One-Terminal Traveling Wave-Based Protection for HVAC and HVDC Transmission Lines

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Co-orientador: Dr. Kai Strunz.  
Co-orientador: Dr. Felipe Vigolvino Lopes.

To God. To my family, especially my parents, Sérgio Augusto Nascimento de França and Eliene Francisca da Silva França, for their guidance throughout my life. To my wife, Allany Katywood Henrique de Miranda, for her tremendous and valuable support in completing this work.
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Abstract

This work proposes developing one-terminal traveling wave-based transmission line protection methods for HVAC (High Voltage Alternating Current) and HVDC (High Voltage Direct Current) systems. It considers the effect of the sampling frequency on the protection, which until now has not been investigated for one-terminal methods. It addresses inaccuracies in wave velocity estimations, which traditionally lead to problems in methods based on traveling waves, and presents solutions to these problems. The proposed methods have been evaluated through computer simulations. The proposed earth fault distance protection for HVAC transmission lines was evaluated using an actual commercial relay with time-domain-based protection functions. The results related to the proposed earth fault distance protection for HVAC transmission lines show that the proposed function, when associated with other existing protection functions, can achieve a remarkable enhancement in the dependability and velocity of the transmission line protection. The results concerning the method based on traveling wave reflections show that it is possible to protect most point-to-point transmission lines quickly, without communication, and independent of the wave speed estimation. Finally, the results concerning distance protection for meshed HVDC systems demonstrate the applicability of the proposed method for such systems. The method showed an operating time below 2 ms for a line of 500 km in length. This operating time meets the likely requirements that HVDC meshed systems will present. Additionally, the method demonstrated selectivity for a 4-terminal system interconnected by five transmission lines.

Keywords: Transmission line protection, traveling waves, one-terminal protection, distance protection, fault location, HVAC systems, meshed HVDC systems, protection selectivity.
Resumo

Este trabalho propõe o desenvolvimento de métodos de proteção de linha de transmissão baseados em ondas viajantes de um terminal para sistemas ATCA (Alta Tensão em Corrente Alternada) e ATCC (Alta Tensão em Corrente Contínua). O efeito da frequência de amostragem na proteção é considerado, o que até agora ainda não foi investigado para métodos de um terminal. As imprecisões nas estimativas da velocidade das ondas, que classicamente são limitações para métodos baseados em ondas viajantes, são abordadas e são apresentadas soluções para tal problema. Os métodos propostos foram avaliados por meio de simulações computacionais. A proteção proposta da distância para faltas envolvendo a terra para linhas de transmissão ATCA foi avaliada utilizando um relé comercial real com funções de proteção baseadas no domínio do tempo. Os resultados relacionados à proteção proposta da distância para faltas à terra para linhas de transmissão ATCA mostram que a função proposta, quando associada a outras funções de proteção existentes, pode alcançar um incremento bastante notável na confiabilidade e velocidade da proteção da linhas de transmissão. Os resultados relativos ao método baseado em reflexão de ondas viajantes mostram que é possível proteger a maioria das linhas de transmissão ponto a ponto de uma forma rápida, sem necessidade de comunicação e independente da estimativa da velocidade da onda. Finalmente, os resultados relativos à proteção da distância para sistemas de ATCC em malha demonstram a aplicabilidade do método proposto para tais sistemas. O método apresentou um tempo de atuação inferior a 2 ms para uma linha de 500 km de comprimento. Esse tempo de atuação atende aos prováveis requisitos que sistemas meshed ATCC apresentarão. Além disso, o método apresentou selectividade para um sistema de 4-terminais interligados por 5 linhas de transmissão.

Palavras-chave: Proteção da linha de transmissão, ondas viajantes, proteção de um terminal, proteção de distância, localização de faltas, sistemas ATCA, sistemas ATCC em malha, selectividade da proteção.
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\( \alpha \)  Line attenuation constant
\( \beta \)  Line phase constant
\( c \)  Speed of light
\( C \)  Per unit transmission line capacitance
\( C_1 \)  Per unit transmission line capacitance in positive sequence component
\( C_0 \)  Per unit transmission line capacitance in zero sequence component
\( d_F \)  Fault distance from the local bus
\( d_x \)  Length constant
\( \varepsilon_\alpha \)  Error related to the discret instant of the first alpha mode wavefront to reach the local bus
\( \varepsilon_F \)  Error associated to the discrete fault inception time
\( \varepsilon_{F\alpha} \)  Total error represented by the sum between the error related to the instant of the first alpha mode wavefront to reach the local bus \( \varepsilon_\alpha \) and the error associated to the discrete fault inception time \( \varepsilon_F \)
\( \varepsilon_{F0} \)  Total error represented by the sum between the error related to the instant of the first zero mode wavefront to reach the local bus \( \varepsilon_0 \) and the error associated to the discrete fault inception time \( \varepsilon_F \)
\( \varepsilon_0 \)  Error related to the discret instant of the first zero mode wavefront to reach the local bus
\( f_s \)  Relay sampling frequency
\( G \)  Per unit transmission line conductance
\( \gamma \)  Propagation constant of the transmission line
\( \Gamma_{r1(I)} \)  Reflection coefficient in bus 1 of the wave in the current signal
\( \Gamma_{r1(U)} \)  Reflection coefficient in bus 1 of the wave in the voltage signal
\( \Gamma_{r2(I)} \)  Reflection coefficient in the fault point of the wave in the current signal
\( \Gamma_{r2(U)} \)  Reflection coefficient in the fault point of the wave in the voltage signal
\( \Gamma_{t1(I)} \)  Refraction coefficient in bus 1 of the wave in the current signal
\( \Gamma_{t1(U)} \)  Refraction coefficient in bus 1 of the wave in the voltage signal
\( \Gamma_{t2(I)} \)  Refraction coefficient in the fault point of the wave in the current signal
\( \Gamma_{t2(U)} \)  Refraction coefficient in the fault point of the wave in the voltage signal
\( i \)  Current signal
\( i_A \)  Current signal in phase A
\( i_\alpha \)  Current signal in alpha mode component
\( i_B \)  Current signal in phase B
\( i_\beta \)  Current signal in beta mode component
\( i_C \)  Current signal in phase C
\( i_{r1} \)  Traveling wave in currents reflected in bus 1
\( i_{r2} \)  Traveling wave in currents reflected in the fault point
\( i_{s1} \)  Sum between the incident and reflected current waves in the bus L
\( i_{r1} \)  Traveling wave in currents refracted in bus 1
$i_{t_2}$ Traveling wave in currents refracted in the fault point

$i_0$ Current signal in zero mode component

$i_1$ Traveling wave in the current signal

$k_{\alpha}$ Sample arrival of the alpha mode traveling wave in bus L

$k_F$ Sample referring to the fault inception time

$k_0$ Sample arrival of the zero mode traveling wave in bus L

$L$ Per unit transmission line inductance

$L_1$ Per unit transmission line inductance in positive sequence component

$L_0$ Per unit transmission line inductance in zero sequence component

$l$ Total length of the monitored transmission line

$l_A$ Total length of the external transmission line A

$l_B$ Total length of the external transmission line B

$m$ Multiplicative factor dependent on real velocities of modal traveling waves

$m_{\text{marg}_{\alpha}}$ Error margin for overestimating the alpha mode wave velocity

$m_{\text{marg}_0}$ Error margin for underestimating the zero mode wave velocity

$m'$ Multiplicative corrected factor dependent on real velocities of modal traveling waves

$m_c$ Estimated value to the variable $m$

$p_{\alpha}$ Multiplicative security factor for $v_{\alpha}$

$p_0$ Multiplicative security factor for $v_0$

$P_l$ Minimum protection reach

$P_{l_{\text{max}}}$ Maximum protection reach

$q$ Threshold to ensure that an internal fault is properly differentiated from an external fault

$q_{\alpha}$ Overestimation factor for the the initial alpha mode wave velocity estimation

$q_0$ Underestimation factor for the the initial zero mode wave velocity estimation

$R$ Per unit transmission line resistance

$R_f$ Fault resistance

$t$ Time instant variable

$t_{\alpha}$ Alpha mode wavefront arrival time in continuous time domain in bus L

$t_F$ Fault inception time in continuous time domain

$t_{F_1}$ First wavefront arrival time in continuous time domain in local bus

$t_{F_2}$ Second wavefront arrival time in continuous time domain in local bus

$t_{F_3}$ Third wavefront arrival time in continuous time domain in local bus

$t_0$ Zero mode wavefront arrival time in continuous time domain in bus L

$t_{1_1}^1$ Arrival time of the first wave to reach the bus 1

$t_{1_2}^1$ Arrival time of the first wave to reach the bus 2

$t_{1_3}^1$ Arrival time of the first wave to reach the bus 3

$t_{2_1}^1$ Arrival time of the second wave to reach the bus 1

$t_{2_2}^1$ Arrival time of the second wave to reach the bus 2

$t_{2_3}^1$ Arrival time of the second wave to reach the bus 3

$\tau_{\alpha}$ Delay between the fault inception time $t_F$ and the first alpha mode wavefront arrival time on the bus L $t_{\alpha}$

$\tau_{F_1}$ Propagation time of the first wavefront to reach the local bus

$\tau_{F_2}$ Propagation time of the second wavefront to reach the local bus
\( \tau_0 \)  Delay between the fault inception time \( t_F \) and the first zero mode wave-front arrival time on the bus L \( t_0 \)

\( u \)  Voltage signal

\( u_A \)  Voltage signal in phase A

\( u_\alpha \)  Voltage signal in alpha mode component

\( u_B \)  Voltage signal in phase B

\( u_\beta \)  Voltage signal in alpha beta component

\( u_C \)  Voltage signal in phase C

\( u_f \)  Instantaneous voltage at the fault point at the fault instant

\( u_{r1} \)  Traveling wave in voltages reflected in bus 1

\( u_{r2} \)  Traveling wave in voltages reflected in the fault point

\( u_{s1} \)  Sum between the incident and reflected voltage waves in the bus L

\( u_{t1} \)  Traveling wave in voltages refracted in bus 1

\( u_{t2} \)  Traveling wave in voltages refracted in the fault point

\( u_0 \)  Voltage signal in zero mode component

\( u_1 \)  Traveling wave in the voltage signal

\( v \)  Real velocity of the traveling waves

\( v_\alpha \)  Velocity of the alpha mode traveling wave

\( v_0 \)  Velocity of the zero mode traveling wave

\( x \)  Position variable

\( Z_0 \)  Characteristic impedance of a specific line

\( Z_1 \)  Characteristic impedance of line 1

\( Z_2 \)  Characteristic impedance of line 2
# List of Abbreviations and Acronyms

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<th>Description</th>
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<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ATCA</td>
<td>Alta Tensão em Corrente Alternada</td>
</tr>
<tr>
<td>ATCC</td>
<td>Alta Tensão em Corrente Contínua</td>
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<tr>
<td>CAPES</td>
<td>Coordination for the Improvement of Higher Education Personnel</td>
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<tr>
<td>CBA</td>
<td>Brazilian Congress of Automatic</td>
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<tr>
<td>CCVT</td>
<td>Coupling Capacitor Voltage Transform</td>
</tr>
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<td>CT</td>
<td>Current Transformer</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
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<tr>
<td>DMR</td>
<td>Dedicated Metallic Return</td>
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<td>DTT</td>
<td>Direct Transfer Trips</td>
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<td>EMTDC</td>
<td>Electromagnetic Transients including DC</td>
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<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<td>HVAC</td>
<td>High Voltage Alternating Current</td>
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<tr>
<td>HVDC</td>
<td>High Voltage Direct Current</td>
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<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
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<tr>
<td>IPST</td>
<td>The International Conference on Power Systems Transients</td>
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<tr>
<td>OC21</td>
<td>Time domain overcurrent function</td>
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<tr>
<td>PD-SPWM</td>
<td>Phase Disposition Sinusoidal Pulse Width Modulation</td>
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<td>ProRedes</td>
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<td>Schweitzer Engineering Laboratories</td>
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<td>SM</td>
<td>Switching Module</td>
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<tr>
<td>SIR</td>
<td>System-to-line Impedance Ratio</td>
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<td>STATCOM</td>
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<td>Workshop on Communication Networks and Power Systems</td>
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Chapter 1

Introduction

This thesis covers investigations related to HVAC and HVDC transmission systems. Therefore, for a better understanding, these two topics are, when possible, presented separately in this chapter.

1.1 HVAC System

The transmission line is a fundamental component of the electrical power system since it transmits energy from generation plants to load centers. It is estimated that 50% of all faults occurring in the electric power system are concentrated in overhead transmission lines (PAITHANKAR; BHIDE, 2003). Therefore, the fast fault clearance in the transmission system is crucial for reducing damage to the electrical power system, increasing its stability, energy transmission capacity (GLOVER; SARMA; OVERBYE, 2012), and availability. Such a context has motivated several studies toward developing fast and reliable protection schemes based on traveling waves (SCHWEITZER; KASZTENNY; MYNAM, 2015; SCHWEITZER et al., 2015).

Traditional protection schemes for AC (Alternating Current) transmission lines, such as distance protection, are based on phasor estimation. These techniques present some limitations that restrict their ability to perform a fast operation (SCHWEITZER et al., 2015), among them the need for an observation window of a fundamental signal wave cycle for accurate phasor estimation (SCHWEITZER et al., 2015). According to Schweitzer et al. (2015), protective relays typically operate between one and one-and-a-half cycles (from 16.67 to 25 ms on a 60 Hz system). The current interruption time by the circuit breaker is between one-and-a-half cycle to three cycles, resulting in an average time for the fault interruption of three to four cycles. Thus, the operation time of the traditional techniques represents 25 to 50% of the total time for the fault interruption. Although traditional methods operate within a quarter of a cycle in specific conditions, stability limit considerations should be made assuming conservative times of protection operation (SCHWEITZER et al., 2015). Eastvedt (1976) demonstrated that, for a specific transmission line, a reduction of one cycle in the fault interruption time increased the power transfer capacity by 250 MW, i.e., 15 MW per millisecond, which highlights the relevance in developing protection methods increasingly fast.

When a fault occurs on an overhead transmission line, high-frequency electromagnetic transients are induced in voltages and currents. The transients propagate from the fault point toward the line terminals, as traveling waves, at a velocity close to the speed of light. When a wavefront arrives at a line terminal, a portion of the traveling wave is reflected and travels back toward the fault point, whereas another portion is refracted and travels toward the next line terminal if there are adjacent lines. The traveling waves reflected at the line terminal suffer another reflection
and refraction at the fault point, reflecting and refracting toward the line terminals, resulting in several coexistent traveling waves attending the wave superposition principle. The complete theory of the traveling wave can be found in Corporation (1964).

The first work related to transients on a distributed parameter line investigated the signal distortion on the planned Trans-Atlantic telephone cable in 1854 (KELVIN, 1884). In the 1920s and 1930s, several works investigated the traveling waves behavior in transmission lines (BUSH, 1923; DOWELL, 1931; BEWLEY, 1931). A general theory based on a graphical method was proposed by Allievi (1902) and applied to the field of hydraulic engineering, which was a direct application of the traveling-wave concept. Based on Allievi (1902), a solution to the analysis of transient waves was proposed by Schnyder (1929) and Bergeron (1935) in order to treat initially transient phenomena in hydraulic systems. It was later applied to electrical transient phenomena. This method is known as Bergeron’s method or Schnyder-Bergeron’s method. Essential works in the 1960s proposed the analysis of transients on electric power transmission lines based on Bergeron’s method through digital computers (FREY; ALTHAMMER, 1961; ARLETT; MURRAY-SHELLEY, 1965; BRANIN, 1967). Based on Bergeron’s method, Dommel (1969) proposed a generalized algorithm capable of solving transients in any network with distributed parameters, which was fundamental to the advance of the traveling waves in transmission line analysis. These computational techniques are generally called time-domain methods or traveling-wave techniques.

Traveling-wave-based transmission line protection can be divided into one- and two-terminal techniques. Two-terminal techniques use information on traveling waves at both line ends, so communication links and GPS (Global Positioning System) are often reported as a mandatory requirement (YU, 2010). Nevertheless, practical data synchronization issues have been extensively reported in the literature, such as the possibility of a loss of the time reference signal (IZYKOWSKI et al., 2010), and the non-installation of common time reference sources in all substations (YU, 2010). This reduces the reliability of two-terminal techniques in existing systems. In this context, one-terminal protection solutions have shown to be a good alternative. This includes traveling wave-based distance protection elements, which require neither communication links nor data synchronization systems. Even so, traveling wave-based functions commonly face the challenge of distinguishing wavefronts reflected from the fault and other transmission line terminals (SAHA; IZYKOWSKI; ROSOLOWSKI, 2010).

The first works focused on traveling wave-based protection principles were published in the 1970s (TAGAGI et al., 1977; DOMMEL; MICHELS, 1978; CHAMIA; LIBERMAN, 1978; JOHNS, 1980). These works mainly investigated the fault directionality employing the voltage and current traveling wave polarities using one terminal. However, unit protection could be implemented using the fault directionality information from both line terminals. However, a communication link between them was required. Crossley and McLaren (1983), Christopoulos, Thomas and Wright (1988), Shehab-Eldin and McLaren (1988) were the first to publish transmission line distance protection methods based on traveling waves and using one terminal without the need for a communication system. Besides the traveling wave polarities and amplitude, these one-terminal protection techniques used the time instant when the traveling waves reached the local line terminal. However, they depended on the correct detection of the wavefront reflected from the fault point, which is still a challenging task today. Reliability problems, such as low sampling frequency available for hardware and limitations in the signal-processing techniques limited the application of these works.

The advances in high-frequency sampling devices have improved the effectiveness of traveling wave-based functions over the years. From the late 1990s, relevant works on traveling waves were published focusing mainly on transmission line fault location (MAGNAGO; ABUR, 1998;
1.1. HVAC SYSTEM

THOMAS et al., 2004). Considering the experience gained over the years on traveling wave-based fault analysis, the attention of relay developers has switched to traveling wave-based ultra-high-speed transmission line protection studies. Dong et al. (2016) proposed a practical method to detect faults on transmission lines based on the polarity analysis of voltage and current traveling waves. Tang et al. (2017) presented a differential protection using equivalent traveling waves. Using the arrival time of current traveling waves and their respective polarities at both line ends, a technique for detecting internal faults and the directionality of forward and reverse faults is proposed by Namdari and Salehi (2017). However, these solutions may fail in close-in fault cases since successive wave reflections can reach the monitored line end within a time period smaller than the data window applied in traveling wave filtering techniques, jeopardizing the detection of traveling waves reflected from the fault. The influence of the sampling frequency in line protection is evaluated by Costa et al. (2017), making it possible to define unprotected zones, within which a fault will never be detected as internal, and protected zones, within which a fault will always be detected as internal. However, this function depends on two-terminal measurements, requiring dedicated communication links and data synchronization.

Although one-terminal traveling wave-based functions are easy to apply in the field, they are less used than two-terminal approaches, mainly due to difficulties in identifying the reflection that comes from the fault point. To properly do so, cross-correlation was applied by Crossley and McLaren (1983), and a technique dependent on line parameters that analyzes the amplitude of traveling waves was proposed by Christopoulos, Thomas and Wright (1988). The traveling wave polarity was investigated by Dong, Ge and Xu (1999) to solve this problem. However, none of the existing techniques reached high levels of accuracy. Thus, further developments have been pursued toward finding solutions irrespective of the analysis of reflected wavefronts. Indeed, some techniques analyze the first incident aerial (alpha) and ground (zero) mode traveling waves rather than the incident and reflected alpha-mode (α-mode) waves in earth fault cases.

Magnago and Abur (1998) used modal traveling waves to differentiate faults between phases from earth faults in a two-terminal fault location method. Abur and Magnago (2000) proposed a one-terminal method based on the arriving instants of the modal traveling waves and the first α-mode traveling wave reflection to pinpoint earth faults. Nonetheless, using only the first wavefront of modal traveling waves, this method can identify whether the fault is within the first or second half of the transmission line. Moreover, an earth fault location method based on the arriving instants of modal waves was also proposed (LIU et al., 2012). However, this method demands multi-measuring points and communication systems. A two-terminal earth fault locator was also proposed (LOPES, 2016). It requires neither settings nor data synchronization, but communication means are still required.

Considering that earth faults represent the majority of fault scenarios on the electrical power system (SAHA; IZYKOWSKI; ROSOLOWSKI, 2010), where 70 to 80% of transmission line faults are single-phase earth faults (GRAINGER; JR., 1994), the methods referenced so far are relevant. Recent patent applications (III; KASZTENNY, 2019b, 2019a) also indicate the potential of traveling wave-based distance protection methods, provided that reliable detections of α-mode waves reflected from the fault point are attained. However, prior works did not investigate the sampling frequency effects on one-terminal traveling wave-based line protection functions.
1.2 HVDC System

The power system is traditionally divided into generation, transmission, and distribution systems. The power generation is mainly centralized and provided by hydroelectric power plants that are far from the load centers. The electric energy is normally delivered to load centers utilizing high-voltage alternating current transmission lines. However, this traditional configuration has several drawbacks, such as the reliability dependence of the entire power system on the concentrated power plant and restrictions according to the environmental condition. Therefore, to overcome these drawbacks, the smart grid concept proposes the diversification and distribution of energy resources, yielding challenges for protecting, controlling, and monitoring the power system (VAAHEDI et al., 2017).

The advent of new technologies, such as the voltage converter coupled with modern communication networks, has enabled the transformation of the traditional power grid into a smart grid (BLOOM et al., 2017). In order to provide the best grid optimization, the smart grid concept directs to the modernization of transmission and distribution systems. This concept leads to the proliferation of renewable energy, distribution of power plants, the resurgence of high-voltage direct current transmission lines, and more (SANTACANA et al., 2010). The smart grid also leads to the reliability and resiliency increasing of the power grid and decreases operating costs and losses. This new reality has faced new challenges related to power grid protection (SHAHIDEHPOUR et al., 2017).

The distributed generation on the smart grid concept is wider than low distances to the load centers. Powerful renewable generation, such as offshore wind farms, may be far distant from the customers, which has demanded the resurgence of HVDC transmission lines. The costs related to the HVDC transmission system implementation have continuously decreased. Moreover, HVDC systems present several technical advantages for long-distance energy delivery compared to HVAC transmission systems (BARNES et al., 2017; BAHRMAN; JOHNSON, 2007).

