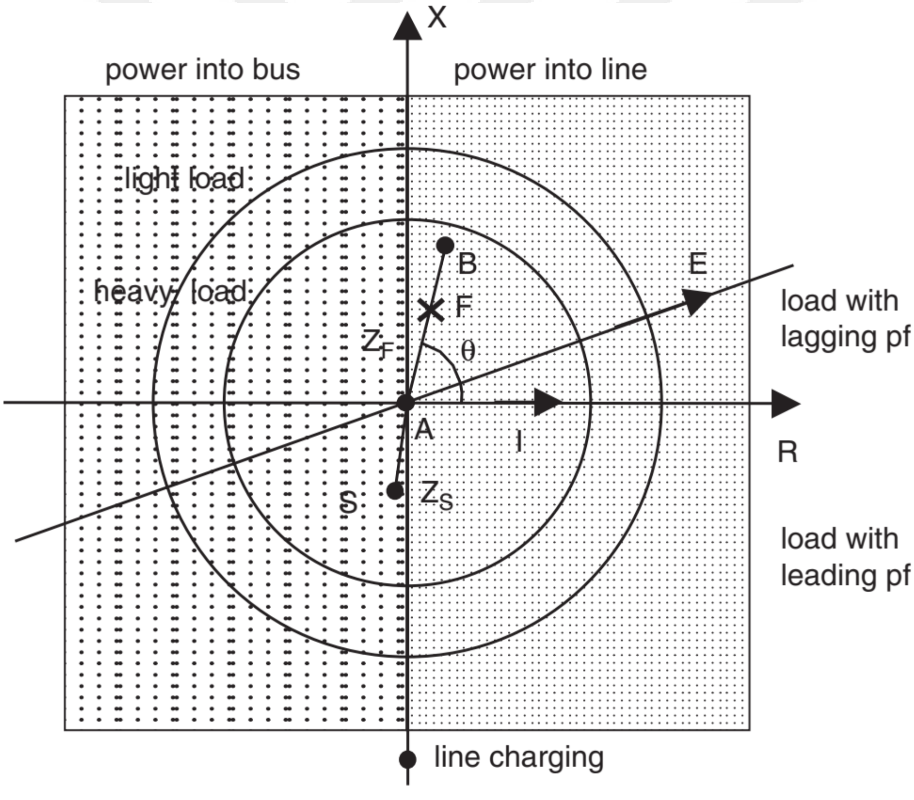

Figure 2.2 : The R-X diagram.

It is clear that a protection system is an interconnected system. As mentioned before, distance protection is a non-unit protection system, generally. Thus, an upstream relay must operate with a time delay for a fault on the next transmission line. This makes the relay appropriate to acts as backup relay for its downstream relay. Therefore, the relay's protective zones are adjusted for specific distances and their proper operating time (time delay). Figure 2.3 illustrates three protective zones of the relay and time delay corresponds to each zone, respectively.

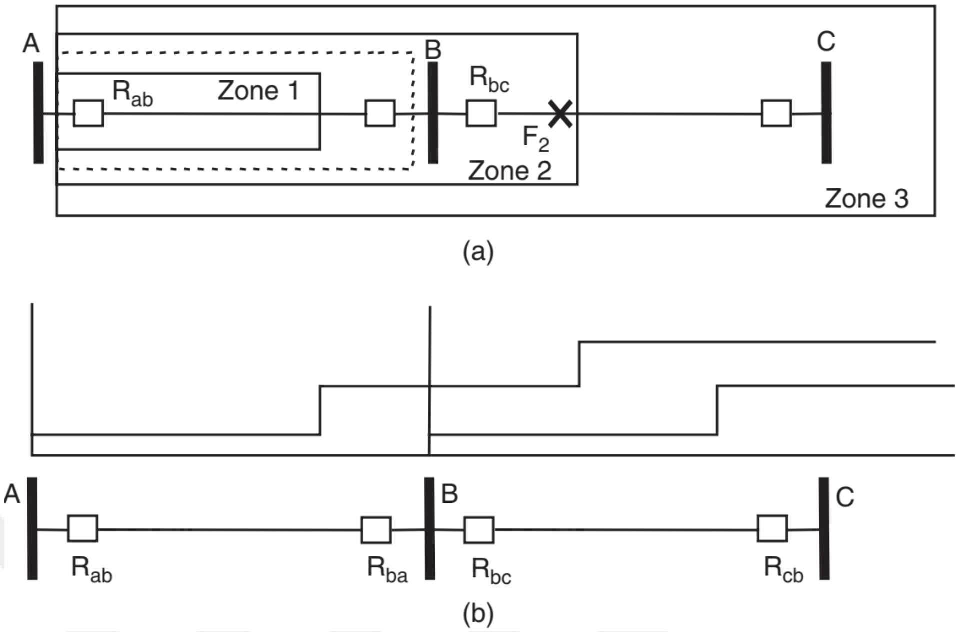

Figure 2.3 : Protective zones and their time delays in distance relay.

Generally, zone 1 of the relay is set to 90 percent of the main protected line, as shown in the figure. In this section of the line, there is no time delay and the relay issues trip decision for all the faults, instantaneously. The second zone of the relay protects the main line and also 20 to 50 percent of the next line. Normally, zone 2 of the relay operates with 0.3 (s) coordination delay. The third zone of the relay monitors 120 to 180 percent of the next transmission line with 1 (s) coordination delay [16].

Moreover, distance relay has 6 distinct units. Three of them are phase to ground units that calculate fault impedance in single phase faults. In addition, the remaining three are phase to phase units, which compute fault impedance in phase to phase and also double phase to ground faults. It is noteworthy that three-phase fault can be detected by all units of the relay. In this regard, the relay uses equation 2.1 to calculate phase *a* to phase *b* fault impedance, for instance.

$$Z_{ab} = \frac{U_a - U_b}{I_a - I_b} \tag{2.1}$$

Where, V_a and V_b are voltages of phases a and b, respectively, and I_a and I_b, represent current values of the same phases. Furthermore, impedance of single phase to ground faults can be computed by the following equations.

$$Z_a = \frac{U_a}{I_a + m \times I_0} \tag{2.2}$$

$$m = \frac{z_0 - z_1}{z_1} \tag{2.3}$$

In these equations, Z_a is the calculated impedance for phase a; m stands for zero sequence compensation factor; Z_0 and Z_1 are zero and positive sequence impedance of transmission line and I_0 is the zero sequence current seen by the relay.

Due to some advantages of distance relay such as simplicity of coordination and setting and lower dependency to the network changings in comparison to overcurrent relays, it is very popular in protection of transmission line. Nevertheless, distance relay has some disadvantages such as impact of fault resistance [17] and impact of power swing, which may lead to mal-operation of the relay. Figure 2.4 depicts the effect of resistive faults on performance of the relay.

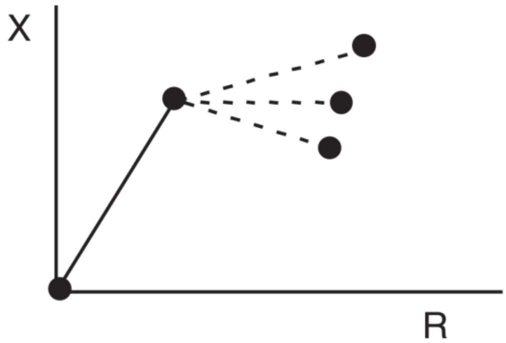

Figure 2.4 : Effect of the fault impedance on performance of the relay.

As depicted in the figure, fault resistance causes the calculated impedance does not enter the operate zone of the relay.

2.2 Unit Protection

Unit protection-based techniques, which is also called tele-protection and pilot protection, equipped with a communication link such as power line carrier (PLC), GPS based channel, microwave, fiber optics, telephone cable, etc. In these methods, there are individual relays at both ends of transmission line that are connected and exchange power (i.e. voltage or current) and control (i.e. tripping or blocking) signals with each other. This kind of protection method is much more reliable than non-unit-based methods. Phase comparison, directional comparison, and current differential are prominent unit protection techniques of transmission lines.

2.2.1 Phase comparison method

Phase comparison protection approach is a kind of differential scheme, which compares the phase angle of currents of local and remote ends. Figure 2.5 illustrates the fundamentals of the method. In this method, the reference direction of CTs are towards the protected transmission line. Therefore, if difference of the phase angles of the current signals is approximately 180 degrees, there is no fault on the line. It is also possible that there is an external fault (F_1 or F_3 in the figure). However, if the current phase angles are in-phase, it shows an internal fault on the line (F_2 in the figure).