According to CIGRÉ (2013), a meshed HVDC system can be generally defined as a system composed of multiple converters connected with branches forming at least one mesh, which creates a parallel path. On the other hand, a multi-terminal HVDC system is composed of several converters but without any mesh. Multi-terminal HVDC systems are a viable solution to the integration of growing renewable energy, such as offshore wind farms. These systems present several advantages, such as interconnection flexibility, efficiency, power supply reliability, and capacity to absorb and consume large amounts of renewable energy. Meshed HVDC systems present all these advantages but with redundancy and higher availability. A parallel path can ensure transmission continuity if a branch is disconnected in a meshed HVDC system. Conversely, a fault in point-to-point or multi-terminal HVDC systems can reduce or completely interrupt transmission capacity (CIGRÉ, 2018). Therefore, it is expected an increase in the development of meshed HVDC systems in order to interconnect a wide variety of renewable generation into the same HVDC grid and improve the power system reliability (CIGRÉ, 2013).

A natural strategy for developing meshed HVDC systems is to build on point-to-point HVDC systems already in operation. These systems can be interconnected or connected to new systems to be built, creating multi-terminal or meshed HVDC systems. However, building a meshed HVDC grid can be more economical when compared with building multiple individual point-to-point HVDC systems or an overlay HVAC system (CIGRÉ, 2013). The first meshed systems are already implemented or under development (TANG et al., 2015, 2019). Other planning or under development projects predict future expansions to meshed HVDC systems. This is the case for the German HVDC corridors (THOMAS et al., 2016) and the HVDC offshore
1.3. MOTIVATION AND OVERALL PROBLEM

DC (Direct Current) transmission is more vulnerable to faults than AC (Alternating Current) transmission due to low DC-side impedances and sensitive power electronics in the converters (CHANG et al., 2017). Emergent protection solutions based on traveling waves, which have presented several advantages on the AC transmission lines (COSTA et al., 2017), can handle the DC protection challenges (WU et al., 2017). Moreover, the availability of the power system can also be improved by accurate fault location since it reduces the maintenance staff searching area and, consequently, the total time for the transmission line recovery. Fault location methods based on traveling waves also presented a good performance for HVDC systems (NANAYAKKARA; RAJAPAKSE; WACHAL, 2012).

The protection traditionally clears the fault by the AC-side circuit breakers for point-to-point or multi-terminal HVDC systems. This strategy would lead healthy DC lines to be out of operation for meshed HVDC grids. This would cause the loss of the advantage of higher availability. For systems with full bridge converters, it is also possible to control the fault current to zero. However, the power flow through healthy sections would also be interrupted for a meshed system. A fully selective fault-clearing strategy could be performed through HVDC circuit breakers at the line terminals. In this way, continuous operation of the HVDC meshed grid would be ensured, as only the faulty section would be isolated. In addition, this would minimize the constraints of the AC grid.

The differential protection of HVDC lines has a prolonged response time due to the telecommunication system. It is, therefore, mainly employed as protection for high-impedance faults or as a backup. Thus, selective fault clearing would hardly be achieved on time for a meshed system with several HVDC breakers (CIGRÉ, 2018). The protection of a meshed system could hardly be based solely on communication-dependent functions at the risk of the short-circuit current exceeding the threshold for opening the HVDC breaker. Therefore, it is necessary that each station is able to determine if and which local HVDC breakers should be tripped using only local measurements (CIGRÉ, 2018).

The sampling frequency effect can significantly influence the protection method based on traveling waves, as demonstrated by Costa et al. (2017) for two-terminal methods. However, this effect has not been evaluated to one-terminal techniques, as well as it was not evaluated to HVDC system methods. Therefore, it is necessary to evaluate the influence of the sampling frequency and to equate its effects in detecting the arrival time of the wavefronts in order to develop one-terminal techniques to HV AC and HVDC transmission lines effectively.

1.3 Motivation and Overall Problem

The primary motivation for developing this work is reducing the protection operation time since it results in a lower risk to the system components and greater power transmission capacity through the transmission lines. Another relevant motivation is the need to analyze the effects of the sampling frequency and its influence on the reliability of the protection, including the definition of a protection zone, which facilitates its real-world application. The evaluation of the effects of errors in the traveling wave velocity estimations is also a strong motivation for developing this work since methods based on traveling waves usually present relevant sensitivity to wave velocity variations.

For meshed HVDC systems, there is a demand for the development of faster protections than those embedded in traditional point-to-point HVDC systems. Furthermore, with the inclusion of several interconnected lines in the HVDC system, there is also a need for selectivity of
1.4 RESEARCH QUESTIONS

This thesis investigates research questions for HVAC/DC protection. Specifically, for AC protection, they are:

1. Can traveling waves be used to speed up transmission line traditional protection?
2. Can protection zones be accurately defined regardless of traveling wave speed estimation errors?
3. Can this traveling wave-based protection function be easily parameterized, independent of the electrical parameters of the transmission lines?

For DC protection, they are:

1. Can traveling waves be used for meshed HVDC transmission line protection?
2. Can this protection function ensure full selectivity?
3. Can it operate within 2 ms according to foreseen CIGRE requirements?

1.5 Objectives

This work’s general objective is to develop one-terminal traveling wave-based protection and fault location for both HVAC/DC transmission lines.

The specific objectives for HVAC protection are:

- development of a protection method based on modal traveling waves to avoid the need for detection of wave reflections;
- development of a protection function based on the reflection of traveling waves independent of telecommunication, but applied only to point-to-point systems.

The specific objective for HVDC protection is:

- evaluation of the applicability of distance protection based on modal traveling waves for HVDC meshed systems.

1.6 Target Protection Functionalities

The target functionalities for the proposed wave-based HVAC transmission line protection for earth faults are:

- no need for detection of wave reflections;
- protection operation time below 2 ms;
- precise definition of the protection zone;
- definition of allowed error margins for the wave velocity estimation;
- easy protection parametrization.

For the proposed HVAC transmission line protection based on the reflection of traveling waves:
• application limited to a point-to-point transmission line;
• detection of the reflected traveling wave to avoid the need for telecommunication;
• precise definition of protection zones;
• no need for wave velocity estimation;
• low sampling frequency requirements, e.g., 6 and 15 kHz;
• easy protection parametrization.

For the proposed meshed HVDC transmission line protection:

• application limited to pole-to-ground faults;
• full selectivity only with local measurements and independent of the system topology;
• reliable definition of the protection zone;
• operation time below 2 ms;
• protection threshold parametrization independent of transmission line electrical parameters and based only on simple detection of local transients;
• low sampling frequency requirements, e.g., 25 kHz, available in real HVDC systems.

1.7 Literature Contribution

The publications referent to this work and to works in a partnership are presented in Tables 1.1 and 1.2.
Table 1.1: Literature contribution for journal papers.

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<th>Journal/Event</th>
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<th>Authors</th>
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<tr>
<td>To be defined - 2023</td>
<td>Applicability of Wave-based Distance Protection for Earth Faults Applied to Meshed HVDC Systems*</td>
<td>R. L. S. França, F. B. Costa, K. Strunz, and F. V. Lopes</td>
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*To be submitted.
## 1.7. LITERATURE CONTRIBUTION

### Table 1.2: Literature contribution for conference papers.

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<th>Authors</th>
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<tr>
<td>XXIII Brazilian Congress on Automation (CBA) - 2020</td>
<td>Analysis of an Eolic-Photovoltaic Hybrid Generation with Synchronverter for Frequency and Voltage Supports in a Microgrid</td>
<td>M. S. Santos, L. S. Barros, R. L. S. França, F. B. Costa, C. M. V. Barros, and K. Strunz</td>
</tr>
<tr>
<td>Brazilian Symposium on Electrical Systems (SBSE) - 2018</td>
<td>Graphical Interface to Aid in Development of Travelling-Wave-Based Line Protection and Fault Location Techniques</td>
<td>S. S. B. Azevedo, F. B. Costa, M. S. R. Leal, R. L. S. França</td>
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1.8 Work Methodology

This work has been carried out in compliance with the following methodology:

- a historical bibliographic review of the published protection and fault location methods for transmission lines was carried out. Then, the state-of-the-art survey was carried out on the latest and most relevant works on developing traveling wave methods for AC and DC transmission lines.
- a mathematical investigation was developed in order to evaluate the effects of the sampling frequency and the traveling wave velocity estimations resulting in: the development of two AC one-terminal protection methods; one distance protection for meshed HVDC systems;
- computational simulations were performed to evaluate all proposed methods;
- the performance of protection functions provided by a real SEL (Schweitzer Engineering Laboratories)-T400L relay were utilized to evaluate the performance of the proposed AC distance protection for earth faults.

1.9 Work Structure

This work is organized into eight chapters:

- Chapter 1: An introduction and the contextualization related to AC and DC transmission line protection and fault location based on traveling waves are presented.
- Chapter 2: The state-of-the-art referring to the main techniques of protection and fault location on AC transmission lines based on traveling waves is presented.
- Chapter 3: The basic theory of traveling waves is presented.
- Chapter 4: The principles of the one-terminal transmission line protection based on reflections of traveling waves and the problem of the detection of the traveling wave reflections are presented.
- Chapter 5: A traveling wave-based AC transmission line earth fault distance protection is proposed.
- Chapter 6: A method of AC transmission line protection based on the first reflection of the traveling wave using one terminal is proposed.
- Chapter 7: A fault localization method using one terminal is proposed. Investigation of the applicability and selectivity of the proposed distance protection applied to meshed HVDC systems.
Chapter 2

State-of-the-Art

This chapter presents a survey of the state-of-the-art of traveling waves, emphasizing fault location and transmission line protection methods using one and two terminals.

2.1 One-Terminal HVAC Traveling-Wave-Based Methods

The first paper to propose a transmission line protection method based on traveling waves using one terminal was published by Crossley and McLaren (1983). The algorithm is based on the principle of distance protection. The wave polarity of the first two waves that reach the local terminal is required to determine fault directionality. The arrival instants of these waves on the local terminal are used to estimate the fault location. Therefore, an internal fault may be detected based on its location. The method depends on correctly detecting the wave reflected from the fault point. It utilizes a cross-correlation technique in order to accomplish this task. However, correctly detecting the wave reflected from the fault point is still challenging today. The method also depends on the wave velocity estimation, which may lead to a protection maloperation depending on the error in this estimation. The voltages measurement is required, which is a limitation of the method due to the poor frequency response of the CCVT (Coupling Capacitor Voltage Transformer) to high-frequency signals. Posteriorly, improvements on this method were proposed by Rajendra and McLaren (1985). However, the main limitations could not be suppressed.

Christopoulos, Thomas and Wright (1988) propose a one-terminal transmission-line distance protection method based on traveling waves, where the detection of the polarity of the first wave on currents and voltages to reach the local bus are required in order to detect the fault directionality. The fault location is estimated from the arrival instants of the first wave to reach the local bus and its reflection from the fault point. The method requires estimating the electrical parameter of the transmission line and measuring the amplitude of the waves in the voltages to detect the correct wave reflected from the fault point. Therefore, errors in the electrical parameters estimation and the poor frequency response of the CCVT are limitations for the method in a field application.

A further investigation of the cross-correlation technique was carried out by Shehab-Eldin and McLaren (1988). The paper demonstrated that the greater the window of the cross-correlation function, the smaller the chances to distinguish between the wave reflected from the fault point and the wave reflected from another discontinuity. Conversely, the smaller the window, the greater the chances of a protection maloperation due to a non-fault transient. Therefore, the paper proposed a composed correlation, where the sum between the output signals from a correlation with a short window and another with a long one is performed. The proposed technique can identify when an internal fault occurs very close to the local bus since a high DC (Direct
Current component occurs in the output signal of the correlation. The method presents difficulty in detecting traveling waves from low fault inception angles. However, a correction factor dependent on the fault inception angle may be applied to the correlation signal, which improves the detection ability of the method. The fault inception angle may be estimated. Despite the proposed improvements to the cross-correlation technique, correctly detecting the wave reflected from the fault point is still challenging today.

One of the first works to apply the wavelet transform to the electrical power system was proposed in the late 1990s (MAGNAGO; ABUR, 1998). The paper proposed a one and two-terminal fault location method based on traveling waves. The synchronized arrival instants of the first wavefront to reach each line terminal are required to estimate the fault location. The fault location may also be estimated by using one terminal. In order to do so, the amplitude of the wavelet coefficients of the aerial and ground modal traveling waves in the voltage signal is utilized to detect the correct wave reflected from the fault point. However, as currently well known, the amplitude of the wavelet coefficients of the reflected waves strongly depends on the electrical parameters of the monitored and adjacent transmission lines, fault resistance, fault inception angle, and impedances connected to the line terminals. Therefore, the proposed method may not apply to power systems other than the one in which it was evaluated. The method requires wave velocity estimation, a source of errors, and data synchronization, which makes the communication system more expensive. When using one terminal, the method requires voltage measurements of successive reflected waves, which is a substantial limitation since the CCVT presents a poor frequency response.

A one-terminal fault location method based on traveling waves was proposed by Abur and Magnago (2000). The arrival instants of the aerial and ground mode traveling waves in the local bus are required to determine if the fault is in the first or second half of the monitored transmission line. In the local bus, the arrival instant detection of the aerial mode wave reflected from the fault point is used to estimate the earth-fault location more precisely. Since there is no ground mode traveling waves, the method cannot distinguish if the fault was in the first or second half of the line to phase-to-phase and three-phase faults. The wave velocity estimation is required, a source of errors for the correct fault location estimation.

A traveling-wave-based transmission line directional protection method was proposed by Chen et al. (2003). The work uses the modulus maxima technique for the detection of traveling waves. The polarities of the first wavefront on the voltage and current signals are used to determine the fault directionality. Chen et al. (2003) demonstrated that the effect of noise could be mitigated by filtering the signal on more than one scale of the wavelet transform. However, this procedure may result in a time delay in detecting the traveling waves. The paper proved that, even with the use of CCVT in the measurement, the polarity detection of the first wavefront in the voltage signal could be accomplished appropriately. Using the modulus maxima technique provided robustness to the method even with noise. The method presents difficulties in detecting traveling waves generated by faults with low inception angles, which can prevent the protection for phase-to-ground faults.

Thomas et al. (2004) proposed a one-terminal traveling-wave-based transmission line fault location method. The method provides fault pre-location information for methods based on cross-correlation. The method applies the wavelet transform at various scales to the current signal to furnish a signal with a precise detection of the traveling waves. The method does not solve the problem of distinguishing the correct wavefront reflected from the fault point. However, it can estimate two possible fault locations, nearest to the local bus or nearest to the remote bus. Since the ideal definition of the cross-correlation window size requires the fault location information, the pre-location estimation provided by the method proposed by Thomas
et al. (2004) facilitates the definition of this size. However, the window size cannot be precisely defined since the method cannot determine if the fault occurred in the first or second half of the transmission line. The method requires the detection of the two first wavefronts to reach the local bus. It assumes that the second wavefront is reflected in the fault point or the remote terminal of the monitored transmission line. Nevertheless, the method will not work properly if a wave reflected from an adjacent line terminal reaches the local bus before the desired reflected wave.

Lin et al. (2012) proposed a fault location method based on traveling waves using one terminal. An evaluation of the variation of the modal parameters of the transmission line as a function of the signal frequency was performed. It was demonstrated that the higher the traveling wave frequency, the greater its velocity and the smaller its amplitude. It has been illustrated that traveling waves suffer attenuation as they propagate along the transmission line. The paper also demonstrated that the higher-frequency components that compose the traveling wave suffer a more significant power attenuation, which makes them more challenging to be detected by a high-frequency filter. The proposed method estimates the frequency of the detected traveling wave. It estimates its propagation velocity as a function of the estimated frequency. Therefore, a different wave propagation velocity is assumed for each wave to reach the local bus. Hence, the fault location can be more precisely estimated. The method requires the polarity detection of the two first wavefronts to reach the local bus to identify if the fault occurred on the first or second half of the line. However, the polarities of the traveling waves vary according to the system’s parameters, so different systems may have different wave polarity patterns, which limits the application of the method. In addition, the method will not work correctly if the first reflected wave to reach the local bus comes from an adjacent transmission line terminal.

2.2 Two-Terminal HVAC Traveling-Wave-Based Methods

One of the first works to investigate transmission line protection based on traveling waves was developed by Chamia and Liberman (1978). A two-terminal transmission-line method was proposed. The polarity behavior of the traveling waves in each terminal of the protected transmission line was investigated in the voltage and current signals, considering the pre-fault voltage signal for internal and external faults. It was demonstrated that the polarities of the current and voltage traveling waves present different behavior depending on the measurement position regarding the fault location. The proposed method can detect internal and external faults and their directionality. However, since the method requires voltage measurement, its application was limited by the still incipient signal processing methods available at that time, which presented limitations in detecting the polarity of the traveling waves in voltage signals due to the poor frequency response of the CCVT.

A method of directional protection for transmission lines using two terminals and based on traveling waves was proposed by Johns (1980). The method detects the fault directionality at each terminal of the protected transmission line and, after communication between the two relays, an internal fault can be detected. The directionality of the fault is detected from an equation whose variables are the amplitude data of the first wavefront on the voltage and current signals and the characteristic impedance value of the protected line. Since the characteristic impedance is a value that must be estimated typically from the physical data of the transmission line, this is an error source. The amplitude data of the voltage and current waves depend on transducer measurements, so if the transducer does not present a reliable high-frequency response, as in the case of CCVT, the method may malfunction since the amplitudes of the signals will suffer distortion.
Liu et al. (2012) proposed an earth-fault location method based on modal traveling waves using multiple measurement points, at least two. From the difference between the arrival time of the air and ground modal waves at each measurement point distributed along the line, the method can estimate a mean fault location point according to the estimated velocities of the traveling waves. The paper demonstrated that the propagation velocity of the ground-mode traveling wave varies according to the fault location. To overcome this problem, the paper proposes to computationally model the system and simulate several fault points along the line to estimate the traveling wave velocity in the ground mode as a function of the fault location. Although the method does not require synchronism, it requires several measuring points and a communication system that connects all of them, which could make its implementation unfeasible. In addition, the method’s effectiveness in the field depends on the reliability of the existing system computationally modeled.

A fault location method based on traveling waves using two terminals was proposed by Lopes et al. (2015). Although the proposed method requires communication between the two terminals of the monitored transmission line, it does not require data synchronization between the relays, i.e., the line terminals do not need to be within the same time frame. The paper investigates the latency in the processing and sending of data between the line terminals. Thus, the method does not require the arrival time of the waves in each terminal, but rather the difference between the arrival times of the first wavefront in each terminal, thus making it possible to locate a fault within the monitored transmission line. The method can locate faults in data transmission situations with high latency variation.

Schweitzer et al. (2016) implemented in a real system a fault location method based on the arrival instants of the traveling waves in the two terminals of the monitored transmission line. The method uses a high-frequency filter technique known as differentiator-smoother, applied to traveling wave detection since 1985. This technique uses an interpolation process that may reduce the error in detecting the wave arrival instant due to the sampling process. For the implementation of the method in the field, the traveling wave velocity was estimated based on the wave propagation delay along the monitored transmission line, generated from the energization of the remote bus of the monitored line. The reliability of the data synchronization strategy limits the method.

A practical implementation of transmission line directional protection based on traveling waves was developed and applied by Dong et al. (2016). The directionality of the fault is identified by comparing the polarities of the modulus maxima of the first wavefront in the voltage signal with that of the current signal. The work mathematically evaluates the influence of CCVT and CT (Current Transformer) on the measurement of traveling waves. It concludes that the CT correctly measures the wave’s polarity for high frequencies and that the CCVT adequately transfers the voltage to frequencies between 10 Hz and 2 kHz. However, this frequency response cannot be accomplished by most commercial CCVT. Using two terminals, the method can detect internal faults. A prototype was evaluated through laboratory tests and a real 750 kV transmission system. The method worked properly for sampling frequencies of 500 and 20 kHz.

Lopes (2016) developed a method of earth-fault location in transmission lines based on modal traveling waves. The method uses the arrival times of the aerial and ground modal components of the first wavefront of the current signal at each terminal of the monitored transmission line. From the ratio between the difference of the arrival times of the modal waves at each terminal, the proposed method equates the percentage of the line where the fault occurred. The method does not require any electrical parameters data of the power system or wave velocity estimations. The method does not require any setting for the relay, which is a relevant improve-
2.2. **TWO-TERMINAL HVAC TRAVELING-WAVE-BASED METHODS**

ment for a field application since its installation in the power system can be easily performed. The results demonstrated that errors do not influence the method in wave velocity estimation and data synchronization. However, the method assumes that the velocity of the modal traveling waves is constant during their propagation along the transmission line. This may not be true, especially for the ground mode wave, which may suffer a more significant attenuation than the aerial mode wave. Therefore, as with all methods based on traveling waves, the proposed method presents susceptibility to errors for non-homogeneous transmission lines, i.e., when the transmission line presents variations in its electrical parameter along its length.

Costa et al. (2017) proposed a transmission line protection method based on traveling waves using two terminals in which the effect of the sampling frequency was evaluated, which improved its reliability. The method requires the arrival time of the first wavefront in the current signal to reach each terminal of the protected transmission line. It can detect internal faults and the directionality of the external ones. The proposed method breaks the paradigm that methods based on traveling waves require a very high sampling frequency, usually hundreds of kHz, and presented good results at a sampling frequency of 20 kHz. The method equates zones inside the protected line: a protection zone, where all the faults will be detected as internals; uncertainty zones, where the faults may be or may not be detected as internals, depending on the fault inception error; and unprotected zones, where faults will never be detected as internals. For the method, the greater the sampling frequency, the greater the protected zone. In addition, the method is independent of line electrical parameters estimation and does not require wave velocity estimation. However, it is dependent on a synchronization system between the relays.

A method of differential protection of transmission lines based on traveling waves was proposed by Tang et al. (2017). From the principle of superposition, the concept of equivalent traveling waves was used, which are caused by the DC component of the sudden voltage that appears in the fault point soon after the fault. The method applies the modulus maxima technique to the Dyadic wavelet transform of the current signals at each terminal of the monitored transmission line. The modulus maxima data in each line terminal are sent from one to the other. These data are used, in each terminal, in order to reconstruct the equivalent traveling waves of the opposite terminal. Since only a few peak samples of the modulus maxima signal are required, the data transmitted between the terminals is low. This is a significant contribution since the high sampling frequency, normally required for the detection of the traveling waves, would request higher storage capacity of the hardware and a more expensive communication system between the line terminals. Each relay, connected to each terminal of the protected transmission line, has the equivalent traveling wave signal relative to the terminal where it is installed and the equivalent traveling wave signal reconstructed from the opposite terminal. With this, a differential equation is applied between the two signals to detect internal faults. The method depends on the synchronization accuracy between the data of the two relays.

Namdari and Salehi (2017) proposed a transmission line protection method using two terminals. A new high-frequency filter was proposed using morphological mathematics capable of detecting traveling waves and their polarities. From the arrival time and polarity of the first wavefront of the current signal to reach each terminal of the protected transmission line, the proposed protection method can identify whether the fault was internal to the protected line and its directionality. The paper demonstrated that the detection method was more efficient when compared to the wavelet transform. The protection method remained efficient even to fault cases with high fault impedance and low fault inception angle. These factors negatively influence the detection of traveling waves. However, the protection method depends on the wave velocity estimation, usually performed from the transmission line electrical parameter estimations, which is a source of errors.
2.3 State-of-the-Art Summary for HVAC Methods

The state-of-the-art of HVAC methods investigated in this work, in chronological order, is summarized in Tables 2.1 and 2.2, indicating the number of terminals used by the method, the sampling frequency value adopted in the performance assessment of the method, the need for parameter estimations of the monitored transmission line, the need for wave velocity estimations, the need for wave polarity detections, the usage of the modal traveling waves, and, in case of the two-terminal methods, the need for data synchronization.

**Table 2.1: State-of-the-art summary for HVAC one-terminal methods.**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Objective</th>
<th>Freq. (kHz)</th>
<th>Par. Estim.</th>
<th>Wave Vel.</th>
<th>Wave Pol.</th>
<th>Modal Waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crossley and McLaren (1983)</td>
<td>Protection</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rajendra and McLaren (1985)</td>
<td>Protection</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Christopoulos, Thomas and Wright (1988)</td>
<td>Protection</td>
<td>25</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>Shehab-Elidin and McLaren (1988)</td>
<td>Protection</td>
<td>14.25</td>
<td>-</td>
<td>✓</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Magnago and Abur (1998)</td>
<td>Fault Location</td>
<td>100</td>
<td>-</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
</tr>
<tr>
<td>Abur and Magnago (2000)</td>
<td>Fault Location</td>
<td>303</td>
<td>-</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
</tr>
<tr>
<td>Chen et al. (2003)</td>
<td>D. Protection</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>Thomas et al. (2004)</td>
<td>Fault Location</td>
<td>1.25 x 10^3</td>
<td>-</td>
<td>✓</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lin et al. (2012)</td>
<td>Fault Location</td>
<td>10^3</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>-</td>
</tr>
</tbody>
</table>

D. - Directional; Estim. - Estimations; Freq. - Sampling Frequency; Par. - Parameters; Pol. - Polarity; Vel. - Velocity.

**Table 2.2: State-of-the-art summary for HVAC two-terminal methods.**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Objective</th>
<th>Freq. (kHz)</th>
<th>Par. Estim.</th>
<th>Wave Vel.</th>
<th>Data Sinc.</th>
<th>Wave Pol.</th>
<th>Modal Waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chami and Liberman (1978)</td>
<td>Protection</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Johns (1980)</td>
<td>Protection</td>
<td>-</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>Magnago and Abur (1998)</td>
<td>Fault Location</td>
<td>100</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
</tr>
<tr>
<td>Liu et al. (2012)</td>
<td>Fault Location</td>
<td>10^3</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>Lopes et al. (2015)</td>
<td>Fault Location</td>
<td>20</td>
<td>-</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Schweitzer et al. (2016)</td>
<td>Fault Location</td>
<td>1.5 x 10^3</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dong et al. (2016)</td>
<td>Protection</td>
<td>500</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lopes (2016)</td>
<td>Fault Location</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>Costa et al. (2017)</td>
<td>Protection</td>
<td>4</td>
<td>-</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tang et al. (2017)</td>
<td>Protection</td>
<td>250</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Namdari and Salehi (2017)</td>
<td>Protection</td>
<td>10^3</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Estim. - Estimations; Freq. - Sampling Frequency; Par. - Parameters; Pol. - Polarity; Sinc. - Synchronization; Vel. - Velocity.

As shown in Table 2.1, few traveling-wave-based methods developed in recent years use only one terminal. The last one-terminal transmission line protection method based on traveling waves was proposed in 1988 (SHEHAB-ELDIN; MCLAREN, 1988). The main reason for this is the great difficulty in correctly detecting the traveling wave reflected from the fault point, a problem still under investigation by the scientific community. Some methods proposed along the years (MAGNAGO; ABUR, 1998; ABUR; MAGNAGO, 2000; THOMAS et al., 2004; LIN...
2.4. ONE-TERMIAL TRAVELING-WAVE-BASED METHODS FOR MESSED HVDC SYSTEMS

et al., 2012) depend on the correct detection of the wave reflected from the fault point. However, their application is restricted to systems with certain conditions and cannot be applied to all transmission systems. From Table 2.2, most of the recently proposed methods of fault location and transmission line protection based on traveling waves require measurements on both terminals of the monitored transmission line. Only one paper (COSTA et al., 2017) analyzed the effect of the sampling frequency on the effectiveness of the method, which improves its reliability. The same analysis has never been done in any one-terminal method based on traveling waves. Some studies have used the earth modal traveling wave to extract additional information from the fault conditions. However, none of them exploited such phenomenon applied to transmission line protection. Therefore, it is necessary to investigate the effect of the sampling frequency on a one-terminal transmission line protection method based on traveling waves, as proposed in this thesis. In addition, the usage of the earth mode of the traveling wave may avoid the need for detecting the correct traveling wave reflected from the fault point, which would guarantee the reliability required by a protection method.

Many works have been devoted to the development of methods for detecting high-frequency transients (COSTA; SOUZA; BRITO, 2010; LOPES; FERNANDES; NEVES, 2013; COSTA, 2014a; SCHWEITZER et al., 2016; NAMDARI; SALEHI, 2017), which have direct applications for protection based on traveling waves. Therefore, this thesis focuses only on developing a transmission line protection method based on traveling waves without the objective of developing a high-frequency transient detection technique.

2.4 One-Terminal Traveling-Wave-Based Methods for Meshed HVDC Systems

Li, Gong and Jiang (2018) proposed a fault directionality detection method based on the polarity of the traveling waves. The method can detect the directionality of the fault with time under 2 ms for transmission lines up to 200 km and a sampling frequency of 1 MHz. Lower sampling frequencies, up to 50 kHz, have been tested. However, as noted by the authors, the method’s reliability is higher for higher sampling frequencies. This may make the practical implementation of the method more difficult. The method can be selective for faults applied on different transmission lines for a meshed HVDC system. However, it requires communication between stations. As discussed later in this thesis, the need for communication between stations can be limiting for the protection of meshed HVDC systems.

Tang et al. (2019) proposed a one-terminal traveling wave-based protection method for a meshed HVDC system. The method presented total selectivity with low protection operation time, below 1.2 ms for a sampling frequency of 1 MHz and a fault distance of 183.5 km. This is a possible sampling frequency for IEDs dedicated to implementing the method, as demonstrated by the authors in the experimental results. However, in real systems, where each IED is responsible for a vast amount of protection and control functionality, the sampling frequency adopted is much lower, in the order of a few tens of kHz. The method considers boundary conditions for a given system’s topology under study. However, the method was developed for boundary conditions in which all transmission lines are connected to the system. Thus, if the system operates in a different topology, e.g., with a disconnected transmission line, the boundary conditions change and the method can no longer be applied to the new topology.

Tong et al. (2019) proposed a distance protection method for earth faults in HVDC transmission lines. The proposed protection is capable of being selective for a meshed HVDC system without the need for interstation communication. The method is based on the time difference
between the arrival instants of the alpha and zero mode waves. The protection operation time was below 5 ms even for a transmission line of 1000 km in length. However, as the authors state, the minimum sampling frequency for the adopted test transmission system should not be less than 110 kHz. The sampling frequency adopted for the parameterization of the protection was 200 kHz. These sampling frequency values are well above those currently adopted in existing HVDC systems. This represents a limitation for the practical implementation of the method.

Sabug Jr. et al. (2020) proposed a boundary wavelet transform-based protection for meshed HVDC systems. The method uses the real-time boundary wavelet transform (RT-BWT) to compute the energy of transients measured by meters connected between the line inductor and the line. Thus, the authors determine the faulty section by identifying the transients with the highest energy. The method does not require communication between stations, i.e., it relies only on local measurements. Simulation results have shown that the method can perform at a low sampling frequency, 10 kHz. The method presented reliable operation within 7 ms for a transmission line of 450 km in length. This operation time delay may not fulfill future speed requirements for protecting meshed HVDC systems, as further discussed in this thesis. The method is capable of being fully selective for system-wide faults. To do this, thresholds must be defined by comparing the energy of transients for faults applied at various points in the system. However, it is known that transients are strongly affected by the frequency response of the actual meters installed in an existing system. Thus, it is impossible to establish whether the thresholds set for transients presented in simulations would be in accordance with transients measured in a real system. Furthermore, setting thresholds for the energy of fault transients in an existing system would not be a trivial task.

Liu et al. (2021) proposed a protection method based on traveling wave simulation to detect abrupt transients in a meshed HVDC system. The method applies the concept of median absolute deviation on locally measured voltages and currents on each line connected to a given station. The method can be selective for faults applied on all system lines, with operation time below 2 ms for lines up to 200 km. The method was evaluated for a low sampling frequency of 10 kHz. However, to parameterize the method to be fully selective, without communication between stations, it is necessary to define thresholds for the transient variations at each station. These thresholds are defined from comparisons of transients between stations. However, the measurement setup installed in the real system strongly affects current and voltage transients. Thus, the thresholds defined through simulation may not be sufficient for application in the real system. Furthermore, setting these thresholds in a real system may not be feasible since real faults must be applied.

Zhao et al. (2023) proposed a one-terminal method based on the rising time of the traveling wave. The method presented an operating time below 2 ms for a 400 km transmission line. Results showed that the method can perform for frequencies of 20 and 50 kHz, with low sensitivity to the fault resistance. An important criterion for the correct detection of internal faults to guarantee the method’s selectivity is the rising time of the traveling wave. This parameter is defined analytically, considering the fault point and the transmission line parameters. Simulation results have shown that the rising time of the traveling wave for internal faults can be reliably established analytically. However, the authors disregarded the effects that transducers could have on the traveling wave measurement. Thus, the analytically calculated parameters are not reliable enough to apply the method in actual systems.
2.5 State-of-the-Art Summary for HVDC Methods

The state-of-the-art of HVDC methods investigated in this work, in chronological order, is summarized in Table 2.3. The table indicates the minimum sampling frequency used by the method, the protection speed, the longest line length on which the method has been tested, whether modal waves are used, whether there is a need for communication between the stations in order to have full selectivity of the method and the level of difficulty for the selectivity strategy to be applicable in actual systems.

Table 2.3: State-of-the-art summary for HVDC methods.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Samp. Frequency (kHz)</th>
<th>Prot. Speed (ms)</th>
<th>Length (km)</th>
<th>Modal Waves</th>
<th>Tel.</th>
<th>Selectivity Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li, Gong and Jiang (2018)</td>
<td>50</td>
<td>2</td>
<td>200</td>
<td>-</td>
<td>✓</td>
<td>Easy</td>
</tr>
<tr>
<td>Tang et al. (2019)</td>
<td>1000</td>
<td>1.2</td>
<td>183.5</td>
<td>-</td>
<td>-</td>
<td>Medium</td>
</tr>
<tr>
<td>Tong et al. (2019)</td>
<td>200</td>
<td>5</td>
<td>1000</td>
<td>✓</td>
<td>-</td>
<td>Easy</td>
</tr>
<tr>
<td>Sabug Jr. et al. (2020)</td>
<td>10</td>
<td>7</td>
<td>450</td>
<td>-</td>
<td>-</td>
<td>Hard</td>
</tr>
<tr>
<td>Liu et al. (2021)</td>
<td>10</td>
<td>2</td>
<td>200</td>
<td>-</td>
<td>-</td>
<td>Hard</td>
</tr>
<tr>
<td>Zhao et al. (2023)</td>
<td>20</td>
<td>2</td>
<td>400</td>
<td>-</td>
<td>-</td>
<td>Hard</td>
</tr>
</tbody>
</table>

Samp. - Sampling; Prot. - Protection; Tel. - Telecommunication.

Table 2.3 points out important factors for the applicability of the methods in actual systems. Methods with sampling frequencies up to 50 kHz are in accordance with protection methods applied in actual HVDC systems. Thus, methods that require higher sampling frequencies would be more difficult and costly to apply in actual systems. As discussed later in this thesis, the optimal time for protection operation is below 2 ms. However, since commercial protections can operate below 2 ms without selectivity, there is still an important contribution if the proposed method is capable of being selective within 5 ms. This is the estimated time for fault clearing in meshed HVDC systems. Some methods can operate below 2 ms with low sampling frequency but have practical limitations to be selective in actual systems. One method presents low operation time at low sampling frequency. However, it requires communication between stations to be selective, which will make its operation time infeasible for meshed HVDC systems, as discussed later in this thesis. One method uses modal waves to decrease its complexity for application in actual systems with short operation times. However, it requires a high sampling frequency.

Neither method simultaneously meets the best requirements for applicability in actual meshed HVDC systems. That is, fast operation, low sampling frequency, and easy selectivity strategy to implement in actual systems. None of the methods investigated the effect of sampling frequency on the protection. Such investigation can ensure reliability to the protection at a low sampling frequency. The investigation of the effect of sampling frequency associated with the use of modal waves has the potential to ensure the development of a method that is easy to implement in real systems without the need for communication between stations for earth faults.
Chapter 3

Basic Theory of the Traveling Waves

This chapter presents the principles of the traveling waves theory in single-phase transmission lines, highlighting the basic equation of the transmission line model and the wave propagation equations in discontinuities.

3.1 Transmission Line Equations

As presented by Araújo and Neves (2005), for a given transmission line with inductance $L$, capacitance $C$, resistance $R$, and conductance $G$, all per unit length, the time domain transmission line equations are given by:

\[-\frac{\partial u(x,t)}{\partial x} = R i(x,t) + L \frac{\partial i(x,t)}{\partial t},\]  
\[-\frac{\partial i(x,t)}{\partial x} = G u(x,t) + C \frac{\partial u(x,t)}{\partial t},\]

(3.1) (3.2)

where $u(x,t)$ and $i(x,t)$ are the voltage and current in the line at instant $t$ and position $x$. In the frequency domain, the equations of the transmission line become:

\[-\frac{\partial U(x,s)}{\partial x} = (R + sL) I(x,s),\]  
\[-\frac{\partial I(x,s)}{\partial x} = (G + sC) U(x,s),\]

(3.3) (3.4)

where $U(x,s)$ e $I(x,s)$ are, respectively, the Laplace transform of $u(x,t)$ and $i(x,t)$.

From the transmission line equations, the wave equations are:

\[\frac{\partial^2 U(x,s)}{\partial x^2} = \gamma^2 U(x,s),\]  
\[\frac{\partial^2 I(x,s)}{\partial x^2} = \gamma^2 I(x,s),\]

(3.5) (3.6)

where $\gamma$ is the propagation constant of the transmission line, given by

\[\gamma = \sqrt{(R + sL)(G + sC)} = \alpha + j\beta,\]

(3.7)

composed of a real part ($\alpha$), called line attenuation constant, and an imaginary part ($\beta$), called line phase constant.
3.2. WAVE PROPAGATION IN DISCONTINUITIES

The general solution of the wave equations (3.5) and (3.6) results in:

\[
U(x,s) = U_0^+ e^{-\gamma x} + U_0^- e^{\gamma x},
\]

(3.8)

\[
I(x,s) = I_0^+ e^{-\gamma x} + I_0^- e^{\gamma x},
\]

(3.9)

where \(e^{-\gamma x}\) represents the wave propagation in the positive direction of \(x\), and \(e^{\gamma x}\) represents the wave propagation in the negative direction of \(x\). From the general solution of the wave equations

\[
\frac{U_0^+}{I_0^+} = \frac{-U_0^-}{I_0^-} = Z_0,
\]

(3.10)

where \(Z_0\) is the characteristic impedance of the transmission line, given by

\[
Z_0 = \sqrt{\frac{(R + sL)}{(G + sC)}}.
\]

(3.11)

Therefore, the equation (3.9) can be rewritten as

\[
I(x,s) = \frac{U_0^+}{Z_0} e^{-\gamma x} - \frac{U_0^-}{Z_0} e^{\gamma x}.
\]

(3.12)

Considering a lossless transmission line \((R = G = 0)\), \(\gamma = s\sqrt{LC}\) e \(Z_0 = \sqrt{L/C}\), the equations (3.8) and (3.12) become:

\[
U(x,s) = U_0^+ e^{-\frac{s}{u} x} + U_0^- e^{\frac{s}{u} x},
\]

(3.13)

\[
I(x,s) = \frac{U_0^+}{Z_0} e^{-\frac{s}{u} x} - \frac{U_0^-}{Z_0} e^{\frac{s}{u} x},
\]

(3.14)

where \(u\) is the wave velocity propagation, given by

\[
v = \frac{1}{\sqrt{LC}}.
\]

(3.15)

3.2 Wave Propagation in Discontinuities

Figure 3.1 depicts a power system with two transmission lines, line 1 and line 2, with distinct characteristic impedances \((Z_1 \neq Z_2)\), with a relay installed between them. There is a fault in line 1 and the occurrence of traveling waves. Some of their respective reflections and refractions at the discontinuity points are represented in the Lattice diagram. In the Lattice diagram, the arrival time of the first wave to reach the bus 2 is also illustrated. It is represented by \(t_2^1\) and some of the other arrival times in all buses. The propagation times of a traveling wave along transmission lines 1 and 2 are, respectively, \(\tau_1\) and \(\tau_2\).

3.2.1 Reflections and Refractions of the Wave

When a fault occurs on line 1, traveling waves in voltages and currents \((u_1\) and \(i_1))\) propagate along both directions of the line from the fault point. As demonstrated by Christopoulos, Thomas and Wright (1988), the amplitudes of these waves are given by:

\[
u_1 = \frac{Z_1}{Z_1 + 2R_f} u_f,
\]

(3.16)
3.2. WAVE PROPAGATION IN DISCONTINUITIES

![Figure 3.1: Lattice diagram of the traveling waves for a fault.](image)

\[ i_1 = -\frac{u_1}{Z_1} = \frac{1}{Z_1 + 2R_f} u_f, \]  
(3.17)

where \( R_f \) is the fault resistance, \( u_f \) is the instantaneous voltage at the fault point at the fault instant, and \( Z_1 \) is the characteristic impedance of line 1.

Traveling waves in the voltage and current signals \( u_1 \) and \( i_1 \) propagate towards line 2 and, when reaching bus 1, suffer reflection \( (u_r, i_r) \) and refraction \( (u_t, i_t) \). The reflected waves propagate back toward the fault point, and the refracted waves follow along line 2. As demonstrated by Bewley (1931), the reflected waves are given by:

\[ u_{r1} = \Gamma_{r1(U)} u_1, \]  
(3.18)

\[ i_{r1} = \Gamma_{r1(I)} i_1, \]  
(3.19)

where \( \Gamma_{r1(U)} \) is the reflection coefficient of the wave in the voltage signal, given by

\[ \Gamma_{r1(U)} = \frac{Z_2 - Z_1}{Z_2 + Z_1}, \]  
(3.20)

and \( \Gamma_{r1(I)} \) is the reflection coefficient of the wave in the current signal, given by

\[ \Gamma_{r1(I)} = -\Gamma_{r1(U)} = \frac{Z_1 - Z_2}{Z_1 + Z_2}, \]  
(3.21)

whereas the refracted waves are given by:

\[ u_{t1} = \Gamma_{r1(U)} u_1, \]  
(3.22)

\[ i_{t1} = \Gamma_{r1(I)} i_1, \]  
(3.23)

where \( \Gamma_{r1(U)} \) is the refraction coefficient of the wave in the voltage signal, given by

\[ \Gamma_{r1(U)} = 1 + \Gamma_{r1(I)} = \frac{2Z_2}{Z_1 + Z_2}, \]  
(3.24)
3.2. WAVE PROPAGATION IN DISCONTINUITIES

and \( \Gamma_{i1(t)} \) is the refraction coefficient of the wave in the current signal, given by

\[
\Gamma_{i1(t)} = 1 + \Gamma_{r1(t)} = \frac{2Z_1}{Z_1 + Z_2}. \tag{3.25}
\]

The reflected waves in bus 1 \((u_{r1} \text{ and } i_{r1})\) propagate back toward the fault point. When reaching the discontinuity point of the fault, new reflected waves \((u_{r2} \text{ and } i_{r2})\) and refracted waves \((u_{t2} \text{ and } i_{t2})\) arise. The reflected and refracted voltage waves at the fault point are given by:

\[
u_{r2} = \Gamma_{r2(U)} u_{r1}, \tag{3.26}
\]

\[
u_{t2} = \Gamma_{t2(U)} u_{r1}, \tag{3.27}
\]

where \( \Gamma_{r2(U)} \) is the reflection coefficient of the wave in the voltage signal, given by

\[
\Gamma_{r2(U)} = \frac{Z_1 R_f}{Z_1 + R_f} - \frac{Z_1}{Z_1 + R_f}, \tag{3.28}
\]

and \( \Gamma_{t2(U)} \) is the refraction coefficient of the wave in the voltage signal given by

\[
\Gamma_{t2(2)} = \frac{2Z_1 R_f}{Z_1 + R_f}. \tag{3.29}
\]

The current waves reflected and refracted at the fault point along the remainder of the line are given by:

\[
i_{r2} = \Gamma_{r2(t)} i_{r1}, \tag{3.30}
\]

\[
i_{t2} = \Gamma_{t2(t)} i_{r1}, \tag{3.31}
\]

where \( \Gamma_{r2(t)} \) is the reflection coefficient of the wave in the current signal, given by

\[
\Gamma_{r2(t)} = -\Gamma_{r2(U)} = \frac{Z_1 - \frac{Z_1 R_f}{Z_1 + R_f}}{Z_1 + \frac{Z_1 R_f}{Z_1 + R_f}}, \tag{3.32}
\]

and \( \Gamma_{t2(t)} \) is the refraction coefficient of the wave in the current signal that propagates toward the rest of the line, given by

\[
\Gamma_{t2(t)} = \frac{2R_f}{Z_1 + 2R_f}. \tag{3.33}
\]

According to Christopoulos, Thomas and Wright (1988), a relay installed in the bus 1 is not able to measure the incident waves \((u_1 \text{ and } i_1)\) and the reflected waves \((u_{r1} \text{ and } i_{r1})\) separately. As the relay is normally installed a few meters from the bus, when a traveling wave reaches the relay at speed close to the speed of light, its reflection occurs soon after. In this way, when a traveling wave reaches the bus, due to the sampling process, the signal collected by the relay is the sum between the incident and reflected waves in the bus. The traveling wave equations measured by the relay are given by:

\[
u_{s1} = u_1 + u_{r1} = u_1 (1 + \Gamma_{r1(U)}) = \frac{2Z_2 u_1}{Z_2 + Z_1}, \tag{3.34}
\]
3.3 Modal Components

In studying traveling waves in transmission lines, it is important to analyze the voltage and current signals considering the electromagnetic coupling between the phases. Thus, for studying traveling waves, the voltage and current signals measured on phase components should be transformed into independent modal components. Clarke’s transformation (CLARKE, 1938) can be used for this purpose. The matrix adopted for Clarke’s transformation was the same published by Namdari and Salehi (2017), as follows:

\[
\begin{bmatrix}
u_0 \\
u_\alpha \\
u_\beta 
\end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ \sqrt{2} & -1 & \sqrt{2} \\ 0 & \sqrt{3} & -\sqrt{3} \end{bmatrix} \begin{bmatrix} u_A \\
u_B \\
u_C 
\end{bmatrix},
\] (3.36)

and

\[
\begin{bmatrix}
i_0 \\
i_\alpha \\
i_\beta 
\end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ \sqrt{2} & -1 & \sqrt{2} \\ 0 & \sqrt{3} & -\sqrt{3} \end{bmatrix} \begin{bmatrix} i_A \\
i_B \\
i_C 
\end{bmatrix},
\] (3.37)

where \(u_A, u_B, u_C, i_A, i_B, \) and \(i_C\) are the voltages and currents in the phase domain; \(u_0, u_\alpha, u_\beta, i_0, i_\alpha, \) and \(i_\beta\) are the voltages and currents in zero, alpha, and beta modal components, respectively. In this way, each modal component behaves as a single-phase circuit signal. This work will always analyze the traveling waves in the alpha or zero mode signals.