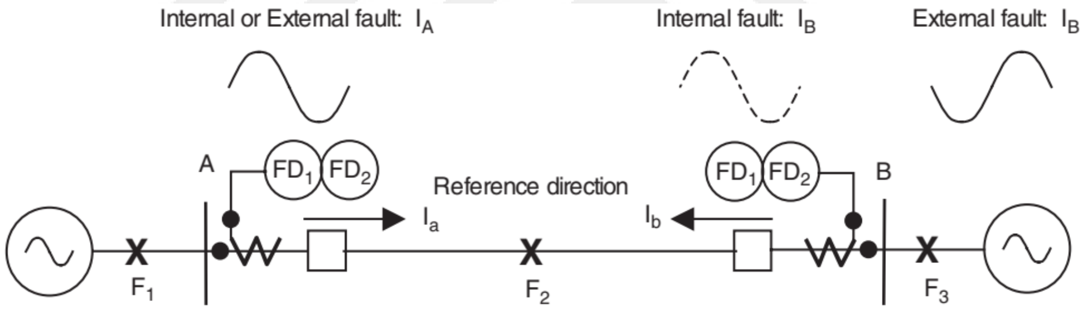

Figure 2.5 : Phase comparison scheme diagram.

As mentioned before, phase comparison is a unit protection-based approach. In this method, the output signals of the CTs' secondary sides are imported to a sequence network that produces a voltage that is proportional to the three phase currents magnitudes and angles. Each end creates a sign on the positive half cycle, whereas, in the negative half cycle creates nothing. Afterwards, they send the signal to the remote end. Hence, each of the line ends can individually compare the local and remote signs. If there is no fault or an external fault, both ends receive a sign and a space, which show 180 degrees difference of phase angles. However, in the case of internal fault condition, both ends comparators receive signs at the same time and issue trip decision for their circuit breakers.

In the figure, FDs are fault detectors. FD_1 is an overreaching low-set fault detection relay that transmit the data and also import it to the local comparator. FD_2 is a high-set fault detection relay that provides tripping upon the result of the comparator.

This method is really expensive because it does not provide backup for adjacent lines and other relays should be installed for backup. Nevertheless, it is capable to identify the faulted phase and provide single phase reclosing and post fault analysis. Furthermore, this method is insensitive to out of step and power swing conditions, because it only depends on the current signal [16].

2.2.2 Current differential method

Current differential protection is one of the most sensitive and precise unit protection methods. It is used for protection of equipment in substations and generating units such as generators, transformers, busbars, etc. However, with the advent of fast and reliable communication technologies and developing them, it is employed for protection of power transmission lines. It computes difference of current signals that are measured at both end terminals of the line. Unlike phase comparison method, in addition to the phase difference, current magnitude is also considered by the relay and can cause to issue trip signal. In this method, three phase current waveforms are sampled and converted to digital signals to be appropriate for transmitting the remote end data to the relay location. Figure 2.6 shows the characteristics of the relay [18].

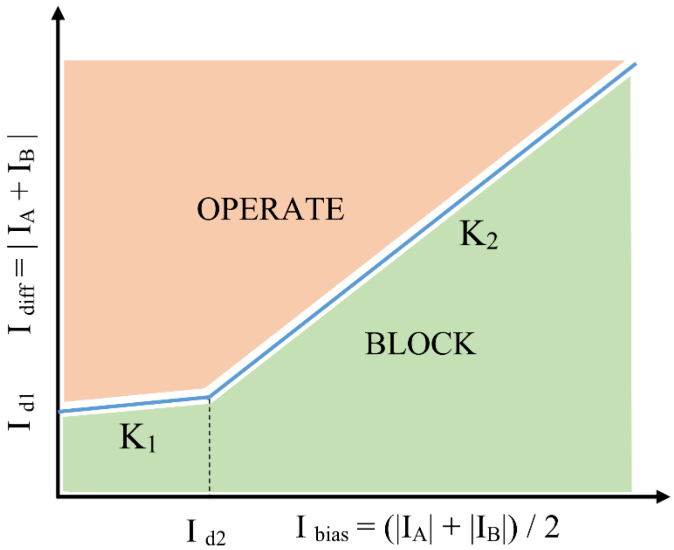

Figure 2.6 : Percentage characteristics of current differential relay.

Afterwards, the relay calculates operating, bias, and differential currents by the following equations:

$$I_{diff} = | I_A + I_B | \tag{2.4}$$

$$I_{bias} = (|I_A| + |I_B|)/2 \tag{2.5}$$

$$I_{op} = \begin{cases} K_1 \times | I_{bias} | + I_{d1} & if\ |I_{bias}| < I_{d2} \\ K_2 \times | I_{bias} | - (K_2 - K_1) \times I_{d2} + I_{d1} & if\ |I_{bias}| \geq I_{d2} \end{cases} \tag{2.6}$$

Where, I_{diff}, I_{op}, and I_{bias} represent differential, operating and bias currents, respectively. K_1 and K_2 stand for first and second slopes.

In fact, if the calculated operating current exceeds each of the slopes and enters the operate region of the relay, a trip signal will be issued.

As an advantage, it does not need to voltage signal, thus, it is not sensitive to power swing phenomenon. However, it has some disadvantages, as well. PLC communication channel is not applicable to this protection method, because a wide bandwidth is needed. Additionally, one of CTs may be saturated in a severe external fault condition. Hence, the relay may undesirably trip the line. Furthermore, CT ratio mismatch and also CT errors are other parameters that may affect the relay performance.

2.2.3 Directional comparison method

Directional comparison method is another current based unit protection technique. It is divided into two relaying method, blocking and unblocking. It utilizes a directional unit along with the main relay at both ends of the line to detect whether the fault is internal or external. In directional comparison blocking scheme, each end sends its local information to the remote end, therefore, it can be determined if any fault occurs on the protected line. In blocking method, if a fault occurs in forward direction of the relay at one end, the relay will issue a trip signal to its corresponding circuit breaker, if it does not receive a blocking signal from its remote end relay. In other words, if an external fault occurs, the fault will be in forward direction of one relay and in backward direction of the other relay. Hence, the relay that the fault is located at its behind (backward) sends a blocking signal to the relay that saw the fault (forward). The employed a communication channel in this scheme uses the protected transmission line, such as PLC. Generally, mho or quadrilateral type distance relay is utilized by directional comparison blocking scheme.

The main advantage of directional comparison blocking scheme is its high dependability.

In directional comparison blocking technique, a blocking signal is sent to the remote relay in fault conditions. It is clear that if a problem occurs in communication system or logic circuit contacts, the blocking signal may not be transmitted and an undesired trip will be happened. Thus, a continuously sending unblocking signal is used to check the correct performance of the communication link. Shifting the frequency of this signal during internal fault conditions causes the relays to operate. It means that, a blocking signal is transmitted in normal conditions. However, in the case of internal faults, the continuous transmitted signals frequency is changed to the unblocking state and allow the relay to issue trip decision. The advantage of unblocking scheme over the blocking is that problem of communication channel is immediately detectable and it cannot cause to mal-operation of the relay.

3. PROPOSED HYBRID TRANSMISSION LINE PROTECTION

In this section of the thesis, the proposed method for fault detection, classification, and its location identification is introduced in detail. First of all, impedance differential method which have been designed for homogeneous transmission lines, is explained. Thereafter, transfer matrix-based method is introduced. At the end, stages of the whole algorithm are discussed.

3.1 Impedance Differential Method

Figure 3.1(a) and (b) represent a π model of a sample power system during external and internal fault, respectively. This model is just applicable for symmetrical faults. As shown in the figure, *D* is entire line length; *M* and *N* are end terminals of the protected line; *d* is the fault distance from bus *M*; *z* is impedance per kilometer of the line; Z_m and Z_n are the equivalent power system impedance; and Z_c is capacitive reactance related to the line capacitance. We assume that the conventional current directions at both ends, i.e. I_m and I_n, are toward the transmission line, as shown in the figure. Therefore, differential voltage and current are introduced as [19]:

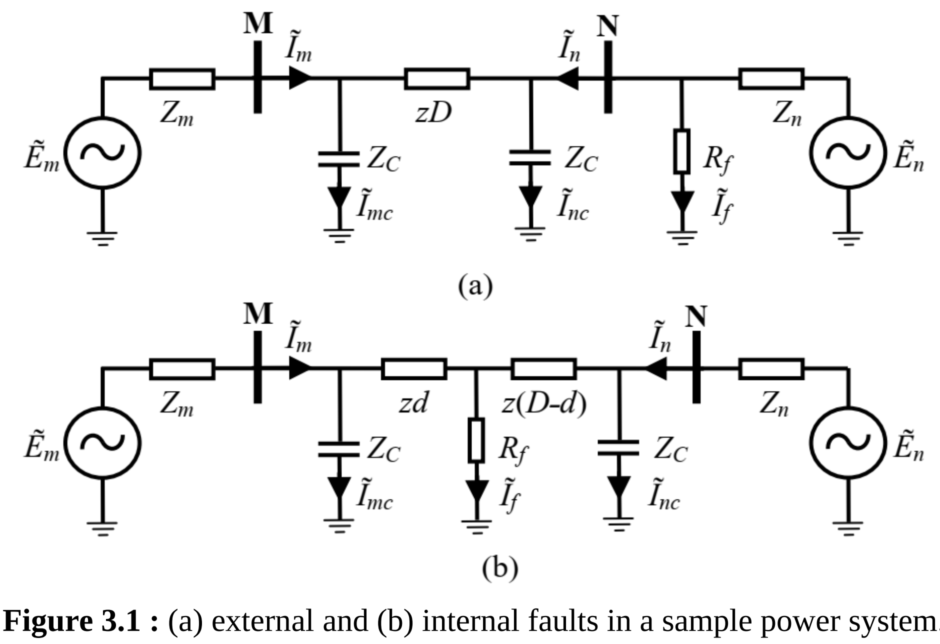

Figure 3.1 : (a) external and (b) internal faults in a sample power system.