Similarly, during a fault transient, a bipolar or symmetric monopolar HVDC system can be seen as a two-phase system. Thus, it is possible to apply a modal decoupling transformation designed for two-phase systems to these systems (FERNANDES et al., 2020). This thesis will apply the Karrenbauer transformation to the voltages and currents of HVDC systems. The modal components of the Karrenbauer transformation are given by:

\[
\begin{bmatrix} u_0 \\
u_\alpha 
\end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} u_+ \\
u_- 
\end{bmatrix},
\] (3.38)

and

\[
\begin{bmatrix} i_0 \\
i_\alpha 
\end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} i_+ \\
i_- 
\end{bmatrix},
\] (3.39)

where \(u_+\) and \(u_-\) are the positive and negative pole voltages; \(i_+\) and \(i_-\) are the positive and negative pole currents; \(u_0, u_\alpha, i_0, \) and \(i_\alpha\) are the voltages and currents in zero and alpha modal components, respectively.

3.4 Chapter Synthesis

In this chapter, the theoretical basis of traveling waves was presented, and the equations of the single-phase transmission line model were demonstrated. The line equations, the characteristic impedance of the line, and the traveling wave velocity to a lossless line were deducted. The propagation equations of the traveling waves along the transmission line were also presented. The reflection and refraction equations of the waves in the fault point and the line
connections were demonstrated. It also presented the equations of the waves seen by a relay installed between two transmission lines. Finally, a brief discussion was held on modal traveling waves.

The simplified analysis presented in this chapter is sufficient for understanding the methods proposed in this thesis, and it is possible to find a more detailed theory of traveling waves in Zanetta Jr. (2003).
Chapter 4

Principles of the One-Terminal Transmission Line Protection Based on Reflections of the Traveling Waves

This chapter presents the principles of one-terminal transmission line protection based on reflections of traveling waves. It also presents the main problems identified for correctly detecting the traveling wave reflected from the fault point, an issue still under investigation by the scientific community.

4.1 Traveling Wave Reflections

Figure 4.1 depicts the general behavior of traveling wave reflections. When a fault occurs on the transmission line, traveling waves propagate toward the line terminals, suffering reflection and refraction. The reflected waves propagate back toward the fault point, whereas the refracted waves propagate toward the terminal of an adjacent transmission line. New reflections and refractions occur when the traveling waves reach the fault point or other line terminals. A relay may detect traveling waves that reach a terminal of the protected transmission line and identify whether an internal fault occurred on the protected line. As detailed in the following sections, internal fault detection can be performed from detecting the arrival instants of the traveling waves on one terminal of the protected transmission line.

4.1.1 Traveling Wave Reflections for a Simple Line

Figure 4.2 depicts a fault in the first half of a simple line (without adjacent lines), with a fault inception time $t_F$ and distanced $d_F$ from the local bus, where $d_F = d_x$ and $d_F < l/2$. Thus, the second wavefront will always come from a reflection at the fault point, so the propagation times of the first and second wavefronts are given respectively by:

$$\tau_{F1} = t_{F1} - t_F = \frac{t_{F2} - t_{F1}}{2} = \frac{d_F}{v},$$  \hspace{1cm} (4.1)

$$\tau_{F2} = t_{F2} - t_F = \frac{t_{F2} - t_{F1}}{2} = \frac{3d_F}{v},$$  \hspace{1cm} (4.2)

where $v$ is the speed of the traveling wave; $t_{F1}$ and $t_{F2}$ are the arrival times of the first and second wavefronts, respectively, at the local bus.

Figure 4.3 depicts a fault in the second half of the line ($d_F > l/2$), distanced $d_x$ from the
4.1. TRAVELING WAVE REFLECTIONS

![Diagram of Traveling Wave Reflections]

Figure 4.1: General behavior of the traveling wave reflections.

![Diagram of Fault Reflections]

Figure 4.2: Lattice diagram to a fault in the first half of the transmission line.

remote bus and $d_F$ from the local bus, where $d_F = l - d_x$. Therefore, the second wavefront will always come from a reflection on the remote bus. Thus, the propagation times of the first and second wavefronts are given respectively by:

$$\tau_{F1} = t_{F1} - t_F = \frac{l}{v} - \frac{t_{F2} - t_{F1}}{2} = \frac{d_F}{v}, \quad (4.3)$$

$$\tau_{F2} = t_{F2} - t_F = \frac{l}{v} + \frac{t_{F2} - t_{F1}}{2} = \frac{2l - d_F}{v}. \quad (4.4)$$

According to equation (4.1), the distance between the local bus and a fault in the first half of the line is given by

$$d_F = d_x = (t_{F1} - t_F)v = \frac{(t_{F2} - t_{F1})v}{2}, \quad (4.5)$$

whereas, according to the equation (4.3), the distance between the local bus and a fault in the
second half of the line is given by

\[ d_F = l - d_x = (t_{F1} - t_F) v = l - \frac{(t_{F2} - t_{F1}) v}{2}. \quad (4.6) \]

From the equations (4.5) and (4.6), for two distinct faults, one in the first half of the line, at a distance \( d_x \) from the local bus, and the other in the second half of the line, distanced \( d_x \) from the remote bus and \( l - d_x \) from the local bus, the difference between the arrival times of the first and second wavefronts \( (t_{F2} - t_{F1}) \) are equal. Therefore, at first, it would not be possible to identify whether a fault occurred on the first or second half of the transmission line only from the arrival times of the traveling waves.

The propagation time of the traveling wave along the entire transmission line (transit time) with length \( l \) is given by

\[ \tau = \frac{l}{v}. \quad (4.7) \]

For faults in the first half of the line, the difference between the arrival times of the first and second wavefronts in the local bus is less than one transit time since the arrival time of the second wavefront is due to the reflected wave from the fault point (Figure 4.2). Regarding the faults in the second half of the line, the difference between the arrival times of the first and second wavefronts in the local bus is also smaller than one transit time since the arrival time of the second wavefront is due to the reflected wave from the remote bus of the transmission line (Figure 4.3). The maximum difference between the arrival times of the first two wavefronts on the local bus occurs for a fault in the middle of the line. Therefore, internal faults are detected if

\[ t_{F2} - t_{F1} \leq \frac{l}{v}. \quad (4.8) \]

Figure 4.4 depicts a fault exactly on the remote bus (external fault). In this situation, the first wavefront will reach the local bus after a transit time \( \tau \) and will be reflected back toward the remote bus, where it will undergo further reflection and propagate again toward the local bar. Therefore, the difference between the arrival times of the first and second wavefronts, due
to a fault in the remote bus, is given by

\[ t_{F2} - t_{F1} = \frac{2l}{v}. \]  

(4.9)

For a fault exactly in the local bus, the time difference between the first and second wavefronts is also given by the equation (4.9).

![Lattice diagram for a fault on the remote bus.](image)

According to equations (4.8) and (4.9), the difference between the arrival times of the first two wavefronts will never be in the range \( l/v < t_{F2} - t_{F1} < (2l)/v \). It is possible to adopt a threshold for detecting internal faults with no detriment to the protection method, considering only the continuous time domain. Therefore, it is proposed that an internal fault is detected if

\[ t_{F2} - t_{F1} \leq \frac{l}{v}, \]

(4.10)

where \( q \) is a threshold to ensure that an internal fault is properly differentiated from an external fault, attending to

\[ \frac{l}{v} \leq \frac{q l}{v} < \frac{2l}{v}, \]

(4.11)

where \( 1 \leq q < 2 \).

### 4.1.2 Traveling Wave Reflections Including Adjacent Lines

The protection scheme must distinguish between internal and external faults to avoid a false trip due to a fault outside the protected line. Traditionally, the two-terminal methods based on traveling waves require only the first wavefront to reach each terminal of the monitored transmission line, i.e., wave reflections are not required. However, more than the first wavefront is required for the correct protection performance for one-terminal methods based on traveling
4.1. TRAVELING WAVE REFLECTIONS

waves. Therefore, the protection scheme reliability of one-terminal methods is dependent on the reliability of the correct detection of the reflected traveling waves.

Figure 4.5 depicts an upstream external fault on the external line A, $l_A$ long, distanced $d_x < l$ from the local bus of the protected line. In this fault configuration, the difference between the arrival times of the first two wavefronts to reach the local bus is less than twice the transit time of a traveling wave along the protected line ($t_{F2} - t_{F1} = (2l)/v$). Thus, the equation (4.9) is not respected, i.e., an external fault would be identified as internal, leading to a protection maloperation.

![Figure 4.5: Lattice diagram for an upstream external fault.](image)

The same occurs for a reverse external fault, on the external line B, $l_B$ long, distanced $d_x < l$ from the remote bus of the protected line (Figure 4.6). Therefore, the difference between the arrival times of the first two traveling wavefronts can be the same for at least four different fault scenarios: internal fault at a distance $d_x < l/2$ from the local bus of the protected line (Figure 4.2); internal fault at a distance $d_x < l/2$ from the remote bus of the protected line (Figure 4.2); external fault at a distance $d_x < l$ from the local bus of the protected line (Figure 4.5); external fault at a distance $d_x < l$ from the remote bus of the protected line (Figure 4.6). Therefore, any one-terminal transmission line protection scheme based on traveling waves has to distinguish such fault situations to avoid that external faults being confused with internal ones. A solution to this problem would be the correct detection of the traveling wave reflected from the fault point.

Figure 4.7 depicts another possible situation that could lead to a protection maloperation: a reverse external fault considering the upstream external line (line A) smaller than the protected line ($l_A < l$). In this situation, the instant $t_{F2}$ would be relative to a traveling wave reflected from the terminal end of the external line A, whereas the reflected wave from the remote bus of the protected line would reach the local bus at the instant $t_{F3}$. Therefore, an external fault would sensitize the protection.

Figure 4.8 depicts an internal fault distanced $d_F$ from the local bus, where $d_F > l$. The second traveling wave to reach the local bus comes from a reflection at the terminal end of the external line A. Despite this situation does not lead to a protection maloperation, it could lead to errors in the fault location estimation based on traveling waves.

Several works have proposed techniques to detect the correct wave reflected from the fault point. Cross-correlation was the first strategy applied to the problem (CROSSLEY; MCLAREN,
4.1. TRAVELING WAVE REFLECTIONS

Figure 4.6: Lattice diagram for a reverse external fault.

Figure 4.7: Lattice diagram for a reverse external fault, considering the upstream external line smaller than the protected line.

1983). However, as mentioned by Magnago and Abur (1998), this technique depends on the correct correlation window size definition, which depends on the fault location, which is unknown information. In order to mitigate the problem of defining the correlation window size, Shehab-Eldin and McLaren (1988) proposed a method that combines short and long window sizes. Christopoulos, Thomas and Wright (1988) proposed a method based on the amplitude of the traveling waves to detect the correct wave reflected from the fault point. However, the method depends on the correct line parameter estimations, a source of errors. The polarities of the traveling waves were also investigated to solve this problem (DONG; GE; XU, 1999; KALE; BHIDE; BEDEKAR, 2012). However, the polarities of the traveling waves vary according to system parameters so that different systems may have different wave polarity patterns. None of the existing techniques was consolidated as a feasible and reliable solution for detecting the correct wave reflection in real-world fault cases. Therefore, this is a problem still under investigation by the scientific community.
4.1. TRAVELING WAVE REFLECTIONS

Figure 4.8: Lattice diagram for an internal fault, considering the upstream external line smaller than $d_F$.

4.1.3 Chapter Synthesis

This chapter presented the principles of one-terminal transmission line protection based on reflections of traveling waves. The main problems regarding detecting the traveling waves reflected in the singularity points were discussed. As presented, the difficulty in distinguishing the traveling wave reflected in the fault point from the ones reflected in other singularity points is a strong limitation for the one-terminal methods based on the reflections of the traveling waves.
Chapter 5

The Proposed Traveling Wave-Based Earth Fault Distance Protection for HVAC Transmission Lines

A traveling wave-based earth fault distance AC protection method (FRANÇA et al., 2020) is proposed in this chapter. The proposed method requires only the modal components of the first wavefront, i.e., detecting traveling wave reflections is not required. However, the method is valid only for earth faults.

5.1 Principles of the Proposed TW-Based Distance Protection Relay

Fig. 5.1 depicts the Bewley diagram and the arrival times of earth-fault-induced $\alpha$- and 0-mode TWs, with fault inception time at $t_F$, at a distance $d_F$ away from the local bus and $l - d_F$ away from the remote bus on a line of length equal to $l$. Fig. 5.1 also depicts the proposed TW21G protection operation logic.

Considering that the $\alpha$-mode propagation velocity is greater than the 0-mode one on overhead lines ($v_\alpha > v_0$) (LIU et al., 2012), the $\alpha$-mode wave reaches the local bus before the 0-mode one (Fig. 5.1). The relay, positioned at the local bus, samples voltages and currents at a fixed sampling frequency $f_S$, so the wavefront arrival times in the continuous-time domain ($t_\alpha$ and $t_0$) are unknown and replaced by respective detectable discrete wavefront arrival times, i.e., $k_\alpha/f_S$ and $k_0/f_S$, where $k_\alpha$ and $k_0$ are samples that represent $t_\alpha$ and $t_0$ in the digital time domain, respectively. The continuous reference time $t_F$ gives the true fault inception time. It is also replaced by its discrete version $k_F/f_S$, where both $t_F$ and $k_F/f_S$ are unknown. Thus, the proposed TW21G function only requires $k_\alpha$ and $k_0$, i.e., it does not require the detection of reflections.

In this chapter, the detection of the discrete wavefront arrival times $k_\alpha/f_S$ and $k_0/f_S$ is carried out by using the DS (differentiator-smoother) filter (SCHWEITZER et al., 2016) in the currents. This is a TW filtering method used in a commercially available relay. It provides the relevant information to the proposed TW21G function (Fig. 5.1). Even so, other existing methods could be alternatively used, such as those based on the wavelet transform (SILVA et al., 2019; COSTA, 2014a, 2014b).

The proposed TW21G function requires auxiliary overcurrent and directional supervision functions to avoid protection maloperation in non-fault situations and reverse faults. Combining the proposed TW21G function with overcurrent and directional supervision functions yields the proposed TW21G distance protection. This work considers an OR (\(\cup\)) operation between the time domain directional function (TD32) (SCHWEITZER et al., 2015) and the TW directional
5.1. PRINCIPLES OF THE PROPOSED TW-BASED DISTANCE PROTECTION RELAY

Figure 5.1: Protection logic using the proposed traveling wave-based distance earth fault protection function TW21G and the Bewley diagram.

The proposed TW21G distance protection includes the voltage TW detection due to the usage of the TW32 function. As well known, in real systems, the poor high-frequency response of the Coupling capacitor voltage transformer (CCVT) can impair the voltage TW detection. Nevertheless, thanks to the added TD32 function, which does not require TW detection, the directional supervision element in the proposed TW21G distance protection can operate even when the TW32 function cannot.
5.2 The Proposed TW21G Function

The proposed TW21G function is derived by considering the sampling frequency effects, accommodating errors in estimated modal traveling wave velocities. To do so, a detailed analysis of these aspects is performed, as addressed next.

5.2.1 Sampling Frequency Effects

The true arrival times of the first modal TWs to reach the local bus in the continuous-time domain, \( t_\alpha \) and \( t_0 \), are unknown due to the sampling process. However, these instants are replaced by their counterparts \( k_\alpha/f_S \) and \( k_0/f_S \) in the discrete-time domain in practical applications considering an IED (Intelligent Electronic Device), such as a protective relay. Therefore, the sampling frequency effects must be considered in traveling-wave-based protection functions (COSTA et al., 2017).

The discrete fault inception time \( k_f/f_S \) is defined in Fig. 5.1 as the reference time and is the first sampling instant following the continuous true fault inception time \( t_f \), given by:

\[
k_f/f_S = \lfloor t_f f_S \rfloor + 1/f_S,
\]

where \( \lfloor \ast \rfloor \) returns the largest integer value not greater than \( \ast \).

The error in the discrete fault inception time corresponds to the time difference between the discrete and continuous fault inception times as follows:

\[
\epsilon_f = k_f/f_S - t_f,
\]

where \( 0 \leq \epsilon_f < 1/f_S \), i.e., \( \epsilon_f \) is lower than a sampling interval.

The discrete arrival time of the \( \alpha \)-mode TW is given by:

\[
k_\alpha/f_S = \lfloor t_\alpha f_S \rfloor + 1/f_S,
\]

which is the sampling instant following the true arrival time in the continuous-time domain of the \( \alpha \)-mode TW at the local bus.

Similarly to \( \epsilon_f \), the error related to the discrete arrival time of the first incident \( \alpha \)-mode TW at the local bus is given by:

\[
\epsilon_\alpha = k_\alpha/f_S - t_\alpha,
\]

where \( 0 \leq \epsilon_\alpha < 1/f_S \). Therefore, from (5.2) and (5.4), the total error for the \( \alpha \)-component is obtained as:

\[
\epsilon_{F\alpha} = \epsilon_\alpha - \epsilon_f = \frac{k_\alpha - k_f}{f_S} - (t_\alpha - t_f),
\]

where \(-1/f_S \leq \epsilon_{F\alpha} < 1/f_S \).

From (5.2), (5.4), and (5.5), considering a fault at the remote bus \( (d_f = l) \), the number of samples covered by the \( \alpha \)-mode TW to travel across the line from the fault point to the local bus is represented by:

\[
k_\alpha - k_f = \left( \frac{d_f}{v_\alpha + \epsilon_{F\alpha}} \right) f_S,
\]
5.2. THE PROPOSED TW21G FUNCTION

where \( v_\alpha \) is the actual \( \alpha \)-mode propagation velocity, given by:

\[
v_\alpha = \frac{d_F}{t_\alpha - t_F}.
\]  

(5.7)

The development for the 0-mode component follows the same steps as for the \( \alpha \)-mode component. Therefore, replacing \( \alpha \) by 0 yields:

\[
k_0 - k_F = \left( \frac{d_F}{v_0} + \varepsilon F_0 \right) f_S,
\]

(5.8)

where \( v_0 \) is the actual 0-mode propagation velocity, given by:

\[
v_0 = \frac{d_F}{t_0 - t_F}.
\]

(5.9)

From (5.6) and (5.8):

\[
k_0 - k_\alpha = d_F f_S m + (\varepsilon_0 - \varepsilon_\alpha) f_S,
\]

(5.10)

where \( m \) is a variable dependent on actual modal TW propagation velocities defined as follows (LIU et al., 2012):

\[
m = \frac{v_\alpha - v_0}{v_\alpha v_0}.
\]

(5.11)

Knowing that \( 0 \leq \varepsilon_\alpha < 1/f_S \), \( 0 \leq \varepsilon_0 < 1/f_S \), and \( k_0 \) and \( k_\alpha \in \mathbb{N} \), the lower limit of (5.10) is given by:

\[
k_0 - k_\alpha = \lfloor d_F f_S m \rfloor.
\]

(5.12)

Considering a fault in the remote bus or further away, \( k_0 - k_\alpha \) will be equal to or greater than the limit in (5.12). Therefore, to ensure that an internal fault will not be confused with an external one at the remote bus or on the downstream adjacent lines, an internal fault is detected only if:

\[
k_0 - k_\alpha < \lfloor l f_S m \rfloor.
\]

(5.13)

5.2.2 TW Velocity Estimation Effects

In real-world conditions, the actual velocities \( v_\alpha \) and \( v_0 \) are unknown. Therefore, they are replaced by their respective estimations \( \overline{v}_\alpha \) and \( \overline{v}_0 \). These velocities may be estimated as \( \overline{v}_\alpha = l/\overline{\tau}_\alpha(l) \) and \( \overline{v}_0 = l/\overline{\tau}_0(l) \), where \( \overline{\tau}_\alpha(l) \) and \( \overline{\tau}_0(l) \) are estimated line propagation times of modal TWs. These line propagation times may be estimated in real-world systems during line commissioning procedures (SCHWEITZER et al., 2016). As the protection reliability depends on the correct estimation of modal TW velocities, errors in this estimation may lead to misoperations. Nevertheless, the proposed TW21G function considers the effect of uncertainties in TW velocity estimations to avoid misoperation.