$$\tilde{U}_{diff} = \tilde{U}_m - \tilde{U}_n \quad (3.1)$$

$$\tilde{I}_{diff} = \tilde{I}_m - \tilde{I}_n \quad (3.2)$$

It is clear that differential impedance can be achieved by dividing the calculated differential voltage by differential current, which is cited below:

$$Z_{diff} = \tilde{U}_{diff} \big/ \tilde{I}_{diff} \quad (3.3)$$

In the case of external faults, we can compute the following equations considering figure 3.1(a).

$$\tilde{I}_m = \frac{\tilde{U}_m}{Z_C} + \frac{\tilde{U}_m - \tilde{U}_n}{zD} \quad (3.4)$$

$$\tilde{I}_n = \frac{\tilde{U}_n}{Z_C} + \frac{\tilde{U}_n - \tilde{U}_m}{zD} \quad (3.5)$$

Hence, the differential impedance is achieved as:

$$\tilde{I}_m - \tilde{I}_n = \frac{\tilde{U}_m - \tilde{U}_n}{Z_C} + \frac{2(\tilde{U}_m - \tilde{U}_n)}{zD} \quad (3.6)$$

Now, we can compute the differential impedance by substitute (3.6) in (3.3) as below:

$$Z_{diff} = (\frac{1}{Z_C} + \frac{2}{zD})^{-1} = \frac{zD}{2}(1 + \frac{zD}{2Z_C})^{-1} \quad (3.7)$$

Afterwards, multiplying (3.7) by ($1+zD/2Z_C$) gives the compensated differential impedance as:

$$Z'_{diff} = (1 + \frac{zD}{2Z_C})Z_{diff} = \frac{zD}{2} \quad (3.8)$$

This equation can be achieved for no fault conditions of the power system. Thus, it can be finalized that the compensated differential impedance is the one that is obtained in (3.8).

However, in the case of internal fault condition the below equations can be obtained considering Figure 3.1(b).

$$\tilde{U}_m - zd\left(\tilde{I}_m - \frac{\tilde{U}_m}{Z_C}\right) = \tilde{U}_n - z\left(D-d\right)\left(\tilde{I}_n - \frac{\tilde{U}_n}{Z_C}\right) \quad (3.9)$$

$$\tilde{U}_m\left(1+\frac{zd}{Z_C}\right) - \tilde{U}_n\left(1+\frac{z(D-d)}{Z_C}\right) = zd(\tilde{I}_m) - z(D-d)\tilde{I}_n \quad (3.10)$$

By substituting the mean value of the voltage coefficients in (3.10), the equation can be expressed as:

$$\tilde{U}_m - \tilde{U}_n\left(1+\frac{zD}{2Z_C}\right) = zd(\tilde{I}_m) - z(D-d)\tilde{I}_n \quad (3.11)$$

Assuming $d=kD$ where k is between 0 and 1, gives $D-d=(1-k)D$. Hence, similar to (3.8), the compensated value of differential impedance is computed as:

$$Z'_{diff} = \left(1+\frac{zD}{2Z_C}\right)\left(\frac{\tilde{U}_m - \tilde{U}_n}{\tilde{I}_m - \tilde{I}_n}\right) = zD\left(\frac{k\tilde{I}_m - (1-k)\tilde{I}_n}{\tilde{I}_m - \tilde{I}_n}\right) \quad (3.12)$$

Now, with subtracting $zD/2$ from (3.12), we have:

$$Z'_{diff} - \frac{zD}{2} = zD\left(k - \frac{1}{2}\right)\left(\frac{\tilde{I}_m + \tilde{I}_n}{\tilde{I}_m - \tilde{I}_n}\right) \quad (3.13)$$

$$\left(Z'_{diff} - \frac{zD}{2}\right)\left(\frac{\tilde{I}_m - \tilde{I}_n}{\tilde{I}_m + \tilde{I}_n}\right) = zD\left(k - \frac{1}{2}\right) \quad (3.14)$$

As a result, (3.14) is multiplied by 2 and its left side is indicated by Z_{op} for simplicity, as follows:

$$Z_{op} = 2\left(Z'_{diff} - \frac{zD}{2}\right)\left(\frac{\tilde{I}_m - \tilde{I}_n}{\tilde{I}_m + \tilde{I}_n}\right) = zD\left(2k-1\right) \quad (3.15)$$

As a conclusion, Z_{op} can be calculated, easily, because I_m, I_n, and Z'_{diff} are available. Thus, k, which represents the fault location, can be calculated by (3.15). It is noteworthy that the value of Z_{op} will be zero in external fault conditions, since Z'_{diff} is equal to $zD/2$. Hence, Z_{op} can be a criterion to discriminate external faults from the internal ones. The method has some important advantages. First of all, the capacitive charging current of the line is considered and compensated in the equations. Additionally, the method is independent of direction of power flow and equivalent sources' strengths, as shown in equation (3.15).

So far, we have discussed three phase symmetrical faults and explained the concepts and elaborated differential impedance equations in this regard. Now, a single phase to ground fault is considered as an asymmetric fault, using symmetrical components. Here, 0, 1, and 2 subscripts represent zero, positive, and negative sequence components, respectively.

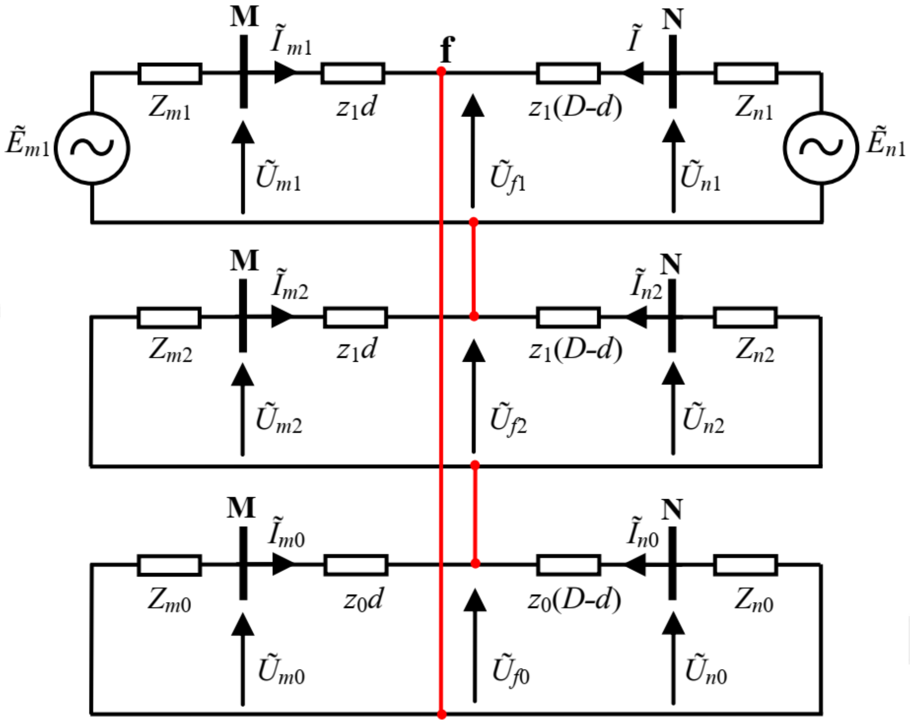

Figure 3.2 : Sequence networks of the grid.

We can write the following equations from the figure.

$$\begin{cases} \tilde{U}_{f1} = \tilde{U}_{m1} - z_1 d\left(\tilde{I}_{m1}\right) = \tilde{U}_{n1} - z_1\left(D-d\right)\tilde{I}_{n1} \\ \tilde{U}_{f2} = \tilde{U}_{m2} - z_1 d\left(\tilde{I}_{m2}\right) = \tilde{U}_{n2} - z_1\left(D-d\right)\tilde{I}_{n2} \\ \tilde{U}_{f0} = \tilde{U}_{m0} - z_0 d\left(\tilde{I}_{m0}\right) = \tilde{U}_{n0} - z_0\left(D-d\right)\tilde{I}_{n0} \end{cases} \tag{3.16}$$

With assumption that the faulted phase is phase *A*, we have:

$$\begin{cases} \tilde{U}_{fa} = \tilde{U}_{ma} - z_1 d\left(\tilde{I}_{ma}\right) - \left(\left(z_0 - z_1\right)d\right)\tilde{I}_{m0} \\ \tilde{U}_{fa} = \tilde{U}_{na} - z_1\left(D-d\right)\tilde{I}_{na} - \left(z_0 - z_1\right)\left(D-d\right)\tilde{I}_{m0} \end{cases} \tag{3.17}$$

$$\tilde{U}_{ma} - z_1 d\left(\tilde{I}_{ma} + \frac{z_0 - z_1}{z_1}\tilde{I}_{m0}\right) = \tilde{U}_{na} - z_1\left(D-d\right)\left(\tilde{I}_{na} + \frac{z_0 - z_1}{z_1}\tilde{I}_{n0}\right) \tag{3.18}$$

$$\tilde{U}_{ma} - \tilde{U}_{na} - \left(z_0 - z_1\right)\left[d\left(\tilde{I}_{m0}\right) - \left(D-d\right)\tilde{I}_{n0}\right] = z_1 d\left(\tilde{I}_{ma}\right) - z_1\left(D-d\right)\left(\tilde{I}_{na}\right) \tag{3.19}$$

Computing the voltage drop from *M* and *N* buses to the fault point in zero sequence network of figure 3.2 gives:

$$\tilde{U}_{m0} - z_0 d\left(\tilde{I}_{m0}\right) = \tilde{U}_{n0} - z_0\left(D-d\right)\left(\tilde{I}_{n0}\right) \tag{3.20}$$

$$d\left(\tilde{I}_{m0}\right) - \left(D-d\right)\left(\tilde{I}_{n0}\right) = \frac{\tilde{U}_{m0} - \tilde{U}_{n0}}{z_0} \tag{3.21}$$

Substituting (3.21) in (3.19), we have:

$$\tilde{U}_{ma} - \tilde{U}_{na} - \frac{z_0 - z_1}{z_0}\left(\tilde{U}_{m0} - \tilde{U}_{n0}\right) = z_1 d\left(\tilde{I}_{ma}\right) - z_1\left(D-d\right)\left(\tilde{I}_{na}\right) \tag{3.22}$$

Dividing equation (3.22) by $\left(\tilde{I}_{ma} - \tilde{I}_{na}\right)$ gives:

$$\frac{\tilde{U}_{ma} - \tilde{U}_{na} - \frac{z_0 - z_1}{z_0}\left(\tilde{U}_{m0} - \tilde{U}_{n0}\right)}{\tilde{I}_{ma} - \tilde{I}_{na}} = \frac{z_1 d\left(\tilde{I}_{ma}\right) - z_1\left(D-d\right)\left(\tilde{I}_{na}\right)}{\tilde{I}_{ma} - \tilde{I}_{na}} = z_1 D\frac{k\tilde{I}_{ma} - \left(1-k\right)\tilde{I}_{na}}{\tilde{I}_{ma} - \tilde{I}_{na}} \tag{3.23}$$

By changing voltage phasors for compensating capacitive current of the line, we can write (3.23) as follows:

$$\frac{\tilde{U}_{ma} - \tilde{U}_{na} - \frac{z_0 - z_1}{z_0}\left(\tilde{U}_{m0} - \tilde{U}_{n0}\right)}{\tilde{I}_{ma} - \tilde{I}_{na}}\left(1 + \frac{z_1 D}{2Z_C}\right) = z_1 D\frac{k\tilde{I}_{ma} - \left(1-k\right)\tilde{I}_{na}}{\tilde{I}_{ma} - \tilde{I}_{na}} \tag{3.24}$$

By comparing the right side of (3.24) with (3.12), it can be understood that they are similar and equal to Z'_{diff}. Thus, similar to symmetrical faults, with subtracting $z_1D/2$ from Z'_{diff} and multiplying both sides of the equation by 2, we have:

$$Z'_{diff} - \frac{z_1 D}{2} = z_1 D\left(k - \frac{1}{2}\right)\frac{\tilde{I}_{ma} + \tilde{I}_{na}}{\tilde{I}_{ma} - \tilde{I}_{na}} \tag{3.25}$$

$$Z_{op} = 2\left(Z'_{diff} - \frac{z_1 D}{2}\right)\frac{\tilde{I}_{ma} - \tilde{I}_{na}}{\tilde{I}_{ma} + \tilde{I}_{na}} = z_1 D\left(2k - 1\right) \tag{3.26}$$

Owing to similarity between (3.26) and (3.15), it can be concluded that it is applicable as a criterion for any fault type even phase to phase faults.

Referring the above equations, there is no difference between an external fault with an internal fault that occurs at the midpoint of the line, because in both conditions *k* is equal to 0.5 and Z'_{diff} value is zD/2. Hence, it seems that the middle of the protected line is a dead zone for this protection method and it cannot detect faults occur in this region. To cope with this problem, the integrated impedance that has been proposed in [20] is employed. Therefore, internal and external faults can be discriminated by the following equation:

$$Z_{ii} = \frac{\tilde{U}_m + \tilde{U}_n}{\tilde{I}_m + \tilde{I}_n} \tag{3.27}$$

It is confirmable that Z_{ii} is equal to the capacitive reactance of the line Z_C in external fault case, whereas, in the case of internal fault at the middle of the line, it is expressed as:

$$Z_{ii} = 2\left(R_f + Z_a \parallel Z_b\right) \tag{3.28}$$

where Z_a and Z_b are m-side and n-side impedances (line impedance plus source impedance), and R_f stands for the fault impedance. As illustrated in Figure 3.3, when an internal fault occurs at the midpoint of the line, imaginary part of Z_{ii} has a positive value, however, it has a negative value in external faults. Hence, it can be employed as a criterion to discriminate internal and external faults.

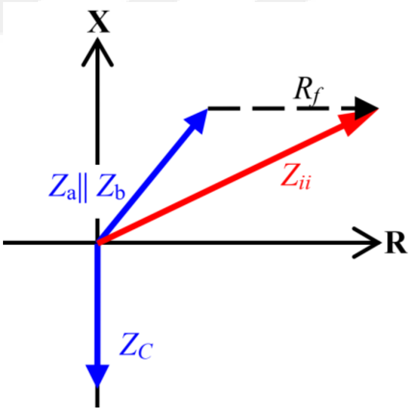

Figure 3.3 : Value of Zii in internal faults at the middle of the line.

As a conclusion, differential impedance method calculates the following equations to achieve the fault location.

$$Z_{op} = 2\left(Z'_{diff} - \frac{z_1 D}{2}\right)\frac{\tilde{I}_{m\varphi} - \tilde{I}_{n\varphi}}{\tilde{I}_{m\varphi} + \tilde{I}_{n\varphi}} \tag{3.29}$$

where

$$Z'_{diff} = \left(1+\frac{zD}{2Z_C}\right)\frac{\tilde{U}'_{ma} - \tilde{U}'_{na}}{\tilde{I}_{m\varphi} - \tilde{I}_{n\varphi}} \tag{3.30}$$

$$\tilde{U}'_{m\varphi} = \tilde{U}_{m\varphi} - \frac{z_0 - z_1}{z_0}\tilde{U}_{m0} \tag{3.31}$$

$$\tilde{U}'_{n\varphi} = \tilde{U}_{n\varphi} - \frac{z_0 - z_1}{z_0}\tilde{U}_{n0} \tag{3.32}$$

As shown in (3.15) and (3.26), Z_{op} is equal to $zd(2k-1)$. This value is also valid for imaginary part of the equation. Thus, the fault location is:

$$kD = \frac{1}{2}\left(\frac{\text{Im}\left(Z_{op}\right)}{\text{Im}\left(zD\right)}+1\right)\times D \tag{3.33}$$

Afterwards, the algorithm checks whether the fault is external or internal at the dead zone, by the equation below:

$$\left|kD - \frac{D}{2}\right| > D_{set} \tag{3.34}$$

where, D_{set} is the dead zone's length that is set to 1% of the line length. This equation shows that if the fault location value (kD) is in the range of 45% to 55% of the line, it may occur on the dead zone or beyond the line.

Thus, equation (3.34) activates equation (3.35) to investigate if the fault internal or external.

$$\text{Im}\left(Z_{ii}\right) > 0 \tag{3.35}$$

3.2 Transfer Matrix-Based Method

As mentioned in the previous section, impedance differential method is capable to discriminate internal faults from external ones and also locate any fault type on the transmission line. Nevertheless, this method is not applicable to hybrid transmission lines, since it assumes that the line is homogeneous. Therefore, in this section, a novel algorithm is proposed to identify the faulted section (OHL or UGC). Thereafter, the proposed algorithm calculates the voltage and current values at junction point of the overhead line and underground cable. Hence, a two-section hybrid line is transferred to a homogeneous line section and, at this condition, impedance differential method can be applied to identify the exact location of the fault.