From (5.11), if the estimated \( \alpha \)-mode velocity is greater than the true one (\( \overline{v}_\alpha > v_\alpha \)) and the estimated 0-mode velocity is smaller than the true one (\( \overline{v}_0 < v_0 \)), then the estimated value for \( m \) is greater than its true counterpart. In this situation, external faults at the remote bus or beyond it could satisfy (5.13), i.e., the relay may overreach and fail. In order to avoid this situation, the wave velocity estimations must result in values of \( m \) that are always smaller than the true one. Nevertheless, \( \overline{v}_\alpha \) and \( \overline{v}_0 \) may be higher or lower than \( v_\alpha \) and \( v_0 \), respectively. Therefore, in this work, it is proposed to systematically overestimate \( v_0 \), increasing \( \overline{v}_0 \) by a security factor \( p_0 \), and to underestimate \( v_\alpha \), decreasing \( \overline{v}_\alpha \) by a security factor \( p_\alpha \). Thus, the overestimation of \( v_0 \) is
given by $v_{0\uparrow} = p_0 v_0$, where $p_0 > 1$. The underestimation of $v_\alpha$ is given by $v_{\alpha\downarrow} = p_\alpha v_\alpha$, where $0 < p_\alpha < 1$. This assumption results in a smaller estimated value for $m$, avoiding false trips to improve the protection function security. Thus, following this recommendation, the protection inequality (5.13) to detect internal faults is to consider overestimated and underestimated velocities $v_{0\uparrow}$ and $v_{\alpha\downarrow}$ instead of the true ones $v_0$ and $v_\alpha$, respectively, as follows:

$$k_0 - k_\alpha < \lfloor l f_S m' \rfloor,$$

(5.14)

where:

$$m' = \frac{v_{\alpha\downarrow} - v_{0\uparrow}}{v_{\alpha\downarrow} v_{0\uparrow}} = \frac{p_\alpha v_\alpha - p_0 v_0}{p_\alpha v_\alpha p_0 v_0}$$

(5.15)

and

$$p_\alpha v_\alpha > p_0 v_0.$$

(5.16)

### 5.3 The Protection Zone of the Proposed TW21G Function

Inaccuracies in TW velocity estimations ($v_\alpha$ and $v_0$) and errors in the detection time of TWs ($k_\alpha/f_S$ and $k_0/f_0$) due to the sampling process lead to variations on the reach of the proposed function. This section defines the protection zone considering error margins in the modal TW velocity estimations.

#### 5.3.1 The Maximum Protection Zone

As aforementioned, $0 \leq \epsilon_\alpha < 1/f_S$ and $0 \leq \epsilon_0 < 1/f_S$, then $-1 < (\epsilon_0 - \epsilon_\alpha)f_S < 1$. Therefore, based on (5.10), the maximum $k_0 - k_\alpha$, obtained when $(\epsilon_0 - \epsilon_\alpha)f_S \to 1$, with true velocities $v_\alpha$ and $v_0$, and with a given internal fault located at a distance $d_F$ from the local bus, is smaller than $d_F f_S m + 1$. Conversely, based on (5.10) and (5.15), the minimum $k_0 - k_\alpha$, obtained when $(\epsilon_0 - \epsilon_\alpha)f_S \to -1$ with estimated velocities $\overline{v}_\alpha$ and $\overline{v}_0$ for a fault located at the remote bus, at a distance $l$ from the local bus, is greater than $l f_S m' - 1$. Therefore, in order to avoid an external fault being detected as an internal one, $l f_S m' - 1$ must be greater than $d_F f_S m + 1$, yielding:

$$d_F \leq l m' - \frac{2}{f_S m'},$$

(5.17)

which in percentage is given by:

$$d_{F\%} \leq \left( \frac{m'}{m} - \frac{2}{l f_S m} \right) 100\%.$$

(5.18)

For a hypothetical $f_S$ tending to infinity, the maximum protection zone within which the method will detect a fault as an internal one is given by:

$$PZ_{\text{max}} = \left( \frac{m'}{m} \right) 100\%.$$

(5.19)

By defining $PZ_{\text{max}} = 100\%$ in (5.19), the protection inequality given by (5.14) ensures that no downstream external fault will be detected as internal one. However, (5.19) uses true propagation velocities in $m$, as defined in (5.11), which are unknown. Therefore, error margins in the wave velocity estimations must be considered to define the protection zone.
5.3. THE PROTECTION ZONE OF THE PROPOSED TW21G FUNCTION

5.3.2 Error Margin for the Wave Velocity Estimation

In what follows, the estimated modal TW propagation velocities \( v_\alpha \) and \( v_0 \) are expressed as approximations of the respective true TW propagation velocities \( v_\alpha \) and \( v_0 \) employing error factors \( g_\alpha \) and \( g_0 \), i.e., \( v_\alpha = g_\alpha v_\alpha \) and \( v_0 = g_0 v_0 \). Therefore, (5.15) is given by:

\[
m' = \frac{pa g_\alpha v_\alpha - p_0 g_0 v_0}{pa g_\alpha v_\alpha p_0 g_0 v_0}.
\]  

(5.20)

To avoid external faults being detected as internal ones, \( PZ_{\text{max}} \) in (5.19) must be smaller than 100%. Therefore, the maximum value for \( m' \) in (5.20) must be equal to the correct value of \( m \) in (5.11), as follows:

\[
\frac{pa g_\alpha v_\alpha - p_0 g_0 v_0}{pa g_\alpha v_\alpha p_0 g_0 v_0} = \frac{v_\alpha - v_0}{v_\alpha v_0}.
\]  

(5.21)

Thus, ideal conditions are satisfied with \( p_\alpha = 1/g_\alpha \) and \( p_0 = 1/g_0 \). However, \( g_\alpha = v_\alpha/v_\alpha \) and \( g_0 = v_0/v_0 \) are unknown because \( v_\alpha \) and \( v_0 \) are unknown. Therefore, \( p_\alpha \) and \( p_0 \) are to be obtained through expected percentage error margins \( g_\alpha \% \) and \( g_0 \% \) for the modal wave velocity estimations instead of \( v_\alpha \) and \( v_0 \), respectively. These margins must ensure that errors below \( g_\alpha \% \) and \( g_0 \% \) are acceptable for \( v_\alpha \) and \( v_0 \), respectively.

Fig. 5.2 depicts the effect of the security factors \( p_\alpha \) and \( p_0 \) in the modal wave velocity estimations, where \( g_\alpha = 1 + (g_\alpha/100) \), \( g_\alpha = 1 - (g_\alpha/100) \), \( g_0 = 1 + (g_0/100) \), and \( g_0 = 1 - (g_0/100) \) are upper- and lower-limit (↑ and ↓) error factors. Fig. 5.2 shows that by respecting \( g_\alpha \% \) and \( g_0 \% \), \( v_\alpha \) and \( v_0 \) may be estimated within regions A or B. However, as discussed in subsection 5.2.2, \( v_\alpha > v_\alpha \) and \( v_0 < v_0 \) must be avoided, i.e., regions A must be avoided. Thereby, the security factors \( p_\alpha \) and \( p_0 \) must be computed considering the worst case, which is \( v_\alpha = v_\alpha = g_\alpha v_\alpha \) and \( v_0 = v_0 = g_0 v_0 \), in the external limit of zones A. Therefore, \( p_\alpha \) and \( p_0 \) are given by:

\[
p_\alpha = \frac{1}{g_\alpha} = \frac{100}{100 + g_\alpha \%}.
\]  

(5.22)

and

\[
p_0 = \frac{1}{g_0} = \frac{100}{100 - g_0 \%}.
\]  

(5.23)

From (5.22) and (5.23), \( p_\alpha \) and \( p_0 \) are automatically computed since \( g_\alpha \% \) and \( g_0 \% \) have been defined previously. In turn, the adopted values for the error margins \( g_\alpha \% \) and \( g_0 \% \) must result in security factors \( p_\alpha \) and \( p_0 \) that ensure (5.16). Thus, considering that the percentage errors on the estimated modal TW propagation velocities \( v_\alpha \) and \( v_0 \) are lower than the adopted margins \( g_\alpha \% \) and \( g_0 \% \), then \( m' < m \) in (5.21) and \( PZ_{\text{max}} < 100\% \) in (5.19). Therefore, (5.14) ensures that faults in the remote bus or downstream external lines will not be detected as internal ones.

\[
\begin{align*}
\text{Region } \alpha A & : v_\alpha > v_\alpha \\
\text{Region } \alpha B & : v_\alpha < v_\alpha \\
\text{Region } 0A & : v_0 > v_0 \\
\text{Region } 0B & : v_0 < v_0
\end{align*}
\]

(a)

\[
\begin{align*}
\text{Region } \alpha A & : v_\alpha > v_\alpha \\
\text{Region } \alpha B & : v_\alpha < v_\alpha \\
\text{Region } 0A & : v_0 > v_0 \\
\text{Region } 0B & : v_0 < v_0
\end{align*}
\]

(b)

Figure 5.2: Modal wave velocity estimation.
5.3.3 The Minimum Protection Zone

The definition of the minimum protection zone $PZ_{\text{min}}$ is necessary for reliable protection because it defines the minimum zone in which all faults are detected as internal ones. When $v_\alpha$ and $v_0$ are estimated in regions B (Fig. 5.2), i.e., when $v_\alpha < v_0$ and $v_0 > v_0$, the protection reach is reduced. In addition, the effect of the security factors $p_\alpha$ and $p_0$ is to reduce it even more. As Fig. 5.2 shows, the boundary condition for $PZ_{\text{min}}$ occurs when $v_\alpha$ and $v_0$ are estimated at the limit of regions B, where $v_\alpha = v_\alpha_3 = g_\alpha v_\alpha$ and $v_0 = v_0_3 = g_0 v_0$. It is now possible to estimate a compensated value of $m$, named here as $m_c$, which allows to express $m$ without the need to use the true values of $v_\alpha$ and $v_0$:

$$m_c = \left( \frac{1}{g_\alpha} \right) v_\alpha - \left( \frac{1}{g_0} \right) v_0 = \left( \frac{100}{100-g_\alpha} \right) v_\alpha - \left( \frac{100}{100-g_0} \right) v_0.$$  \hspace{1cm} (5.24)

Therefore, in the presented boundary condition, when $v_\alpha = g_\alpha v_\alpha$ and $v_0 = g_0 v_0$, $m_c$ is equal to the actual value of $m$.

From (5.18) and (5.24), the minimum protection zone, within which all faults will be detected as internal ones, is given by:

$$PZ_{\text{min}} = \left( \frac{\text{m'}}{m_c} - \frac{2}{1f_5m_c} \right) 100\%.$$  \hspace{1cm} (5.25)

For any other values of $v_\alpha$ and $v_0$ and corresponding $g_\alpha$ and $g_0$, then the protection reach may be greater than $PZ_{\text{min}}$, but will always be lower than $PZ_{\text{max}} = 100\%$.

It is recommended that the adopted values for $g_\alpha$ and $g_0$ ensure $PZ_{\text{min}} > 50\%$, from (5.25). Thereby, by connecting relays with the proposed TW21G protection implemented in both line terminals, a DTT (Direct Transfer Trip) protection scheme can be applied in order to protect 100% of the monitored transmission line.

5.4 Proposed TW21G Function Setup Methodology

Fig. 5.3 depicts the methodology for the offline setup of the proposed TW21G function. The settings can be easily obtained since the protection threshold given by (5.14) can be automatically estimated after defining the input relay parameters. The line length, the sampling frequency, the modal TW propagation velocity estimations, and error margins for the modal wave velocity estimations are input parameters to be set in the relay. The variables $p_\alpha$, $p_0$, $m'$, and $m_c$ are all automatically calculated using the demonstrated equations. Finally, the relay parametrization calculates the reach setting $\lfloor l_5 m' \rfloor$ and the minimum protection zone $PZ_{\text{min}}$.

For instance, consider a transmission line with $l = 200$ km and estimated modal wave velocities equal to $v_\alpha = 0.9285c$ and $v_0 = 0.7143c$, where $c$ is the speed of light. Adopt the error margins $g_\alpha = g_0 = 3\%$, so that $PZ_{\text{min}} > 50\%$ according to (5.25). Then, from (5.22) and (5.23), $p_\alpha \approx 0.9709$ and $p_0 \approx 1.0309$, which ensure (5.16). From (5.15) and (5.24), $m' \approx 8.2881 \times 10^{-7}$ and $m_c \approx 1.3242$. From (5.25), $PZ_{\text{min}} \approx 61.8337\%$, which means that all internal earth faults occurring before 123.66 km will be detected as internal. Finally, according to (5.14), a fault will be detected as internal one when $k_0 - k_\alpha < 165$. Therefore, provided that the errors in modal wave propagation velocity estimations do not exceed 3%, $k_0 - k_\alpha < 165$ will ensure $PZ_{\text{max}} = 100\%$.

As aforementioned, the relay setup may also be performed considering the estimated modal
5.5 Performance Assessment

Two test systems were modeled in order to assess the proposed method. Both were modeled based on actual 230 kV and 60 Hz transmission networks. In the first one, shown in Fig. 5.4, the transmission lines were modeled using the Bergeron frequency-independent distributed parameter model. In this model, the TW velocity depends on line series inductance and shunt capacitance, as follows:

\[ v_\alpha = \frac{1}{p L_\alpha C_\alpha} \]  \hspace{1cm} (5.26)

and

\[ v_0 = \frac{1}{p L_0 C_0}. \]  \hspace{1cm} (5.27)

Therefore, as the exact values of the modal wave velocities are known, it was possible to evaluate the precision of the protection zone of the proposed method as a function of the adopted error margins \( g_\alpha \) and \( g_0 \). The protected line is 200 km long, and adjacent lines of 15 km were connected at buses 2 and 3. The system-to-line impedance ratio (SIR) is equal to 0.1 at buses 2 and 3, and a power system loading angle equal to \(-15^\circ\) was considered. This corresponds to a moderate power system loading. CCVTs and current transformers (CTs) were, respectively, implemented as described in (CARVALHO; FREIRE; OLIVEIRA, 2009) and (IEEE, 2004), in both systems.

In the second system, shown in Fig. 5.5, the transmission lines were modeled with the JMarti frequency-dependent distributed parameter line model with a frequency response up to 10 MHz. Fig. 5.6 depicts the parameters of the tower for this system. The protected transmission line TL 3 was transposed employing four transposition points, following the well-known scheme \( 1/6 + 1/3 + 1/3 + 1/6 \). Two perfectly transposed parallel adjacent lines of 10 km in length were added at each terminal of the protected line. An SNR (signal-to-noise ratio) of 40 dB was considered to hinder the wavefront detection. In this system, the wave velocity varies depending on the fault position due to the frequency-dependent line parameters, especially the 0-modal component. Therefore, the wave velocity can no longer be estimated with (5.26) and (5.27). Furthermore, fault-induced transients present more attenuation than the Bergeron-based counterparts, so traveling waves that reach the line terminals do not present sharp step variation. This is in accordance with traveling wave behavior in real systems. Due to this characteristic,
detecting the true arrival instant of the wavefront becomes more challenging.

Faults were simulated using the ATP software at a sampling frequency of 1 MHz. All the oscillographic records at the relays connected at bus 2, designed to protect the transmission line between buses 2 and 3 in each modeled system, were stored in a database. After that, five procedures were accomplished:

1. the performance assessment of the proposed TW21G distance function, in the first system, as addressed in subsection 5.5.1;
2. the performance assessment of the existing distance protection TD21 in an actual relay by means of its playback functionality (GUZMÁN et al., 2018), in the first system, as addressed in subsection 5.5.2;
3. the performance assessment of the proposed TW21G protection with the logic operation TW21G ∩ OC21 ∩ (TD32 ∪ TW32) in Fig. 5.1, in the first system, where OC21, TD32, and TW32 were available in an actual relay, as addressed in subsection 5.5.2;
4. the procedures 2) and 3) were performed for the second system in order to evaluate the method in a more realistic scenario, as addressed in subsection 5.5.3;
5. complementary operation time comparisons between the proposed TW21G protection and the existing distance protection TD21 were performed, as addressed in subsection 5.5.4.

Transmission lines

\[
Z_0 = 0.522 + j1.432 \, \Omega/km \\
Z_1 = 0.098 + j0.53 \, \Omega/km \\
Y_0 = 2.293 \, \mu\Omega/km \\
Y_1 = 3.252 \, \mu\Omega/km
\]

Figure 5.4: Modeled system 1: 230 kV and 60 Hz power system with distributed parameters.

Figure 5.5: Modeled system 2: 230 kV and 60 Hz power system with frequency-dependent parameters and non-ideal line transposition.
All the applied earth faults were phase-A-to-ground type (AG faults). However, all evaluations performed here can be extended to other earth fault types. The Clarke transformation referenced to phase A was applied to currents so that the arriving instants of the TWs were always detected in the modal domain from the DS filter outputs.

In the first system, where the Bergeron-based distributed parameter transmission line model was implemented, the actual $\alpha$- and 0-modal TW velocities for the protected line, in the simulation environment, are $v_\alpha = 1/\sqrt{L_1C_1} = 2.8716 \times 10^5$ km/s (0.9572$c$) and $v_0 = 1/\sqrt{L_0C_0} = 2.0805 \times 10^5$ km/s (0.6935$c$), respectively. As a result, the travel time of the alpha and zero mode TWs along the protected line are, respectively, 0.6965 ms and 0.9613 ms. However, these values are not used in the proposed protection because they are unknown in a practical situation, and $v_\alpha \neq v_\alpha$ and $v_0 \neq v_0$ were considered, as further discussed in the following subsections. The proposed TW21G function was set considering $g_\alpha\% = g_0\% = 3\%$ for all the evaluated scenarios for the system 1, respecting (5.16). So if follows that $PZ_{\text{min}} > 50\%$ from (5.25).

In the second system, the modal wave velocity estimation was performed through an energization procedure applied in real transmission systems (SCHWEITZER et al., 2016). The protected transmission line TL 3 was energized from bus 3, while the terminal connected to bus 2 was open. A circuit breaker interpole switching delay of 3.3 ms was considered in accordance with what has been observed in real scenarios (MOORE, 2004). The time stamps of the pole closing and the TW reflected from bus 2 were used in order to estimate the modal wave velocities, which were $v_\alpha = 2.9957 \times 10^5$ km/s (0.9986$c$) and $v_0 = 2.7523 \times 10^5$ km/s (0.9174$c$). In order to respect (5.16) and maintain $PZ_{\text{min}} > 50\%$, in accordance with (5.25), $g_\alpha\% = 0.8$ and $g_0\% = 1.79\%$ were adopted for all the tests performed for the system 2.

5.5.1 The Proposed Distance Function TW21G

In order to analyze the effect of fault location variations on the proposed TW21G function, faults from 1 to 199 km, at steps of 1 km, were considered for system 1, amounting to 199 faults being investigated. In this evaluation, solid faults were initiated at a fault inception angle of 90° in the faulted phase in order to result in the highest content of electromagnetic transients (COSTA; SOUZA; BRITO, 2012), avoiding TW detection problems due to the transient attenuation. However, the effect of this parameter is considered in subsection 5.5.3.

Fig. 5.7 depicts the proposed TW21G function operation time for different estimations of $v_\alpha$ and $v_0$. Fig. 5.7(a) considers $v_\alpha$ with underestimation of 3% ($\overline{v}_\alpha = 0.97v_\alpha$) and $v_0$ with overestimation of 3% ($\overline{v}_0 = 1.03v_0$), i.e., estimation errors higher than expected ones, which are supposed to be less than 2% (WANG; XU, 2015). According to (5.25), $PZ_{\text{min}} = 61.8337\%$ (123.66 km). Fig. 5.7(b) also considers significant estimation errors: $v_\alpha$ with overestimation of 3% ($\overline{v}_\alpha = 1.03v_\alpha$) and $v_0$ with underestimation of 3% ($\overline{v}_0 = 0.97v_0$), yielding $PZ_{\text{min}} = 72.0358\%$.
(144.07 km). Fig. 5.7(c) considers an exact estimation of both $v_\alpha$ and $v_0$, i.e., $v_\alpha = v_\alpha$ and $v_0 = v_0$, yielding $PZ_{\text{min}} = 67.7445\%$ (135.49 km).

The relay performed in these situations as follows: 1) no fault within $PZ_{\text{min}}$ was detected as external; 2) most faults beyond $PZ_{\text{min}}$, but inside the protected line, were detected as internals; 3) as the errors for the modal wave velocity estimations were not higher than the adopted margins $g_\alpha\%$ and $g_0\%$ of 3%, no fault at the remote bus or beyond it was detected as internal.

The maximum protection operation time in Fig. 5.7(a) was 0.697 ms, whereas the maximum operation time of the two-terminal TW-based protection in (COSTA et al., 2017) was 2.5 ms, considering a protected line of 200 km length. The maximum operation time in Figs. 5.7(b) and 5.7(c) were 1.057 ms and 0.879 ms, respectively.

![Figure 5.7](image-url)  

Figure 5.7: Protection operation time for: (a) $v_\alpha$ underestimated by 3% and $v_0$ overestimated by 3%; (b) $v_\alpha$ overestimated by 3% and $v_0$ underestimated by 3%; (c) correct estimation for $v_\alpha$ and $v_0$.

According to Fig. 5.7, there is an uncertainty zone between $PZ_{\text{min}}$ and the remote bus where faults may or may not be detected as internal faults, depending on the error in modal TW velocity estimations. In addition, the adopted margins $g_\alpha\%$ and $g_0\%$ ensure that no fault within $PZ_{\text{min}}$ is detected as external, and no fault at the remote bus or beyond it is detected as internal. Therefore, no protection misoperation was verified.