Figure 3.4(a), shows a sample power system including a hybrid transmission line, which consists of two sections, an overhead line and an underground cable. As depicted in the figure, each line section is represented by its symbolic transfer matrix. The precise transfer matrices of overhead line and underground cable are as below:

$$T_{OHL} = \begin{pmatrix} cosh(\gamma_{OHL}\ell_{OHL}) & sinh(\gamma_{OHL}\ell_{OHL})z_{C\,OHL} \\ sinh(\gamma_{OHL}\ell_{OHL})/z_{C\,OHL} & cosh(\gamma_{OHL}\ell_{OHL}) \end{pmatrix} \tag{3.36}$$

$$T_{UGC} = \begin{pmatrix} cosh(\gamma_{UGC}\ell_{UGC}) & sinh(\gamma_{UGC}\ell_{UGC})z_{CUGC} \\ sinh(\gamma_{UGC}\ell_{UGC})/z_{CUGC} & cosh(\gamma_{UGC}\ell_{UGC}) \end{pmatrix} \tag{3.37}$$

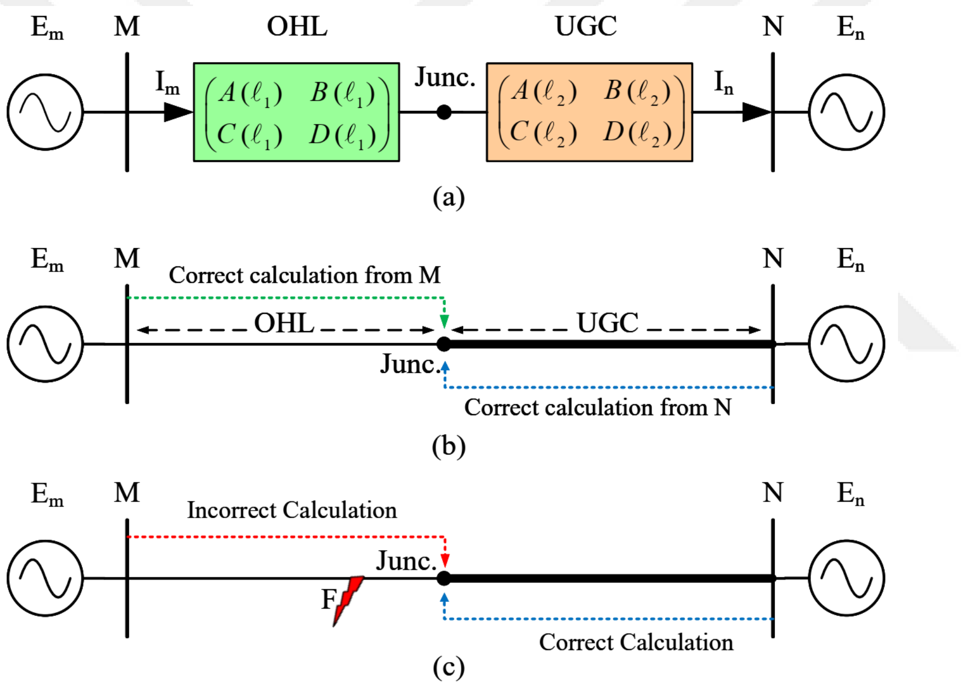

Figure 3.4 : (a) A sample power system including a hybrid line (b) correct calculations from both ends in normal conditions (c) incorrect calculation from the faulted section side.

where, ℓ_{OHL} and ℓ_{UGC} stand for lengths of overhead line and underground cable; and $Z_{C\ OHL}$, $Z_{C\ UGC}$, γ_{OHL} and γ_{UGC} represent characteristic impedance and propagation constant of overhead line and underground cable.

It is obvious that voltage and current values of the junction point can be computed by measuring the voltage and current values at both of the reference buses and substituting their phasor values into corresponding transfer matrix equations. In other words, for instance, if we need to calculate the voltage and current values of the junction point, we should measure the voltage and current values at buses *M* and *N*, initially. Afterwards, phasor values of the calculated voltage and current are required. Thus, full cycle Fourier analysis is utilized for this purpose. Thereafter, transfer matrix of the underground cable is employed for calculating the voltage and current phasor values of the junction point from bus *N*. Furthermore, transfer matrix of the overhead section is used for calculating the electrical parameters of the junction point from bus *M*. Figure 3.4(b) illustrates the explained procedure. Additionally, (3.34) and (3.35) shows the equations that are utilized in this regard.

$$\begin{pmatrix} U_{jm} \\ I_{jm} \end{pmatrix} = \begin{pmatrix} cosh(\gamma_{OHL}\ell_{OHL}) & -sinh(\gamma_{OHL}\ell_{OHL})z_{COHL} \\ -sinh(\gamma_{OHL}\ell_{OHL})/z_{COHL} & cosh(\gamma_{OHL}\ell_{OHL}) \end{pmatrix} \begin{pmatrix} U_m \\ I_m \end{pmatrix} \tag{3.38}$$

$$\begin{pmatrix} U_{jn} \\ I_{jn} \end{pmatrix} = \begin{pmatrix} cosh(\gamma_{UGC}\ell_{UGC}) & sinh(\gamma_{UGC}\ell_{UGC})z_{CUGC} \\ sinh(\gamma_{UGC}\ell_{UGC})/z_{CUGC} & cosh(\gamma_{UGC}\ell_{UGC}) \end{pmatrix} \begin{pmatrix} U_n \\ I_n \end{pmatrix} \tag{3.39}$$

where, V_{jm}, I_{jm}, V_{jn}, and I_{jn} are voltage and current of the junction point that are computed from bus *M* and *N*, respectively.

In this application, the proposed method uses voltage angle, since it is approximately constant and is not severely changed over a transmission line. Hence, due to high accuracy of transfer matrix equations, the calculated phasor values of the voltage and current belong to the junction point from both ends are equal in normal conditions (see equation (3.38) and (3.39)).

$$ang(V_{jm}) \approx ang(V_{jn}) \tag{3.40}$$

$$\left| ang(V_{jm}) - ang(V_{jn}) \right| \approx 0 \tag{3.41}$$

Nonetheless, transfer matrix equations are not designed for fault conditions. It means that, when an internal fault occurs on one of the line sections, the junction point’s voltage angle is not correctly computed from the bus that is adjacent to the faulted section. Figure 3.4(c) depicts the condition of the calculations in the fault condition. As illustrated in the figure, calculation of the junction point voltage angle from bus *M* is completely wrong, since a fault occurs on the overhead line section. On the other hand, calculation from bus *N* is correctly implemented, as there is no fault between the reference bus (*N*), at which the measurements are done, and the desired point (the junction point). Hence, in the fault condition, the obtained results from bus *M* have a large difference with the achieved results from bus *N*, as cited below:

$$\left| ang(V_{jm}) - ang(V_{jn}) \right| > 0 \tag{3.42}$$

Thus, absolute difference of the calculated voltage angle (ADVA) of the junction point from both ends is employed as a criterion for fault detection by the proposed algorithm.

However, the algorithm needs to identify the fault section and, consequently, the correct calculated values for the junction point from the bus that is adjacent to the healthy section. In this regard, the algorithm compares the differences of voltage angle that measured at each bus with the computed voltage angle of the junction point from the same bus.

$$ADVA_{mj} = \left| ang(V_m) - ang(V_{jm}) \right| \tag{3.43}$$

$$ADVA_{nj} = \left| ang(V_n) - ang(V_{jn}) \right| \tag{3.44}$$

where, $ADVA_{mj}$ and $ADVA_{nj}$ represent the absolute differences of the voltage angles of buses *M* and *N* and with the junction point, respectively. Then, the rate of change for each of the difference values are computed using superposition theorem. Indeed, the algorithm calculates the superimposed values of $ADVA_{mj}$ and $ADVA_{nj}$ to detect a severe change in the calculated voltage angle from both ends.

$$\Delta\, ADVA_{mj} = ADVA_{mj}(t) - ADVA_{mj}(t - \Delta t) \tag{3.45}$$

$$\Delta\, ADVA_{nj} = ADVA_{nj}(t) - ADVA_{nj}(t - \Delta t) \tag{3.46}$$

where, $\Delta ADVA_{mj}$ and $\Delta ADVA_{nj}$ are superimposed values of $ADVA_{mj}$ and $ADVA_{nj}$; and t and Δt represent current time and one cycle before.

As mentioned before, this change determines the faulted line section. In this respect, $\Delta ADVA_{mj}$ and $\Delta ADVA_{nj}$ are compared by the algorithm to identify whether the fault occurs on the overhead section or underground section. Furthermore, the faulted phase is also detected (see the following equation).

$$\Delta\, ADVA = \Delta\, ADVA_{mj} - \Delta\, ADVA_{nj} \tag{3.47}$$

As a result, the proposed algorithm is capable to detect faults with any type. Thereafter, it recognizes the bus that its calculated voltage angle is not changed and, consequently, identifies the faulted section. At the end, the faulted section as the only section of the line that is considered for applying impedance differential approach is selected and the exact fault location is identified. Figure 3.5 depicts flowchart of the proposed algorithm.

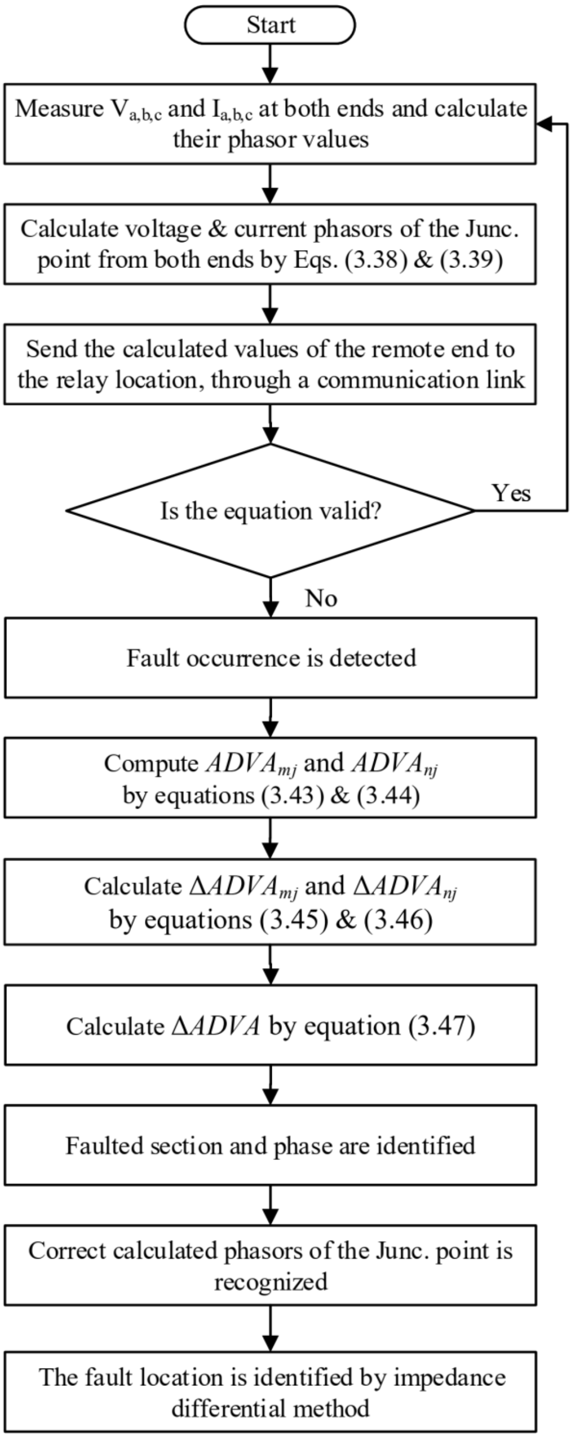

Figure 3.5 : Flowchart of the proposed algorithm.

4. PERFORMANCE ANALYSIS BY SIMULATION STUDIES

In this chapter of the thesis, performance analysis of the proposed novel method is implemented by the computer-based simulation studies. In this regard, a 132 kV, 50 Hz sample power system is considered for simulation studies. Figure 4.1 shows the power system. As illustrated in the figure, the power system includes two main buses and two equivalent sources that connect to each other through a two-section hybrid transmission line, which is composed of 80 km overhead line and 30 km underground cable.

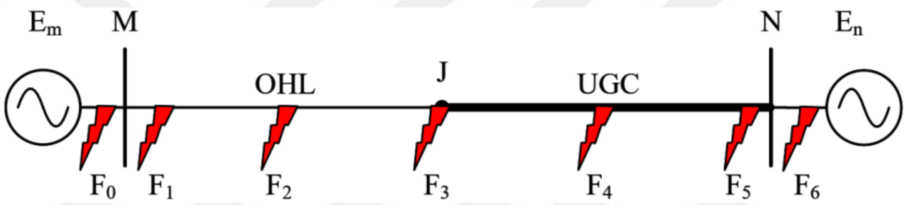

Figure 4.1 : The sample power system.

Table 4.1 : The simulated system data.

Parameter	**OHL**	**UGC**	**Unit**
Positive sequence resistance	0.3317	0.024	Ω/km
Positive sequence inductance	1.326	0.4278	mH/km
Positive sequence capacitance	8.688	281.1	nF/km
Zero sequence resistance	0.4817	0.412	Ω/km
Zero sequence inductance	4.595	1.5338	mH/km
Zero sequence capacitance	4.76	152.9	nF/km
Line length	80	30	km

Table 4.1 represents the power system parameters. For the purpose of simulation studies, the sampling frequency is set to 1 kHz and the phasor values are computed by the full cycle Fourier method. To test the proposed algorithm's performance, different fault types (FT), fault impedances (FI), fault locations (FL), which varies from F_0 to F_6, and fault inception angles (FIA) are applied to the simulated power system. As depicted in the figure, F_0 and F_6 are external faults beyond buses *M* and *N*, and F_1 to F_5 represent internal faults at the beginning of the line, at midpoint of the overhead section, at the junction point, at midpoint of the cable section, and at the end of the line, respectively.

4.1 General Simulation results to Confirm Effectiveness of the Algorithm

To evaluate the algorithm, a double phase to ground fault on phases *A* and *B* with zero impedance and 90 degree inception angle (for phase *A*) is located 20 (km) away from bus *M*, which occurs at 0.065 (s). Figure 4.2(a) presents the difference of Δ $ADVA_{mj}$ and Δ $ADVA_{nj}$, according to equation (3.47). As shown in the figure, the algorithm is able to detect the fault and its associated phases, immediately. Furthermore, the changes are toward positive direction that proves the fault occurrence on the overhead line section. Hence, the proposed algorithm finds out that the calculations of the voltage and current of the junction point at bus *M* are incorrect. Thus, it utilizes the calculations of bus *N*. Consequently, the overhead section is just considered by impedance differential method as its both ends current and voltage values are available.

Figure 4.2.(b) displays *kD* value that is related to the fault location. As shown in the figure, the algorithm is capable to identify the exact fault location, at 20th kilometer of the line.

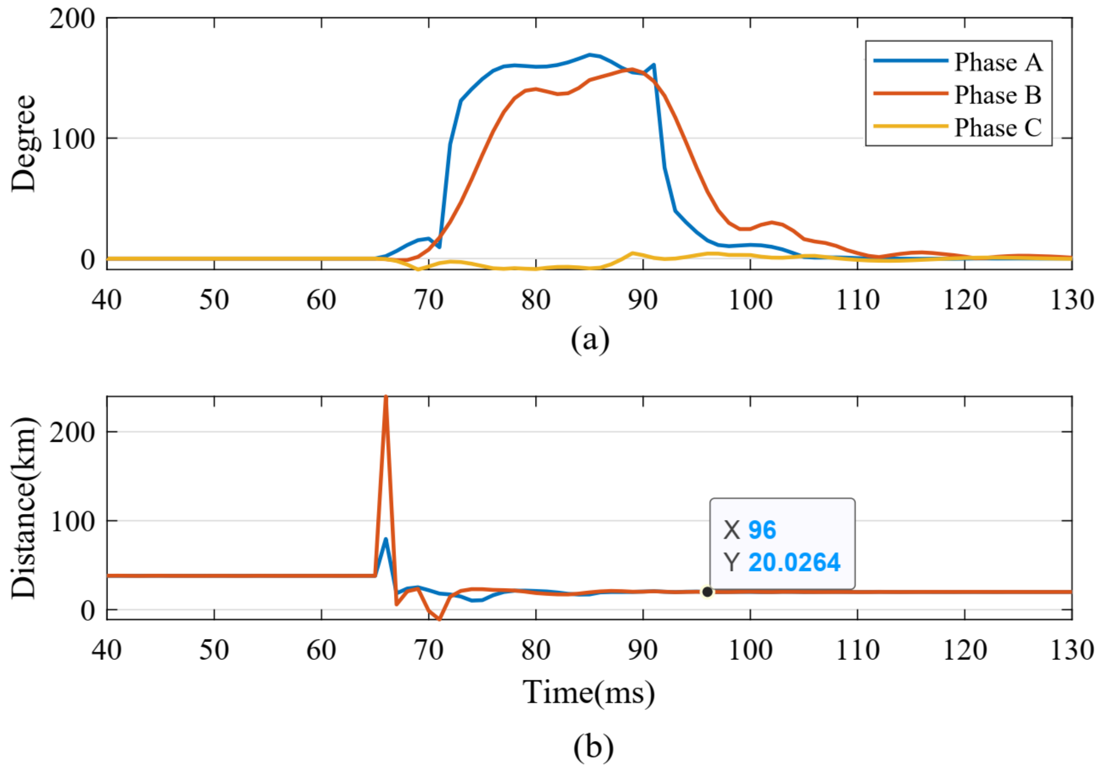

Figure 4.2 : (a) Difference of Δ ADVAmj and Δ ADVAnj and (b) kD value after double phase to ground fault occurrence.

4.2 Effect of Different Fault Locations and Types

Discriminating an internal fault from an external one is one of the significant duties of all protection systems. In addition, protection algorithms must not be sensitive to fault location and type allover the protected transmission line. Thus, the proposed algorithm's performance is investigated by variety of cases including different fault locations (F_0 to F_6) and different fault types (LG, LL, LLG, LLLG). In this regard, first of all, single line to ground faults at phase *B* with 5 (Ω) impedance and 90 degree inception angle occur at F_0 and F_1 to compare the algorithm performance in internal and external fault conditions.