### 5.5.2 The Proposed TW21G Function with Supervision of Existing Functions

Performances of the proposed distance protection with the logic $\text{TW21G} \cap \text{OC21} \cap (\text{TD32} \cup \text{TW32})$ and of the existing distance protection TD21 were evaluated and compared for system 1. The results consider variations on line parameters to verify the effect of inaccuracies of relay settings on the operation of its functions. They also consider errors in modal wave velocity estimations to verify the minimum and maximum reaches of the proposed protection TW21G.
5.5. PERFORMANCE ASSESSMENT

5.5.2.1 Effect of Uncertainty in Line Parameters

Fig. 5.8 depicts the operation time of the proposed TW21G and the existing TD21 protections as a function of the fault distance considering the correct estimation of the modal wave velocities ($v_\alpha = v_\alpha$ and $v_0 = v_0$). Faults from 1 to 199 km, at steps of 1 km, were considered, totaling 199 faults. The TD21 protection resulted in a maximum operation time equal to 10.133 ms and mean operation time equal to 4.08 ms, giving a very fast operation time when compared to the one to one-and-a-half cycle typical operating time of traditional phasor-based protection (SCHWEITZER et al., 2015). In addition, it detects faults up to 124 km, which is at 62% of the line. The proposed TW21G protection was able to speed up the distance protection operation in all simulated scenarios, with maximum and mean operation times of 1.5 ms and 1.09 ms, respectively. In addition, the proposed TW21G protection detected faults beyond the maximum reach of the TD21 protection.

Fig. 5.9 depicts the operation times of the existing TD21 protection and the proposed TW21G protection, considering uncertainties in line parameters. In Fig. 5.9(a), the $\alpha$-mode line parameters, which are equal to the positive sequence parameters, were underestimated by 3%. The 0-mode line parameters, which are equal to the zero sequence parameters, were overestimated by 3%. Regarding Fig. 5.9(b), the aerial mode line parameters were overestimated by 3%, whereas the 0-mode line parameters were underestimated by 3%. In these cases, the relay parameters were not modified for both TD21 and TW21G protections. Since there is a certainty that all faults within the minimum protection zone $PZ_{\text{min}}$ are properly detected as internal events, only the results for faults from 100 to 199 km, at steps of 1 km, are presented, amounting to 100 fault cases, demonstrating the uncertainty zone variation from the end of $PZ_{\text{min}}$ to the remote bus.

According to Fig. 5.9, the operation time and reach of the TD21 protection did not present relevant variation, proving its robustness regarding deviations of line parameters. As mathematically predicted and according to what was presented in subsection 5.5.1, the TW21G protection presented variation in its reach. However, no fault at the remote bus or beyond was detected as internal. The proposed TW21G protection was again able to significantly speed up the distance protection scheme, with a maximum operation time of 1.6 ms.

5.5.3 The Proposed TW21G Function with Supervision of Existing Functions Considering Frequency-dependent Parameters

A more realistic scenario was considered to evaluate and compare the performance of the proposed distance protection with the logic $\text{TW21G} \cap \text{OC21} \cap (\text{TD32} \cup \text{TW32})$ and the existing distance protection TD21. Frequency-dependent line electrical parameters, a non-ideal line transposition, electrical noise, and fault inception angle variations, which may affect the wave
5.5. PERFORMANCE ASSESSMENT

The proposed protection is the fastest

The proposed protection detects more faults

Figure 5.9: TD21 and TW21G protection operation times for: (a) $R_1$, $L_1$, and $C_1$ underestimated by 3%, and $R_0$, $L_0$, and $C_0$ overestimated by 3%; (b) $R_1$, $L_1$, and $C_1$ overestimated by 3%, and $R_0$, $L_0$, and $C_0$ underestimated by 3%.

5.5.3.1 Effect of the Fault Location

Fig. 5.10 depicts the operation time of the proposed TW21G and of the existing TD21 protections as a function of the fault distance. Faults from 0 to 210 km, at steps of 5 km, were considered, amounting to 43 faults being evaluated. Despite the errors in the modal wave velocity estimations being unknown, the adopted error margins $g_\alpha$ and $g_0$ ensured the protection reliability since no fault in the remote bus or beyond it was detected. The proposed TW21G protection detected all applied faults up to 160 km, which corresponds to 76.19% of the transmission line length and is in accordance with the projected $PZ_{\text{min}} > 50\%$. The maximum operation time was 1.3 ms. The maximum reach of the existing TD21 protection was 125 km, which corresponds to 59.52% of the transmission line, while the maximum operation time was 9.7 ms.

5.5.3.2 Effect of the Fault Inception Angle

Fig. 5.11 depicts the operation time of the proposed TW21G and of the existing TD21 protections as a function of the fault inception angle. Faults were applied from 0 to 210 km, at steps of 15 km, considering fault inception angles equal to $0^\circ$, $30^\circ$, $60^\circ$, and $90^\circ$, totaling 60 faults being investigated. As expected for TW-based algorithms, the proposed TW21G distance protection did not detect faults with an inception angle equal to $0^\circ$ since the fault-induced transients were severely damped. This is a challenge to be faced by the TW filtering method. However, the development or detailed analysis of the TW filtering method is out of the scope of this work. Moreover, the protection reach was slightly lower to faults with a fault inception angle equal to $30^\circ$. In addition, the mean and the maximum operation times were about 1.1 ms and 1.5 ms, respectively.

Although the fault inception angle variation modifies the TD21 protection operation, it does not present a clear tendency. The existing TD21 protection detected faults with fault-induced transients severely damped. The mean operation time was about 3.2 ms, whereas the maximum
operation time was about 9.4 ms. Therefore, considering cases in which TW21G operations were verified, the proposed method was the fastest.

5.5.3.3 Effect of the Fault Resistance

Fig. 5.12 shows the effects of the fault resistance on the operation time of the proposed TW21G and the existing TD21 protections. Faults were applied from 0 to 210 km, at steps of 15 km, considering fault inception angle of 90° and fault resistances equal to 10, 50, 100, and 200 Ω, amounting to 60 faults in total. The TD21 and the TW21G protections presented higher operation times for fault resistance values. The existing TD21 protection had its reach decreased with the increase of the fault resistance and could not detect faults with resistances greater than 100 Ω. The proposed TW21G protection was able to detect all the applied faults up to 150 km with a maximum operation time of 1.6 ms. Thus, the TD21 protection is more influenced by the fault resistance variation. Therefore, the proposed TW21G protection could accelerate the existing TD21 protection for all the jointly detected faults and detect some others that the TD21 protection could not detect. The increase in the operation time of the proposed TW21G distance protection performing the logic TW21G ∩ OC21 ∩ (TD32 ∪ TW32) (Fig. 5.1) occurred due to the increase in the operation time of the OC21 function. The traveling-wave-based functions TW21G and TW32 did not present variations in their operation times.

![Figure 5.10: TD21 and TW21G protection operation times.](image)

5.5.3.4 DTT Protection Scheme

As the proposed TW21G distance protection is under-reach protection and presents good dependability, it can be applied in a DTT protection scheme. Two of the used actual relay were employed in order to evaluate this application. Table 5.1 shows the operation time of the POTT (Permissive Overreaching Transfer Trip) and the DTT protection schemes for the actual relay and the operation time of the proposed TW21G distance protection in a DTT scheme. The operation time is related to the instant when both relays give trip signals. Since the adopted optical fiber to connect both relays is very small, the observed communication delays in these test cases were smaller than expected for a real transmission system. The same communication delays observed for the DTT scheme with the proposed TW21G distance protection were adopted for the DTT scheme of the actual relays. Those delays were 77 µs and 23 µs for the local and remote terminals, respectively.

Table 5.1 shows that the proposed TW21G distance protection accelerated the trip of the actual relay for all the evaluated test cases. These results demonstrate the potential of the proposed TW21G distance protection to speed up the earth-fault protection, even considering existing ultra-fast two-terminal methods.
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Figure 5.11: Protection operation time as a function of the fault inception angle to: (a) the proposed TW21 protection; (b) the existing TD21 protection.

Figure 5.12: Protection operation time as a function of the fault resistance to: (a) the proposed TW21 protection; (b) the existing TD21 protection.

5.5.4 Operation Time Comparison

The operation times between the proposed TW21G protection and the existing TD21 protection was compared to verify the ability of the proposed TW21G function to speed up the time-domain distance protection. Fig. 5.13 depicts the scatter plot to compare the operation time between the TD21 protection and the proposed TW21G protection for all the 225 jointly detected by both protection schemes in the assessments presented in subsections 5.5.2, 5.5.3.1, 5.5.3.2, and 5.5.3.3.
Table 5.1: POTT and DTT scheme operations.

<table>
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<th>Fault Location (km)</th>
<th>Operation Time (µs)</th>
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<td>Actual Relay</td>
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<tr>
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</tr>
<tr>
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</tr>
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</tbody>
</table>

As shown in Fig. 5.13, in some cases, the proposed TW21G protection scheme was six times faster than the TD21 protection, being about two times faster in the remaining cases. The operation time of the proposed TW21G protection did not exceed 1.4 ms, whereas the TD21 element presented operation times varying from 1.6 ms to about 10.1 ms. Therefore, for all the 225 fault cases jointly detected by both protection schemes, the proposed TW21G protection accelerated the TD21 protection.

Fig. 7.17 depicts the cumulative frequency of the operation time for the TD21 protection and the proposed TW21G protection for all detected internal faults. The maximum operation times of the proposed TW21G protection and the TD21 protection were about 1.6 ms and 10.1 ms, respectively. When the proposed TW21G protection reached a cumulative frequency of 100%, the TD21 protection detected only one fault. These results demonstrate that using the proposed TW-based earth fault distance protection to speed up the protection operation is efficient and reliable.

Figure 5.13: Scatter plot of the existing TD21 protection and the proposed TW21G protection operation times.
5.6 Conclusion

This chapter proposes a traveling wave-based earth fault transmission line distance protection, which only requires arrival instants of the first incident modal traveling waves at one line terminal and the estimation of modal propagation velocities with uncertainties. Therefore, the proposed protection overcomes traditional limitations of one-terminal traveling-wave-based methods, which require the challenging task of detection of reflected waves and accurate wave propagation velocity estimations. The proposed function setup procedure is straightforward, facilitating practical implementation.

A thorough investigation of the sampling frequency effect allowed the definition of error margins for the modal wave velocity estimations, ensuring the reliability of the protection in well-defined protection zones. The proposed function provides a protection reach, considering the adopted error margins for the modal wave velocity estimations, wherein all the internal faults will always be detected. This facilitates the application of the proposed function in real-world systems. Reach values greater than 60% in the worst evaluated cases were achieved. A greater portion of the transmission line may be protected, depending on the error in velocity estimations. Therefore, unitary protection, where 100% of the transmission line is inside the protected zone, may be achieved via a DTT scheme whether a relay is connected at each line terminal of the protected line, considering the additional cost of applying a communication channel.

When associated with other existing auxiliary protection functions, the proposed function presented an ultra-fast operation time well below those presented by a commercially existing time domain distance protection. Errors in the wave velocity estimations and inaccuracies in line parameters were evaluated. The effect of the fault location was also evaluated. The proposed method accelerated the evaluated time-domain distance element available in the analyzed actual relay for all detected earth faults. The presented maximum operation time was smaller than 2 ms for all detected internal faults, without misoperations in cases of external faults. In addition, it was demonstrated that the proposed distance protection has the potential to speed up earth-fault protection, even considering existing ultra-fast two-terminal methods. This represents an important contribution since fast fault detection provides greater stability to the electrical system and reduces the risk of damage to its components. The results have also demonstrated that the method presents good dependability, even considering errors in the wave velocity estimations.
5.7 Chapter Synthesis

This chapter proposed a traveling wave-based earth fault distance protection method for AC lines. The effects of the sampling frequency and the velocity estimations of the modal components of the traveling waves on the protection reliability were evaluated. From these evaluations, a protection zone was delimited, as well as error margins for the modal wave velocity estimations were defined, with no loss of protection reliability.
This chapter will present the proposed method for transmission line protection based on traveling wave reflections using one terminal. The correct detection of the reflected wave at the fault point is an issue still under investigation by the scientific community. Therefore, the proposed method only applies to point-to-point lines without adjacent lines.

A previous version of the method presented here was investigated in (FRANÇA, 2017). However, this chapter has carried out a thorough and unprecedented investigation of the effect of traveling wave speed estimation. In this way, a more robust method has been developed.

6.1 Discrete Time Domain for a Single Line

For application in protection relays, the voltage and current signals are discretized. Therefore, the effect of the sampling frequency needs to be considered. Costa et al. (2017) has investigated such an effect for a protection method using two terminals. However, this effect has not been investigated so far for one-terminal methods.

Figure 6.1 depicts the arrival time of traveling waves at the local terminal due to a \( d_F \) distant fault from the L-bar on a \( l \) km long line. It also depicts the discrete time instants of the wavefronts due to the effect of sampling frequency.

Considering the effect of the sampling frequency, the first and second wavefront arrival times \( t_{F1} \) and \( t_{F2} \), as well as the fault inception time \( t_F \), all in the continuous time domain, should be converted to their respective discrete times. These can be detected with high accuracy by various high-frequency digital filtering methods (COSTA; SOUZA; BRITO, 2010; COSTA, 2014a; NAMDARI; SALEHI, 2017). Therefore, this work assumes that the discrete times of wavefront detections are known, and no detection method will be investigated. The times in the discrete-time domain are given by:

\[
\frac{k_F}{f_s} = \left\lfloor \frac{t_F f_s}{f_s} \right\rfloor, \tag{6.1}
\]

where

\[
t_F - \frac{1}{f_s} < \frac{k_F}{f_s} \leq t_F, \tag{6.2}
\]

\[
\frac{k_{F1}}{f_s} = \left\lfloor \frac{t_{F1} f_s}{f_s} \right\rfloor + \frac{1}{f_s}, \tag{6.3}
\]
6.1. DISCRETE TIME DOMAIN FOR A SINGLE LINE

Figure 6.1: Lattice diagram of traveling waves seen from a terminal, considering the effect of sampling frequency.

where

\[ t_{F1} < \frac{k_{F1}}{f_s} \leq t_{F1} + \frac{1}{f_s}, \]  
(6.4)

and

\[ \frac{k_{F2}}{f_s} = \left\lfloor \frac{t_{F2}f_s}{f_s} \right\rfloor \frac{1}{f_s}, \]  
(6.5)

where

\[ t_{F2} < \frac{k_{F2}}{f_s} \leq t_{F2} + \frac{1}{f_s}, \]  
(6.6)

where \( k_F \) is the reference sample and represents the discrete time of fault incidence; \( k_{F1} \) and \( k_{F2} \) are the samples at which the relay detects the first and second wavefronts; \( \left\lfloor \cdot \right\rfloor \) is the floor operation, which returns the minimum integer value of the argument; \( f_s \) is the sampling frequency.

Due to the sampling process, the variables in the discrete-time domain have errors concerning the correct values in the continuous-time domain. According to equations (6.1)-(6.5), the errors associated with the instant of fault incidence (\( \varepsilon_F \)) and arrival times of the first and second wavefronts (\( \varepsilon_{F1} \) and \( \varepsilon_{F2} \)) are given by:

\[ \varepsilon_F = t_F - \frac{k_F}{f_s}, \]  
(6.7)

where

\[ 0 \leq \varepsilon_F < \frac{1}{f_s}, \]  
(6.8)

\[ \varepsilon_{F1} = \frac{k_{F1}}{f_s} - t_{F1}, \]  
(6.9)

where

\[ 0 \leq \varepsilon_{F1} < \frac{1}{f_s}, \]  
(6.10)

and

\[ \varepsilon_{F2} = \frac{k_{F2}}{f_s} - t_{F2}, \]  
(6.11)
6.1. DISCRETE TIME DOMAIN FOR A SINGLE LINE

where

\[ 0 \leq \varepsilon_{F2} < \frac{1}{f_s}, \quad (6.12) \]

The difference between the discrete arrival times of the second and first wavefronts is given by:

\[ \frac{k_{F2}}{f_s} - \frac{k_{F1}}{f_s} = (t_{F2} + \varepsilon_{F2}) - (t_{F1} + \varepsilon_{F1}) = (t_{F2} - t_{F1}) + (\varepsilon_{F2} - \varepsilon_{F1}), \quad (6.13) \]

which makes it possible to calculate a total error associated with the difference between the discrete times:

\[ \varepsilon_T = (\varepsilon_{F2} - \varepsilon_{F1}) = \frac{k_{F2} - k_{F1}}{f_s} - (t_{F2} - t_{F1}), \quad (6.14) \]

where \(-1/f_s < \varepsilon_T < 1/f_s\), since \(0 \leq \varepsilon_{F1} < 1/f_s\) and \(0 \leq \varepsilon_{F2} < 1/f_s\).

From equations (4.8) and (6.14), a fault will be detected as internal when:

\[ k_{F2} - k_{F1} \leq \left( \frac{lf_s}{v} + 1 \right), \quad (6.15) \]

Considering the upper limit of the total error, the inequality (6.15) becomes:

\[ k_{F2} - k_{F1} < \left( \frac{lf_s}{v} + 1 \right), \quad (6.16) \]

on the other hand, considering the lower limit, the inequality (6.15) becomes:

\[ k_{F2} - k_{F1} < \left( \frac{lf_s}{v} - 1 \right), \quad (6.17) \]

Since \(k_{F2} \geq k_{F1}\) and \((k_{F2} - k_{F1}) \in \mathbb{N}\), then from equations (6.16) and (6.17), an internal fault will be detected when:

\[ k_{F2} - k_{F1} \leq \left\lfloor \frac{lf_s}{v} \right\rfloor + 1. \quad (6.18) \]

From equations (4.9) and (6.14), an external fault will be detected when:

\[ \frac{k_{F2} - k_{F1}}{f_s} + (\varepsilon_{F1} - \varepsilon_{F2}) = \frac{2l}{v} \therefore k_{F2} - k_{F1} - \varepsilon_T = \frac{2l}{v} \therefore k_{F2} - k_{F1} = \left( \frac{2l}{v} + \varepsilon_T \right) f_s. \quad (6.19) \]

Therefore, considering the upper and lower limits of the total error, an external fault will be detected when:

\[ \left( \frac{2lf_s}{v} - 1 \right) < k_{F2} - k_{F1} < \left( \frac{2lf_s}{v} + 1 \right). \quad (6.20) \]

Since \(k_{F2} \geq k_{F1}\) and \((k_{F2} - k_{F1}) \in \mathbb{N}\), the inequality (6.20) becomes:

\[ \left\lfloor \frac{2lf_s}{v} \right\rfloor \leq k_{F2} - k_{F1} \leq \left\lfloor \frac{2lf_s}{v} \right\rfloor + 1. \quad (6.21) \]

According to equations (6.18) and (6.21), to ensure a correct distinction between internal and external faults, a threshold \((p)\) for the detection of internal faults can be adopted as follows:

\[ \left\lfloor \frac{lf_s}{v} \right\rfloor + 1 < \left\lfloor \frac{plf_s}{v} \right\rfloor < \left\lfloor \frac{2lf_s}{v} \right\rfloor, \quad (6.22) \]
where $1 \leq p < 2$. Therefore, the inequality (6.22) is the discrete analog of the inequality (4.11).

6.1.1 The Protected, Unprotected, and Uncertain Zones

In the sampling process, it is taken as true that the relay is unable to identify multiple wavefronts arriving between two consecutive samples. Suppose the first and second wavefronts reach the local terminal in the same sampling period. In that case, the relay will identify them as only one wavefront. Therefore, when:

$$k_{F2} - k_{F1} \leq 1,$$  \hspace{1cm} (6.23)

it is not possible to guarantee that only two wavefronts arrived at the local bus, as multiple wavefronts may have arrived at the local bus before sample $k_{F1}$ and between samples $k_{F1}$ and $k_{F2}$, which could have occurred due to a switching at one of the line terminals.

In terms of wavefront arrival times, the inequality (6.23) becomes:

$$\frac{k_{F2}}{f_s} - \frac{k_{F1}}{f_s} \leq \frac{1}{f_s} \cdot (t_{F2} + \varepsilon_{F2}) - (t_{F1} + \varepsilon_{F1}) \leq \frac{1}{f_s} \cdot (t_{F2} - t_{F1}) + \varepsilon_T \leq \frac{1}{f_s}. \hspace{1cm} (6.24)$$

To ensure that any event at the line terminal is not mistaken for an internal fault, it is required that for an internal fault to be detected, the first and second wavefronts must reach the local terminal in non-consecutive samples, as follows:

$$k_{F2} - k_{F1} \geq 2.$$  \hspace{1cm} (6.25)

In terms of the arrival times of the traveling waves, the inequality (6.25) becomes:

$$\frac{k_{F2}}{f_s} - \frac{k_{F1}}{f_s} \geq \frac{2}{f_s} \cdot (t_{F2} + \varepsilon_{F2}) - (t_{F1} + \varepsilon_{F1}) \geq \frac{2}{f_s} \cdot (t_{F2} - t_{F1}) + \varepsilon_T \geq \frac{2}{f_s}. \hspace{1cm} (6.26)$$

Due to the limitation given by the inequation (6.25), whenever the inequation (6.23) is true, the fault should be detected as external. This means there will be an unprotected zone in the local terminal and another, of the same length, in the remote terminal.

Maneuvers at the line terminals, such as transformer energization, capacitor bank switching, or load switching, may result in multiple wavefronts arriving at the local terminal within the same sampling period. This leads the relay to detect wavefronts in consecutive samples. A fault too close to the line terminals will also result in detections of wavefronts in consecutive samples by the relay. Therefore, the defined unprotected zones are important to avoid unwanted protection sensitization. Thus the need for a backup protection scheme to detect faults near the line terminals is evident.

According to the inequality (6.26), and considering that $-1/f_s < \varepsilon_T < 1/f_s$, the limit for the difference between the arrival times of the first two wavefronts, in the continuous time domain, in which an internal fault may be detected as internal, sensitizing the protection, is given by:

$$(t_{F2} - t_{F1}) > \frac{1}{f_s},$$  \hspace{1cm} (6.27)

which means that a fault will be detected as external whenever:

$$(t_{F2} - t_{F1}) \leq \frac{1}{f_s},$$  \hspace{1cm} (6.28)

That is, the fault will have occurred in an unprotected zone.
According to the inequation (6.24), and considering that $-1/f_s < \varepsilon_T < 1/f_s$, the limit for the difference between the arrival instants of the first two wavefronts, in the continuous time domain, in which an internal fault could be detected as external, not sensitizing the protection, is given by:

\[(t_{F2} - t_{F1}) < \frac{2}{f_s}, \quad (6.29)\]

which means that for an internal fault to be reliably detected as internal, one has to:

\[(t_{F2} - t_{F1}) \geq \frac{2}{f_s}, \quad (6.30)\]

which will define that a fault has occurred in the protected zone.