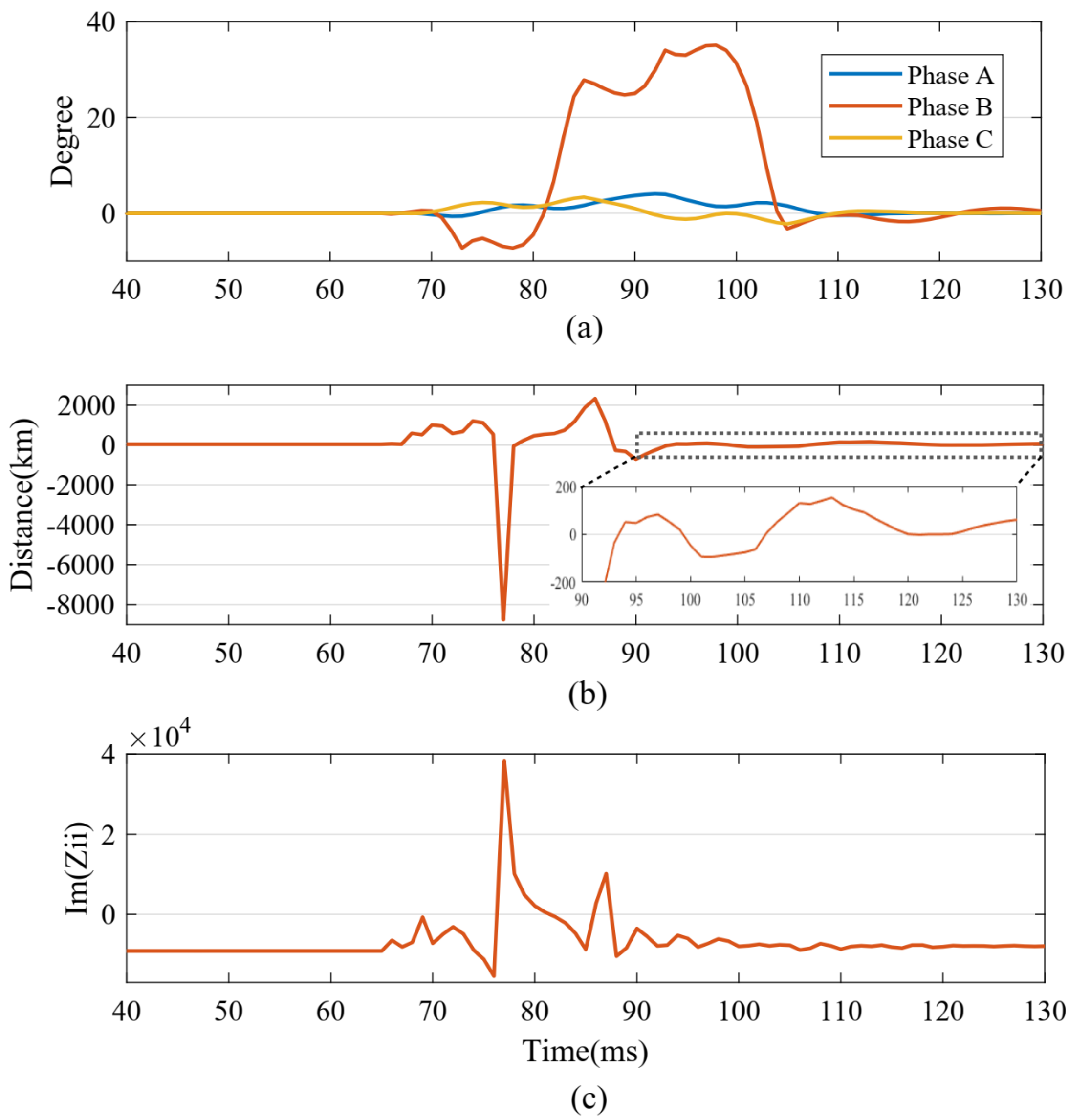

Figure 4.3 : (a) Difference of Δ ADVAmj and Δ ADVAnj (b) kD value and (c) imaginary part of Zii in external fault condition (F0).

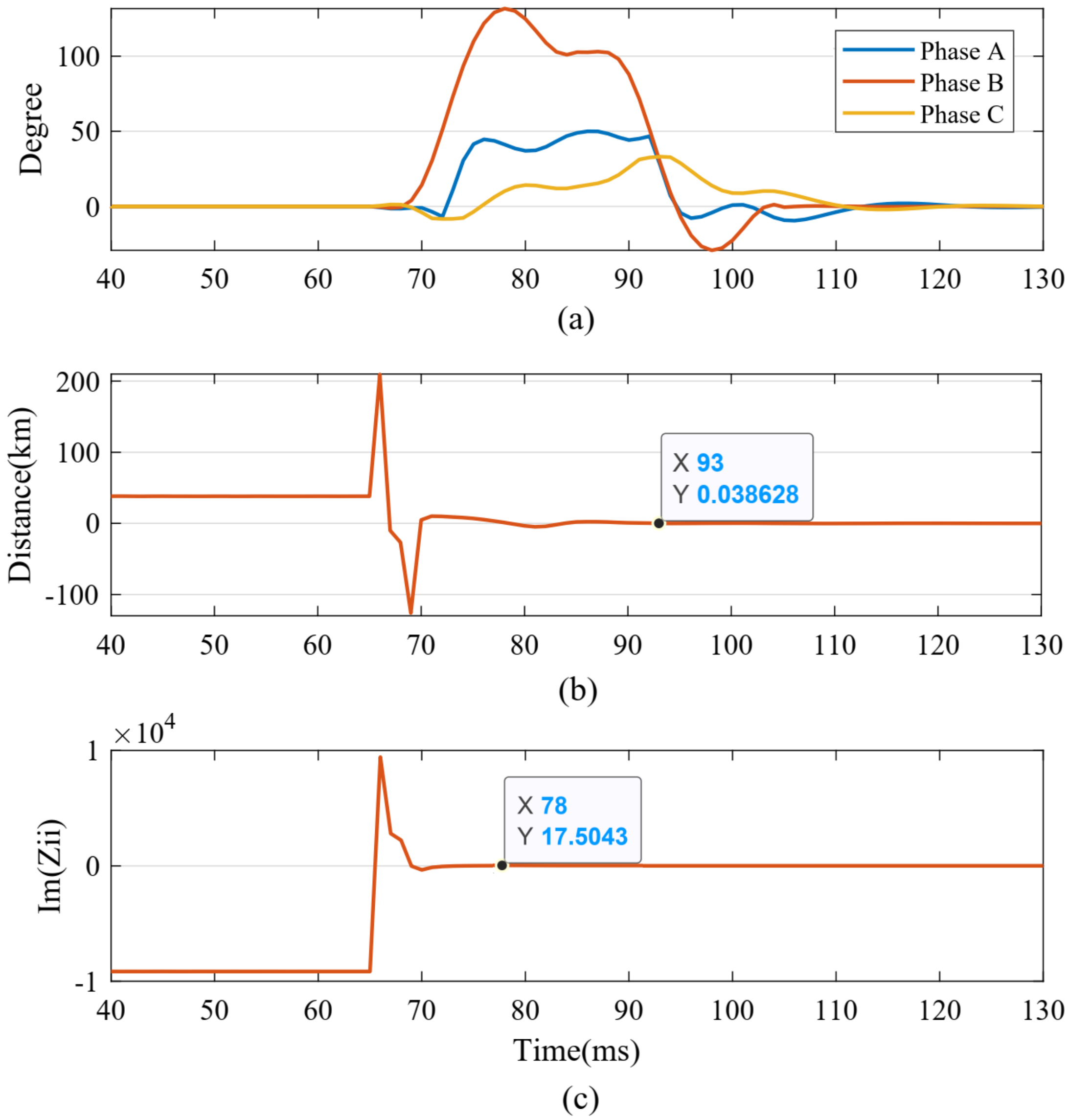

Figure 4.4 : (a) Difference of Δ ADVAmj and Δ ADVAnj (b) kD value and (c) imaginary part of Zii in internal fault condition (F1).

In the case of external fault at F_0, as displayed in figure 4.3(a), the faulted phase and section are clearly detectable. However, according to figure 4.3(b) the fault location (*kD*) value faces oscillation that makes the fault location impossibe to identify. Nevertheless, external fault occurrence can be detected using imaginary value of Z_{ii}. As shown in figure 4.3(c), *Im*(Z_{ii}) has a negative value in post fault steady state condotion.

In the case of internal fault at F_1, the algorithm is capable to detect not only the faulted phase and section, as illustrated in figure 4.4(a), but also the fault location according to figure 4.4(b). Moreover, by using *Im*(Z_{ii}) the algorithm can be sure that the fault is internal, since it has a positive value in post fault steady state condotion.