According to the inequations (6.27)-(6.30), there is an uncertainty zone where a fault can be detected as internal or external, depending on the value of the total error ($\varepsilon_T$). Therefore, the fault will have occurred in the uncertainty zone if:

\[\frac{1}{f_s} < t_{F2} - t_{F1} < \frac{2}{f_s}. \quad (6.31)\]

According to the inequation (6.28), the boundary of the unprotected zone occurs when

\[t_{F2} - t_{F1} = \frac{1}{f_s}. \quad (6.32)\]

Knowing that the distance traveled by the traveling wave in one sample period ($1/f_s$) is given by:

\[\Delta d = \frac{v}{f_s}, \quad (6.33)\]

then, according to equations (6.32) and (6.33), the length of the unprotected zones at each end of the line is given by:

\[\Delta d = \frac{v}{2f_s}, \quad (6.34)\]

since the traveling wave must travel the distance between the fault point and the line terminal twice in one sampling period. Thus, the total length of the unprotected zone is given by:

\[UPZ = 2\frac{\Delta d}{2} = \Delta d = \frac{v}{f_s}. \quad (6.35)\]

The beginning of the protected zone, according to the inequation (6.30), occurs when:

\[t_{F2} - t_{F1} = \frac{2}{f_s}. \quad (6.36)\]

Thus, the protected zone starts at:

\[\Delta d = \frac{v}{f_s}, \quad (6.37)\]

and its length is given by:

\[PZ = l - 2\Delta d = l - \frac{2v}{f_s}. \quad (6.38)\]

Two uncertainty zones are positioned between the end of each unprotected zone at the line terminal and the beginning of the protected zone. The length of each of the uncertainty zones
at each end of the line is given by:

$$\frac{l - (l - 2\Delta d) - 2\frac{\Delta d}{2}}{2} = \frac{\Delta d}{2} = \frac{v}{2f_s}. \quad (6.39)$$

Consequently, the total length of the uncertainty zone in the transmission line is given by:

$$UZ = 2\frac{\Delta d}{2} = \Delta d = \frac{v}{f_s}. \quad (6.40)$$

In summary, according to equations (6.34)-(6.35) and (6.37)-(6.40), faults in the region $d \leq d_F \leq l - \Delta d$ are always detected as internal, while faults in the $0 \leq d_F \leq \frac{\Delta d}{2}$ and $l - \frac{\Delta d}{2} \leq d_F \leq l$ are always detected as external. Furthermore, for the regions $\frac{\Delta d}{2} < d_F < \Delta d$ and $l - \Delta d < d_F < l - \frac{\Delta d}{2}$, faults can be detected as internal or external, depending on the total error ($\varepsilon_T$).

Percentage-wise, with respect to the total line length $l$, the zones given by the equations (6.35), (6.38) and (6.40) can be given, respectively, by:

$$UPZ(\%) = \frac{2\Delta d}{l} \times 100\% = \frac{\Delta d}{l} \times 100\% = \frac{v}{lf_s} \times 100\%, \quad (6.41)$$

$$PZ(\%) = \frac{l - 2\Delta d}{l} \times 100\% = \left(1 - \frac{2v}{lf_s}\right) \times 100\%, \quad (6.42)$$

and

$$UZ(\%) = \frac{2\Delta d}{l} \times 100\% = \frac{\Delta d}{l} \times 100\% = \frac{v}{lf_s} \times 100\%. \quad (6.43)$$

### 6.1.2 Effect of Traveling Wave Speed Estimation

A significant problem for traveling wave-based protection schemes is the error in estimating the traveling wave speed, which depends on the transmission line parameters. In turn, the line parameters are estimated with possible errors in a real system so that the exact value of the real traveling wave speed is unknown. Thus, the discrete-time internal fault detection inequality from inequality (6.22) becomes:

$$\frac{lf_s}{v_T} + 1 \leq \left\lfloor \frac{p lf_s}{v_T} \right\rfloor < \left\lfloor \frac{2lf_s}{v_T} \right\rfloor,$$

where $v_T$ is the estimated speed of the traveling wave.

The error in estimating the traveling wave speed increases the possibility of operation error in the protection scheme. For example, in Figure 6.2 the estimated speed of the traveling waves is greater than the actual speed ($v_T > v$). With this, the difference between the wavefront detection samples ($k_{F2} - k_{F1}$) is greater than the left-hand portion of the inequality (6.44). Thus, the protection will not be sensitized, depending on the value of $p$, even though the fault occurred in the transmission line’s protected zone ($PZ$).

Similarly, an external fault can be detected as internal if the estimated speed of the traveling waves is less than the actual speed ($v_T < v$). Figure 6.3 depicts an external fault where the difference between the wavefront detection samples ($k_{F2} - k_{F1}$) is smaller than the portion to the right of the inequation (6.44). Therefore, due to the error in estimating the traveling wave speed, the protection could act, depending on the value of $p$. 
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Figure 6.2: Estimated speed higher than the actual speed of the traveling waves for an internal fault.

It is then evident that the effect of the error in estimating the wave speed needs to be overcome to ensure the robustness of the protection method.

Figure 6.3: Estimated speed lower than the actual speed of the traveling waves for an external fault.
6.1.3 Error Margin for Estimation of Wave Speed in the Continuous Time Domain

According to equation (4.9) and inequations (4.8), (4.10) and (4.11), in the continuous time domain, for an internal fault to be detected as an external fault, in the most critical case - which is a fault in the center of the protected line (Figure 6.3) -, and for an external fault to be detected as internal, the following inequalities must be satisfied, respectively:

\[
\frac{l}{v} > \frac{ql}{v_T} \Rightarrow \frac{v_T}{v} > q \tag{6.45}
\]

and

\[
\frac{2l}{v} \leq \frac{ql}{v_T} \Rightarrow \frac{v_T}{v} \leq \frac{q}{2}. \tag{6.46}
\]

According to the inequation (6.45), when the estimated speed \( v_T \) is greater than the actual speed \( v \), the maximum tolerated error for an internal fault not to be detected as external is \((q - 1)100\%\). Consequently, if this limit is exceeded, analyzing only from the continuous time domain point of view, an internal fault may be detected as external. On the other hand, when the estimated speed is lower than the actual speed, the maximum tolerated error for an external fault not to be detected as internal is \((1 - q/2)100\%\). Thus, if this limit is exceeded, an external fault may be detected as internal.

6.1.4 Error Margin for Wave Speed Estimation in the Discrete Time Domain

In the discrete-time domain, according to equation (6.13) and inequation (6.44), for an internal fault to be detected as external, in the most critical case, and an external fault to be detected as internal, the following inequalities must be respected, respectively:

\[
\frac{k_{F2} - k_{F1}}{f_s} > \left[ \frac{pl f_s}{v_T} \right] \frac{1}{f_s} \cdot \varepsilon_T + \frac{l}{v} \Rightarrow \left[ \frac{pl f_s}{v_T} \right] \frac{1}{f_s} = \varepsilon_x \tag{6.47}
\]

and

\[
\frac{k_{F2} - k_{F1}}{f_s} \leq \left[ \frac{pl f_s}{v_T} \right] \frac{1}{f_s} \cdot \varepsilon_T + \frac{2l}{v} \leq \left[ \frac{pl f_s}{v_T} \right] \frac{1}{f_s}. \tag{6.48}
\]

Similar to what was done for the continuous time domain, it is possible to determine an acceptable value for the error in the speed estimation. Considering that:

\[
\frac{pl}{v_T} - \left[ \frac{pl f_s}{v_T} \right] \frac{1}{f_s} = \varepsilon_x \tag{6.49}
\]

and

\[
\varepsilon_R = \varepsilon_T + \varepsilon_x, \tag{6.50}
\]

where

\[
0 \leq \varepsilon_x < \frac{1}{f_s} \tag{6.51}
\]

and

\[
-\frac{1}{f_s} < \varepsilon_R < \frac{2}{f_s}. \tag{6.52}
\]
Then, from inequality (6.47), we have:

\[ \varepsilon_T + \frac{l}{v} > \frac{pl}{v_T} - \varepsilon_x \Rightarrow \frac{l}{v} > \frac{pl}{v_T} - \varepsilon_R. \]  
(6.53)

Therefore, an internal fault is detected as external when the ratio between the estimated speed and the actual speed satisfies:

\[ \frac{v_T}{v} > \frac{p}{1 + \frac{\varepsilon_R v}{l}}. \]  
(6.54)

To ensure that there is an acceptable margin of error where the estimated speed is greater than the actual speed without resulting in the possibility of an internal fault being detected as external (Figure 6.2), the forward term in the inequation (6.54) must be greater than one. In this situation, respecting the error margin, an internal fault within the protection zone will never be detected as external.

Analyzing now the possibility of an external fault being detected as internal, from inequality (6.48), we have:

\[ \varepsilon_T + \frac{2l}{v} \leq \frac{pl}{v_T} - \varepsilon_x \Rightarrow \frac{2l}{v} \leq \frac{pl}{v_T} - \varepsilon_R. \]  
(6.55)

Therefore, an external fault will be detected as internal when the ratio between the estimated speed and the actual speed satisfies:

\[ \frac{v_T}{v} \leq \frac{p}{1 + \frac{\varepsilon_R v}{2l}}. \]  
(6.56)

To ensure that there is an acceptable margin of error where the estimated speed is less than the actual speed without resulting in the possibility of an external fault being detected as internal (Figure 6.3), the forward term in the inequation (6.56) must be less than one. In this situation, respecting the error margin, an external fault will never be detected as internal.

The smallest margin for the estimated speed to be greater than the actual speed occurs when the right-hand term in the inequation (6.54) has the largest value for the denominator, which occurs for \( \varepsilon_R = 2/f_s \). In this situation, which is the most critical for an overestimation of the wave speed, the inequation (6.54) is rewritten as:

\[ \frac{v_T}{v} > \frac{p}{1 + \frac{2v}{lf_s}}. \]  
(6.57)

In turn, the smallest margin for the estimated speed to be smaller than the actual speed occurs when the term to the right of (6.56) has the smallest value for the denominator, which occurs for \( \varepsilon_R = -1/f_s \). In this situation, which is the most critical for an underestimation of the wave speed, (6.56) is rewritten as:

\[ \frac{v_T}{v} \leq \frac{p}{1 - \frac{v}{2lf_s}}. \]  
(6.58)

According to the above discussion, there is no margin for error in estimating the wave speed when the right-hand terms in inequations (6.57) and (6.58) are both equal to one, as follows, respectively:

\[ \frac{p}{1 + \frac{2v}{lf_s}} = 1 \because p = 1 + \frac{2v}{lf_s} \]  
(6.59)
and

\[
\frac{\nu}{1 - \frac{\nu}{2f_s}} = 1 \therefore p = 2 - \frac{\nu}{f_s}.
\]  

(6.60)

According to equations (6.59) and (6.60), it follows that there is a minimum sampling frequency at which there is a positive and negative margin of error for the estimation of the traveling wave speed, and it is given by:

\[
1 + \frac{2\nu}{f_s} = 2 - \frac{\nu}{f_s} \therefore f_s = \frac{3\nu}{l}.
\]  

(6.61)

Substituting equation (6.61) into equation (6.59) or equation (6.60) gives:

\[
p = 1 + \frac{2}{3} = 1.\bar{6},
\]  

(6.62)

which means that, considering \( p = 1.\bar{6} \), for \( f_s < 3\nu/l \), it is not possible to obtain a speed estimation that guarantees the correct detection of internal and external faults simultaneously, since there is no simultaneous positive and negative margin for error in speed estimation. On the other hand, for \( f_s \geq 3\nu/l \), the higher the sampling frequency, the higher the positive and negative error margins for speed estimation.

### 6.1.5 Minimum Frequency as a Function of Speed Estimation

For easier mathematical manipulation and future practical implementation, \( p = 1.7 \) is adopted in the method. However, the minimum sampling frequency that ensures positive and negative error margins for the estimation of the traveling wave speed must be computed. From equation (6.59), the minimum sampling frequency that ensures a positive margin of error for the speed estimation is given by:

\[
f_s > \frac{2\nu}{l(1.7 - 1)} \therefore f_s > 2.86\frac{\nu}{l} \therefore \frac{f_s}{\nu} > 2.86.
\]  

(6.63)

From equation (6.60), the minimum sampling frequency that ensures a negative margin of error in the speed estimation is given by:

\[
f_s > \frac{\nu}{l(2 - 1.7)} \therefore f_s > 3.3\frac{\nu}{l} \therefore \frac{f_s}{\nu} > 3.3.
\]  

(6.64)

Considering \( p = 1.7 \), according to inequations (6.63) and (6.64), the minimum frequency that simultaneously ensures that the term on the right in inequation (6.57) is greater than one and the term on the left in inequation (6.58) is less than one, i.e., the minimum frequency that guarantees positive and negative error margin without a fault in the protection zone being considered external or an external fault being considered internal, must be greater than \( 3.3\nu/l \). However, it is necessary to prove that the inequation (6.22) is always true, i.e., that the left-hand portion in the inequation (6.22) is the minimum value of the inequation and the right-hand portion is the maximum value, for \( p = 1.7 \) and a given sampling frequency. A property of the floor function \( (\lfloor \cdot \rfloor) \) is that when \( x - y \geq 1 \) then \( \lfloor x \rfloor - \lfloor y \rfloor \geq 1 \). Thus, to prove the right-hand portion in the inequality (6.22), one has:

\[
2\frac{f_s}{\nu} - 1.7\frac{f_s}{\nu} \geq 1 \therefore \frac{f_s}{\nu} \geq 3.3 \therefore f_s \geq 3.3\frac{\nu}{l}.
\]  

(6.65)
6.1. DISCRETE TIME DOMAIN FOR A SINGLE LINE

Similarly, to prove the left-hand side in the inequality (6.22), one has:

\[
1.7 \frac{f_s}{v} - \frac{f_s}{v} \geq 1 : \: \frac{f_s}{v} \geq 1.43 : f_s \geq 1.43 \frac{v}{l}. \tag{6.66}
\]

Therefore, for \( p = 1.7 \) and \( f_s \geq 3.3v/l \), the inequality (6.22) will be respected. The protection will act correctly even if the estimated speed has presented a positive or negative error, within the error margin given by the inequalities (6.57) and (6.58).

According to the inequations (6.57) and (6.58), it is possible to calculate positive and negative error margins for estimating the speed as a function of the actual traveling wave speed. However, the actual speed of the traveling wave is unknown information. Thus, to determine the tolerable margin of error for a particular transmission line, it is necessary to vary the actual value of the speed in the inequations (6.57) and (6.58) and compute the corresponding values for the positive and negative margins of error. Although the exact value of the wave speed is unknown, it is known that for alternating current transmission lines, the speed of the alpha component of the traveling wave is approximately 98% of the value of the speed of light \((c)\) (ZIMATH; RAMOS; FILHO, 2010). Thus, it can be guaranteed that the actual speed of the alpha-mode component of the traveling wave lies between 0.9\( c \) and \( c \), where \( c = 3 \times 10^5 \) km/s.

Figures 6.4 and 6.5 depict the positive and negative error margins, respectively, for sampling frequencies equal to \( f_s = 5 \) kHz and \( f_s = 960 \) kHz, as a function of the actual speed, which ranges from 0.9\( c \) to \( c \). For both cases, the wave speed was estimated to be equal to the speed of light \( c \). Figures 6.4 and 6.5 depict that the margin of error for a positive error in speed estimation is always larger than the margin for a negative error. Figure 6.4 depicts that for actual wave speeds greater than 0.91\( c \), the error in the speed estimation - for an estimated speed of 0.9\( c \) - is always smaller than the margin of error for \( f_s = 5 \) kHz. Therefore, it is possible to identify a minimum sampling frequency at which estimating \( v_T = c \) guarantees that the protection will act correctly. For instance, when considering \( v_T = c \) and the actual speed of the wave equal to 90% of the speed of light \((v = 0.9c)\), from the inequation (6.57), one has:

\[
f_s \geq \left( \frac{2 \ast v}{l} \right) \left( \frac{1 + \varepsilon_v}{0.7 - \varepsilon_v} \right) : f_s \geq \left( \frac{2 \ast 0.9c}{l} \right) \left( \frac{1 + \frac{0.1}{0.9}}{0.7 - \frac{0.1}{0.9}} \right), \tag{6.67}
\]

where \( \varepsilon_v \) is the error between the estimated speed \((v_T = c)\) and the actual speed \((v = 0.9c)\), and is given by:

\[
\varepsilon_v = \frac{c - 0.9c}{0.9c} = \frac{1}{9}. \tag{6.68}
\]
The inequality (6.67) was obtained from the inequality (6.57), which defines a positive error margin so that an internal fault is not detected as an external fault. Therefore, the inequality establishes a minimum sampling frequency for any value of $v$ greater than 0.9$c$.

The minimum sampling frequency that enables a positive margin of error in speed estimation is lower than the minimum sampling frequency that enables a negative margin of error for external faults not to be detected as internal, as shown by inequations (6.63) and (6.64). It is necessary to ensure that the sampling frequency given by inequality (6.67) ensures that there is room for negative error in the speed estimation, i.e., the sampling frequency must respect the inequality (6.65) as well. This procedure is necessary to ensure that even if the wave velocity is overestimated ($v_T = c$), the right-hand plot in the inequation (6.58) is not greater than one because if it is, even if the estimated wave velocity is greater than the real one, an external fault could be considered as internal due to the low sampling frequency. Therefore, by multiplying the frequency given by the inequality (6.67) by a constant $n$, it is possible to ensure that the inequality (6.65) is respected, as follows:

$$n \left( \frac{2 \times 0.9c}{l} \right) \left( \frac{1 + \frac{0.1}{0.7 - \frac{0.1}{0.9}}}{l} \right) > 3.3 \frac{v}{l} \therefore v < c \left( \frac{n + 1.5}{2.83} \right),$$

(6.69)
where, to ensure that \( v < c \), we have:

\[
\left( \frac{n + 1.6}{2.83} \right) \geq 1 \quad \Rightarrow \quad n \geq 1.16.
\]  
(6.70)

According to the inequation (6.69), adopting \( n = 1.17 \), for any actual value of the traveling wave speed between 0.9c and c, the minimum sampling frequency that guarantees a correct protection operation for internal and external faults, when estimating the wave speed as being equal to the speed of light \( (v_T = c) \), is given by:

\[
f_s \geq 1.17 \left( \frac{2 \star v}{l} \right) \left( \frac{1 + \varepsilon_v}{0.7 - \varepsilon_v} \right) \quad \therefore \quad f_s \geq 1.17 \left( \frac{2 \ast 0.9c}{l} \right) \left( \frac{1 + \frac{0.1}{0.9}}{0.7 - \frac{0.1}{0.9}} \right).
\]  
(6.71)

According to the inequation (6.71), the higher the actual value of the traveling wave speed \( v \), the lower the value of the error \( \varepsilon_v \) and, consequently, the lower the value of the sampling frequency \( f_s \). Therefore, by adopting the lowest sampling frequency considering \( v = 0.9c \), the protection scheme will act correctly for any actual traveling wave speed equal to or greater than 90% of the speed of light \( (v \geq 0.9c) \).

### 6.2 Proposed Method

According to the above, estimating the wave speed always equal to the speed of light is a good strategy, respecting the inequality (6.71). When estimating the wave speed equal to the speed of light, there is no need to try to estimate the actual speed of the wave. Therefore, an internal fault will be detected if:

\[
k_{f2} - k_{f1} \leq \left\lfloor \frac{1.7lf_s}{c} \right\rfloor.
\]  
(6.72)

Whereas an external fault will be detected if:

\[
k_{f2} - k_{f1} > \left\lfloor \frac{1.7lf_s}{c} \right\rfloor
\]  
(6.73)

and, according to inequality (6.23), if:

\[
k_{f2} - k_{f1} \leq 1.
\]  
(6.74)

### 6.3 Performance Assessment

Due to the limitation of the method regarding the correct distinction between the wave reflected from the fault point and waves reflected at adjacent line terminals, all faults were performed inside the protected line and at its terminals.

#### 6.3.1 The Power System

Figure 6.6 depicts the electrical system used. The system contains three transmission lines at a base voltage level of 500 kV. There are two transmission line configurations, type 1 and type 2. The type 1 transmission line was modeled based on a real transmission line from Chesf,
6.3. PERFORMANCE ASSESSMENT

whose parameters are the same as those published by Costa et al. (2017). The type 2 line was modeled based on a real transmission line from a system in China, whose geometric data refers to the first type of line described by Pathirana, Dirks and McLaren (2003). The lines were modeled from distributed parameters. All lines are 200 km long. A relay at bus 2 measured the signals to protect the line between buses 2 and 3.

![500 kV transmission system](image)

**Figure 6.6: 500 kV transmission system.**

6.3.2 Fault Configuration

The traveling wave-based method presented in this chapter depends on accurately detecting the arrival times of traveling waves. However, the performance evaluation of a detection method is beyond the scope of this paper. Therefore, critical cases of traveling wave detection, such as high fault resistance and low angle of fault incidence, were not analyzed, making it possible to evaluate the performance of the protection algorithm exclusively. The detector used was the redundant wavelet transform (COSTA; SOUZA; BRITO, 2010), whose wavelet family was Daubechies 4, as suggested in (COSTA; SOUZA; BRITO, 2010).

The simulations were performed with an integration step ten times larger than the sampling step. All faults were of phase A to ground type, the fault resistance was set at 10 Ω and the fault incidence angle at 90° for the phase A voltage, providing a higher incidence of electromagnetic transients. The Clark transform was applied to the voltage and current signals so that traveling waves were always detected in alpha or ground mode signals.

All evaluations were conducted with faults applied at the line terminals and inside the line, from 5 km from the local bus up to 195 km, with a 5 km step. The faults were applied with inception time $t_F$ assuming random values between $k_F/f_S$ and $k_F/f_S + 1$ with a step of $(k_F/f_S)/10$ (Figure 6.1), i.e., the fault inception error ($\varepsilon_F$) assuming random values between 0 and 0.9/$f_S$ with step of 0.1/$f_S$.

In computing the operation time for internal fault detection, the time relative to one sampling period was added, which is more than enough time for digital processing of the relay and sending the trigger signal to the circuit breaker.
6.3. PERFORMANCE ASSESSMENT

6.3.3 Minimum Sampling Frequency

Figure (6.7) depicts the minimum sampling frequency as a function of line length from the inequation (6.71). According to the theory presented, this sampling frequency should guarantee that the error in the estimation of the wave speed will always be smaller than the acceptable error margin so that an internal fault is not considered external (Figure 6.4) and an external fault is not considered internal (Figure 6.5), regardless of the line parameters. For this, the actual speed of the traveling wave must be equal to or greater than 90% of the speed of light ($v \geq 0.9c$), and the speed of light must be adopted as the estimated speed of the wave ($v_T = c$).