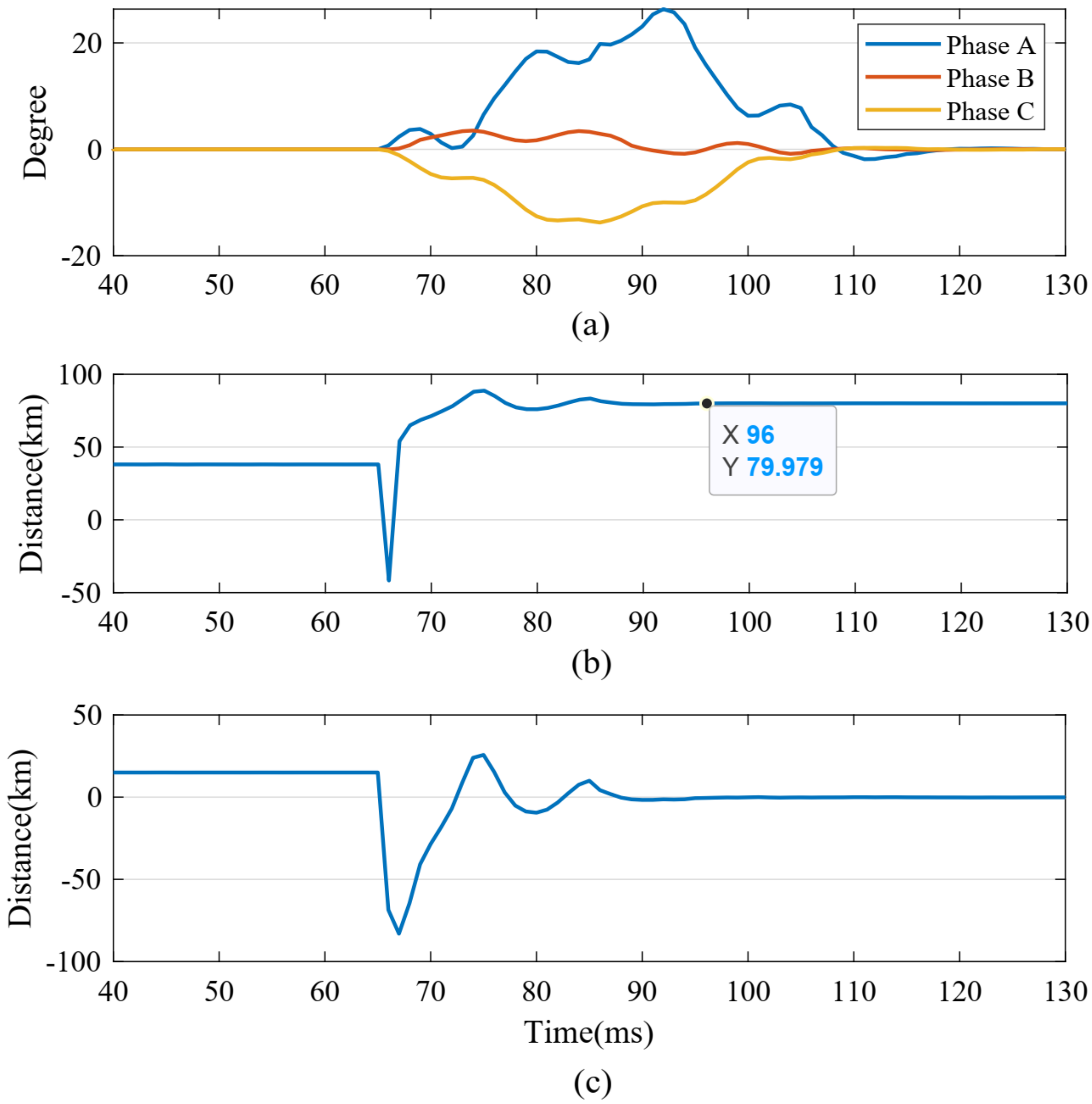

Figure 4.5 : (a) Difference of Δ ADVAmj and Δ ADVAnj (b) kD value of OHL section and (c) kD value of UGC section in internal fault condition (F3).

Additionally, hybrid line protection methods generally experience problem encountering faults that occur around or exactly on the junction point. However, the proposed method can surprisingly identify such faults, as shown in figure 4.5. According to figure 4.5(a), phase *A* has the highest peak value among the other phases. Thus, the faulted phase is diagnosed. By checking the fault location values (*kD*) of both sections (OHL and UGC) in figures 4.5(b) and 4.5(c), it can be obvious that exact location of the fault is identified by the proposed algorithm.

In addition to the mentioned simulation studies, all possible fault type and locations are applied to the power system and the results are summarized in table 4.1 as shown below:

Table 4.1 : Effect of different fault types and locations.

FL	FT	Calc. Loc. (km)	Error (%)	Tripping status Ph. A	Ph. B	Ph. C
F_1	AG	0.003	0.002	√	×	×
	ABG	0.011	0.010	√	√	×
	ABCG	0.021	0.019	√	√	√
F_2	BG	40.010	0.009	×	√	×
	BC	40.012	0.011	×	√	√
	ABC	40.011	0.010	√	√	√
F_3	CG	80.075	0.068	×	×	√
	AC	79.906	0.085	√	×	√
	ACG	80	0	√	×	√
F_4	AG	94.990	0.009	√	×	×
	ABG	95.018	0.016	√	√	×
	ABC	95.009	0.008	√	√	√
F_5	BG	110	0	×	√	×
	BC	109.922	0.071	×	√	√
	ABCG	109.93	0.064	√	√	√
F_0 & F_6	CG	-	-	×	×	×
	ACG	-	-	×	×	×
	ABC	-	-	×	×	×

4.3 Effect of Different Fault Inception Angles

Inception angle, which is related to corresponding electrical degree of power signal that a fault occurs, affects the fault behavior such as amount of DC offset of current signal. Hence, different inception angles from the weakest (zero) to the highest (90 degree) are applied to a 5 (Ω) impedance fault on the underground cable section 90 (km) away from bus *M*, to evaluate the proposed algorithm. Table 4.2 cites the results.

Table 4.1 : Effect of different fault inception angles.

FL (km)	FI (Ω)	FT	FIA	Calc. Loc. (km)	Error (%)
90	5	AG	0	89.978	0.020
			30	89.986	0.013
			60	89.967	0.030
			90	90.020	0.018

4.4 Effect of Different Fault Impedances

Fault impedance is one of the important characteristics of short circuit faults in transmission lines. Some of transmission line protection methods are sensitive to fault impedance, which may cause maloperation of the relay. In this respect, performance of the proposed algorithm is investigated by applying faults 20 (km) away from bus *M* with different fault types and impedances. Table 4.3 shows the simulation results for this case. According to the table, the algorithm can detect the faults with different types and impedances.

Table 4.4 : Effect of different fault impedances.

FT	FL (km)	FI (Ω)	Calc. Loc. (km)	Error (%)	Tripping status		
					Ph. A	Ph. B	Ph. C
AG	20	0	19.980	0.018	√	×	×
BC		5	19.990	0.009	×	√	√
ACG		10	20.048	0.043	√	×	√
ABCG		30	20.104	0.094	√	√	√

5. CONCLUSIONS AND RECOMMENDATIONS

Lorem In this thesis, a novel approach is proposed for fault detection and its location identification for hybrid transmission lines. The proposed method is based on transfer matrices of the line sections (OHL and UGC) and impedance differential method. The approach is utilized voltage and current samples that measured at both ends of the line with 1 kHz sampling frequency. Their phasor values are computed by a full cycle Fourier analysis. Then, the junction point's voltage and current phasors are calculated by transfer matrix equations from both ends. In the case of no-fault and external fault conditions, the calculated phasors for the junction point are equal from both ends. In the case of internal faults, the calculated voltage and current phasors of the junction point from both ends are different, since there is a fault on the section between the reference bus and the junction point. Thus, it leads to incorrect calculations. In this condition, the proposed algorithm searches for the faulted section and consequently the end that has correct calculations for the junction point. The wrong computations cause the calculated voltage angle of the junction point to be distanced from the voltage angle of its reference bus. Therefore, the proposed algorithm employs the voltage angles-based criterion to identify the faulted section and also the correct values of voltage and current phasors. This divides a hybrid line to separated homogeneous sections. Afterwards, impedance differential algorithm is employed to detect the faults and identify their locations on the hybrid line. As confirmed by the computer-based simulation results, the proposed method is not sensitive to fault and power system characteristics.

The main achievements of the thesis are listed below:

- The proposed novel algorithm has a satisfactory performance in any fault location
- It can work properly encountering any fault inception angle
- It is capable to detect/locate any fault type
- It is not sensitive to fault resistance

- It is not affected by changing the power system topology and impedance.
- The protection algorithm can be utilized in real world applications, due to its simplicity and satisfactory performance.

5.1 Future Research Opportunity

It is obvious that single ended-based protection approaches can be reliable that unit protection methods, owing to elimination of possibility of the communication channel failure. Hence, the author thinks that single ended fault detection and location algorithms for hybrid transmission systems can be the next step for doing research in this area.

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