![Figure 6.7: Minimum sampling frequency as a function of line length.](image)

From equations (6.41)-(6.43), we have the percentages of the protected, uncertainty, and unprotected zones of the transmission line as a function of the sampling frequency, line length, and wave speed. Figure 6.8(a) depicts the variation of the protected zone as a function of line length for different sampling frequencies, while Figure 6.8(b) depicts the same parameter but added to the uncertainty zone. The higher the sampling frequency, the higher the percentages of these zones. As depicted in Figure 6.8(a), adopting 20 kHz sampling frequency, the protected zone will be equivalent to 80% of the line length for lines longer than 150 km, a value traditionally adopted for distance protection. Whereas, if the goal is to achieve such a percentage by adding the protected zone with the uncertainty zone for 20 kHz, this is achieved for lines from 75 km. Almost 100% of the line can be protected for lengths longer than 50 km by adopting a sampling frequency of 1 MHz. On the other hand, when adopting 2 kHz, it is impossible to guarantee a protected zone of 80% for lines shorter than 500 km.
6.3. PERFORMANCE ASSESSMENT

Figure 6.8: Estimation of the protected and uncertainty zones as a function of line length for specific frequencies: a) protected zone; b) protected + uncertainty zone.

By analyzing Figures 6.7 and 6.8, it can be seen that by adopting a minimum sampling frequency that guarantees 80% of the protected line, necessarily the minimum frequency for a fault in the protection zone not to be detected as external and an external fault not to be detected as internal will be respected. Thus, the minimum frequency to be adopted for the protection to act correctly can be defined as ensuring 80 percent of the protected line. Suppose the desired percentage of the protected zone is below 80%. In that case, care must be taken to respect the minimum frequency depicted in Figure 6.7 for the length of the protected line.

From equations (6.41)-(6.43), it is also possible to plot the relation between sampling frequency and protection zone for given line lengths. Such a relation is depicted in Figure 6.9(a) for 50, 200, and 500 km line lengths. The same relation is depicted in Figure 6.9(b) but with the sum between the protected and uncertainty zones. The longer the line length, the lower the sampling frequency needed to guarantee certain percentages of the zones. Note that for lines longer than 50 km, the protected zone of 80% is guaranteed for a frequency of 60 kHz, while if the objective is that the protected zone added to the uncertainty zone reaches this percentage, the frequency drops to 30 kHz for lines longer than 50 km. For a 200 km line, which will be analyzed in more detail in this chapter, a protected zone of 80% is guaranteed with a sampling frequency of 15 kHz.

As in Costa et al. (2017) for two-terminal methods, this method breaks the paradigm of high sampling frequencies for one-terminal methods if the goal is to protect a percentage of the transmission line. To have broader protection, higher rates will be required.

6.3.4 Method Performance

According to Figure 6.7, a sampling frequency of 6 kHz guarantees that, for a 200 km long line, a fault in the protected zone is not detected as external, and an external fault is not detected
as internal. Adopting this frequency, the protected zone of the line is 50%, and the unprotected zones in each line terminal compose 12.5% of the line and the uncertainty zones.

Figure 6.10 illustrates the method’s performance for a frequency of 6 kHz and a line length of 200 km. As mathematically predicted, no faults were detected as internal in the unprotected zones, whereas all faults in the protected zone were detected, as well as some in the uncertainty zones. Therefore, the method was 100% correct. The maximum operating time was 1.2 ms, and the average was 1.01 ms. This is considerably below the average operating time for traditional distance protections, which operate after one wave cycle of the fundamental signal, which is 16.67 ms for 60 Hz. For specific cases, such as faults close to the local terminal of the line, the operating time of traditional distance protections is 8 ms. The two-terminal protection method based on traveling waves proposed by Costa et al. (2017) showed a maximum operating time of 2.85 ms for 4 kHz and 2.5 ms for 20 kHz, i.e., more than double the time required for the method proposed here, thus evidencing the potential of one-terminal methods for fast performance.
Figure 6.11 depicts the protection behavior for a sampling frequency of 1.8 kHz, well below the minimum required for external faults not to be detected as internal. For the 1.8 kHz frequency, the line has no protected zone, but only the unprotected zones, composing 83.33% of the line, and an uncertainty zone in the center of the line, which composes 16.67% of the line. Therefore, only one fault was detected inside the line in the uncertainty zone. However, an external fault at the remote terminal was detected as internal. It is evident, therefore, that frequencies below the defined theoretical minimum do not guarantee the correct performance of the protection.

![Figure 6.11: Protection operation for a 200 km line and $f_S = 1.8$ kHz.](image)

In Figure 6.12, the method’s performance is presented for a sampling frequency of 15 kHz, which is the frequency from which 80% of the 200 km line will be within the protected zone. The protection operated correctly for the faults within the protection zone. It was not sensitized for any fault in the unprotected zone or at the terminals of the protected line. The maximum operating time was 1.11 ms and the average was 0.806 ms, demonstrating that the method’s operating time is inversely proportional to the value of the sampling frequency.

![Figure 6.12: Protection operation for a 200 km line and $f_S = 15$ kHz.](image)

A sampling frequency rate of 15360 Hz is commercially viable for relays. It ensures that at least 80% of a transmission line of up to 200 km is protected very quickly, regardless of its electrical parameters. Faults very close to the line terminals would be handled by traditional protections, which are efficient for close faults.
6.4 Conclusion

This chapter proposed a method for protecting transmission lines using only one terminal. An extensive mathematical investigation of the effect of sampling frequency and error on estimating the traveling wave speed was performed.

The method establishes a clear mathematical parameter for defining a minimum sampling frequency, which makes it possible to adopt low sampling frequencies. Such a mathematical definition is unprecedented for one-terminal traveling wave-based methods. This also represents a paradigm break since traveling wave-based methods require high sampling frequencies of hundreds of kHz. The method is also independent of the estimation of the traveling wave velocity. This also represents a paradigm break for traveling wave-based methods, especially those based on one terminal.

The proposed method achieved 100% accuracy for the protected zone defined by the adopted sampling frequency, regardless of the line’s electrical parameters. The operation time of the method was well below those presented by traditional methods. It also performed well when compared to traveling wave-based two-terminal methods.

The correct and reliable distinction between the reflected wave from the fault point and reflected waves at line terminals when adjacent lines occur has not been investigated in this thesis. Thus, this is still an open issue for the scientific community. Therefore the method is only valid for point-to-point lines, not connected to adjacent lines. Furthermore, the method only applies to transmission lines where the actual speed of the traveling wave is between 90 and 100% percent of the speed of light. This covers almost all overhead lines, whose wave speed is around 98% of the speed of light.

6.5 Chapter Synthesis

In this chapter, a one-terminal method based on traveling waves has been presented. The method applies to simple, point-to-point transmission lines with no adjacent lines. It is also limited to transmission lines with traveling waves with speed above 90% of the speed of light. An extensive investigation of the effect of sampling frequency and error on estimating the traveling wave speed has been performed. Consequently, the method is independent of estimating the traveling wave speed and can also be applied for low sampling frequencies.
Chapter 7
Applicability of Wave-based Distance Protection for Earth Faults Applied to Meshed HVDC Systems

This chapter investigates the applicability of a distance protection method for earth faults applied to a meshed HVDC system. A traveling wave-based fault location method is proposed, starting from the analysis of the effect of sampling frequency. Traveling wave detections are also used to define the faulty section and guarantee selectivity to the method.

7.1 The Need for Full Protection Selectivity

The objective of the protection in both HVAC and HVDC systems can be summarized as fault clearing in the system. That is, after detecting the fault, protection needs to act to prevent the system from continuing to supply the short-circuit current. However, HVDC systems are more flexible concerning the mode of operation after the fault has been eliminated. For example, in the case of a permanent fault on one pole of the transmission line, symmetrical monopolar or bipolar systems can decouple from the transmission line. Their converters can enter in static synchronous compensator (STATCOM) mode, supplying reactive power to the HVAC system. A flexible bipolar system, on the other hand, would be able to act in monopolar mode through, for example, a DMR (Dedicated Metallic Return). However, for the correct operating mode selection, the protection must be fully selective and inform the system of the correct fault zone.

Traditional HVDC protection functions can protect the system for transmission line faults quickly and without communication between stations. This is the case for the 76DC (IEEE., 2008) overcurrent protection. HVDC converters have a dedicated and highly sensitive overcurrent detection (OCD) function with a short trip time. However, these functions have no selectivity capability and can be sensitized by faults at any point in the system.

Commercial HVDC systems can achieve full selectivity capability for transmission line faults through station communication. However, the need for communication slows down significantly the protection selectivity (CIGRÉ, 2018).

For meshed HVDC systems, the protection must operate below 2 ms, and the fault must be cleared within 5 ms (CIGRÉ, 2018). Thus, even if non-selective protection can detect the fault below 2 ms, selectivity should still be achieved below 5 ms. After this time, there would be no more fault currents, and determining the fault zone would no longer be possible. For transmission line faults, the currently commercially available protection functions for HVDC systems cannot be selective without communication between the terminals. Therefore, due to the communication delay, full fault selectivity cannot be achieved within 5 ms.
In this context, fast-acting distance protection would be of great relevance for HVDC systems without a communication system between the system terminals. This protection would guarantee protection selectivity for most faults on the transmission line. For meshed HVDC systems, it could be of even more relevance if it is able to guarantee protection selectivity on multiple interconnected transmission lines.

7.2 Principles of Distance Protection Applied to Meshed HVDC Systems

The general idea of traveling-wave-based distance protection for earth faults as described in the section 5.1. Fig. 7.1 depicts the Lattice diagram for an earth fault applied to one of the transmission lines of a meshed HVDC system. Due to the difference in speed of the modal waves (LIU et al., 2012), they arrive at each system bus at different times. This time difference can be used to estimate the location of the fault. Due to the sampling process of the voltages and currents at each bus, the arrival times in the continuous-time domain \( t_\alpha \) and \( t_0 \) are unknown. Thus, they are replaced by their counterparts in the discrete-time domain, \( k_\alpha/f_S \) and \( k_0/f_S \), where \( k_\alpha \) and \( k_0 \) are samples that represent \( t_\alpha \) and \( t_0 \) in the digital time domain, respectively.

Since multiple lines are in the system, a fault on any line may lead to buses not being connected to the faulty line detecting these waves. Thus, without a correct estimation of the location of the fault, protections on different buses may mistakenly detect the fault as internal. In addition, as it propagates through a faulty line, the traveling wave reaches the bus and is

![Diagram of HVDC system with distance protection principles](image_url)

Figure 7.1: Principles of the distance protection for earth faults applied to a meshed HVDC system.
transmitted to a subsequent line, also connected to the same bus. In this way, all the voltage and current measurements for the lines connected to the same bus can simultaneously detect the traveling wave. Therefore, it becomes a challenge to correctly detect from which line the traveling wave propagated, making it difficult to estimate the location of the fault.

For full selectivity of protection in a meshed HVDC system, the traveling wave-based distance protection function at each bus must detect which section of line the traveling wave came from. From there, the protection function must estimate the location of the fault and be able to define whether the fault is internal to the protected line.

### 7.3 The Proposed Distance Protection Function

The proposed earth fault distance protection function is developed by considering the sampling frequency effects on the fault location estimation. Modal traveling waves are required to detect the faulty section and the fault location on the faulty line. Below is addressed a detailed analysis.

#### 7.3.1 Continuous Time Domain

The time delay between the fault inception time \( t_F \) and the first wavefront arrival times in the bus \( L \), \( t_\alpha \) and \( t_0 \), depends on the modal traveling wave speeds and fault distance from the bus \( L \), as follows:

\[
t_\alpha - t_F = \frac{d_F}{v_\alpha},
\]

and

\[
t_0 - t_F = \frac{d_F}{v_0}.
\]

The difference between the time delays is given by:

\[
(t_0 - t_F) - (t_\alpha - t_F) = t_0 - t_\alpha = \frac{d_F}{v_0} - \frac{d_F}{v_\alpha} = \frac{v_\alpha - v_0}{v_\alpha v_0} d_F.
\]

Therefore, the fault distance from the local bus is given by (LIU et al., 2012):

\[
d_F = \frac{t_0 - t_\alpha}{m},
\]

where \( m \) is a variable dependent on the modal traveling wave speeds, given by (LIU et al., 2012):

\[
m = \frac{v_\alpha - v_0}{v_\alpha v_0}.
\]

#### 7.3.2 Discrete Time Domain

The IEDs (Intelligent Electronic Devices) that measure the voltages and currents at the transmission line terminals are digital devices. Thus, the measured signals must be discretized employing a fixed sampling frequency. Therefore, the exact arrival time of the modal traveling waves at the local bus \( t_\alpha \) and \( t_0 \) are unknown and are replaced by their respective discrete time
7.3. THE PROPOSED DISTANCE PROTECTION FUNCTION

\( (k_\alpha/f_s \text{ and } k_0/f_s) \). The discrete wavefront arrival times are given by:

\[
\frac{k_\alpha}{f_s} = \left\lfloor \frac{t_\alpha f_s}{f_s} \right\rfloor + \frac{1}{f_s},
\]

where

\[
t_\alpha < \frac{k_\alpha}{f_s} \leq t_\alpha + \frac{1}{f_s},
\]

and

\[
\frac{k_0}{f_s} = \left\lfloor \frac{t_0 f_s}{f_s} \right\rfloor + \frac{1}{f_s},
\]

where

\[
t_0 < \frac{k_0}{f_s} \leq t_0 + \frac{1}{f_s},
\]

where \( \left\lfloor * \right\rfloor \) is the largest integer value not greater than * (floor function).

The discrete fault inception time \( k_F/f_S \), which is the new reference time, is given by:

\[
\frac{k_F}{f_S} = \left\lfloor \frac{t_F f_S}{f_S} \right\rfloor,
\]

where

\[
t_F - \frac{1}{f_S} \leq \frac{k_F}{f_S} \leq t_F.
\]

The sampling frequency process yields errors in the wavefront arrival times and the reference time. The error on the fault inception time is given by:

\[
\varepsilon_F = t_F - \frac{k_F}{f_S},
\]

where

\[
0 \leq \varepsilon_F < \frac{1}{f_S},
\]

The errors on the wavefront arrival times are given by:

\[
\varepsilon_\alpha = \frac{k_\alpha}{f_S} - t_\alpha,
\]

where

\[
0 \leq \varepsilon_\alpha < \frac{1}{f_S},
\]

and

\[
\varepsilon_0 = \frac{k_0}{f_S} - t_0,
\]

where

\[
0 \leq \varepsilon_0 < \frac{1}{f_S},
\]

Therefore, the difference between the time delays may also be given by:

\[
t_0 - t_\alpha = \frac{k_0 - k_\alpha}{f_S} + (\varepsilon_\alpha - \varepsilon_0),
\]
where
\[ -\frac{1}{f_s} < \varepsilon_{\alpha} - \varepsilon_0 < \frac{1}{f_s}. \] (7.19)

From (7.4) and (7.18), the fault distance, considering the sampling frequency process, becomes:
\[ d_F = \frac{k_0 - k_{\alpha} + (\varepsilon_{\alpha} - \varepsilon_0)f_s}{m f_s}. \] (7.20)

Assuming the limit values for \( \varepsilon_{\alpha} - \varepsilon_0 \), which are \(-1/f_s \) and \(1/f_s \), the fault location can be estimated by:
\[ \frac{k_0 - k_{\alpha} - 1}{m f_s} < d_F < \frac{k_0 - k_{\alpha} + 1}{m f_s}. \] (7.21)

(7.4) is a particular case of (7.21). The methods that perform the fault location estimation by (7.4) assume \( \varepsilon_{\alpha} - \varepsilon_0 = 0 \) in (7.21), as follows:
\[ d_F = \frac{k_0 - k_{\alpha}}{m f_s}, \] (7.22)
which is not true, for the most faults.

### 7.3.2.1 The Search Zone

Analyzing the sampling frequency effect on the fault location enables the definition of a desired search zone for the fault location. The left and right sides of (7.21) are the minimum and maximum limits for estimating the fault location. Thus, if a search zone of \( p \) km is desired, then:
\[ \frac{k_0 - k_{\alpha} + 1}{m f_s} - \frac{k_0 - k_{\alpha} - 1}{m f_s} \leq p \therefore \frac{2}{m f_s} \leq p, \] (7.23)
or
\[ f_s \geq \frac{2}{m p}. \] (7.24)

Therefore, the fault location can be estimated with 100\% assurance for a specific desired search zone when a minimum sampling frequency is adopted.

From (7.24), the length of the search zone can be estimated by adopting a specific sampling frequency as follows:
\[ p = \frac{2}{m f_s}. \] (7.25)

The distance from \( d_F \) given by (7.22) to the inferior and the superior limits of the search zone, given by (7.21), are equal. Therefore, the estimated point for the fault location given by (7.22) returns a maximum error equal to \( p/2 \).

### 7.4 The Proposed Method

This work proposes a methodology where the fault location is estimated within a range of search as a function of the sampling frequency. The range for the fault location is given by (7.21), where the length of the desired search zone \( p \) is respected by adopting a minimum sampling frequency given by (7.24). A mean fault location is given by (7.22), positioned in the center of the search zone.
For instance, assuming a particular transmission line where $v_\alpha = 2.9429 \times 10^5$ km/s and $v_0 = 1.5975 \times 10^5$ km/s, according to (7.5), $m = 2.8620 \times 10^{-6}$. Adopting $f_S = 100$ kHz, according to (7.25), $p \approx 7$ km. Considering a fault where $k_0 - k_\alpha = 15$, according to (7.21), the range for the fault location is from 48.92 to 55.90 km, i.e., the length of the range is 6.98 km. According to (7.22), the mean location for the fault is 52.41 km.

7.4.1 Definition of the Faulty Section

When reaching a bus in a meshed HVDC system like the one in Fig. 7.1, a traveling wave is attenuated by the inductor connected to the line. Thus, before being transmitted to another line connected to the same bus, it is again attenuated by the inductor of the neighboring line. Therefore, the voltage and current meters connected to the line after the inductor detect a transmitted wave that is more attenuated than before the inductor on the originating line.

Sabug Jr. et al. (2020) calculates the wavelet transform the energy of transients measured by meters connected between the line inductor and the line. Thus, the authors determine the faulty section by identifying the transients with the highest energy.

This thesis compares the amplitudes of traveling waves detected at each line terminal connected to the same bus. Measurements should be taken between the inductor connected to the line and the line, as Fig. 7.1 depicts. In this way, it is possible to define from which line section the traveling wave originated.

7.5 Performance Assessment

Two HVDC test systems were modeled in order to evaluate the proposed method. The first is a multiterminal meshed system whose transmission lines have been modeled with Bergeron’s model. In this model, the traveling wave speeds can be accurately computed. Therefore, the effect of the sampling frequency and the mathematics presented in this work can be precisely evaluated in section 7.5.1.

The second system is a point-to-point LCC system based on an actual system. The transmission line is modeled with the JMarti frequency-dependent distributed parameter line model. This is a more realistic line model in which the traveling wave speed is unknown and needs to be estimated. Thus, the proposed fault location estimation method can be evaluated by accounting for errors in the modal traveling wave speed estimation in section 7.5.2.

7.5.1 Test System 1

Fig. 7.2 depicts the meshed HVDC grid considered in this work. The system is based on the one proposed by Leterme et al. (2015). The system is a symmetrical monopolar with a ± 320 kV voltage. It consists of four terminals with modular multilevel converters (MMC). The terminals are connected by five overhead transmission lines, forming a meshed system. All converters are connected to AC equivalents. The AC systems connected to buses 1 and 2 supply power to the DC system. Whereas the AC equivalents at buses 3 and 4 consume power from the DC system.

The AC systems are modeled as ideal 370 kV, 60 Hz voltage sources connected in series to a concentrated impedance equivalent. Fig. 7.3 depicts the parameters of the HVDC transmission lines. The lines are based on a real Brazilian HVDC system, the Madeira River system (LUZ; JUNIOR; JUNIOR, 2014). The transmission lines are modeled using the Bergeron frequency-independent distributed parameter model. Table 7.1 depicts the transmission line parameters
for the Bergeron model. The modal wave speeds are $v_\alpha \approx 2.9429 \times 10^5 (0.9921c)$ and $v_0 \approx 1.5975 \times 10^5 (0.5325c)$, and computed as follows:

$$v_\alpha = \frac{1}{\sqrt{L_\alpha C_\alpha}} \approx 2.9429 \times 10^5$$

and

$$v_0 = \frac{1}{\sqrt{L_0 C_0}} \approx 1.5975 \times 10^5.$$  

Faults were simulated using MATLAB/Simulink® at a sampling frequency of 100 kHz. On each line, faults were applied by varying the fault location at a 5 km step. Also, faults were applied at 3 km from the stations at each line’s terminal. The faults applied were of the positive pole-to-ground, negative pole-to-ground, and pole-to-pole fault types. 63 faults were applied on each of the lines L12 and L24. Each of the lines L14, L13, and L34 had 123 faults applied.
In total, 495 faults were applied to all five lines in the system. Subsequently, the following performance assessment methodology was adopted:

1. the detection of the faulty section for all 495 faults applied was performed in the subsection 7.5.1.2;
2. a discussion about the sampling frequency to be adopted depending on the search zone was addressed in subsection 7.5.1.3;
3. the performance assessment of the proposed fault location method for all 330 earth faults applied to all transmission lines, as addressed in subsection 7.5.1.4;
4. the evaluation of the protection operation time for all earth faults detected as internal ones, as addressed in 7.5.1.6.

7.5.1.1 Converter Topology and Controls

Each MMC converter has six arms consisting of five switching modules (SMs) connected in series with an impedance $RL$. The SMs are of the half-bridge type composed of insulated-gate bipolar transistors (IGBTs).

Fig. 7.4 depicts the diagram of high-level and low-level controllers of MMCs. The low-level control consists of a phase disposition sinusoidal pulse width modulation (PD-SPWM). It is responsible for voltage balancing for the SMs. The high-level control, in turn, is divided into two sub-controls, one for active power control and one for reactive power control. Each sub-control consists of two control loops, external and internal. The external control provides the internal control’s current reference $dq$. The internal control loop provides voltage reference for the PD-SPWM.

The high-level control follows a master-slave strategy. The converter station at bus 4 is the main master station for voltage control on the $d$ axis. The bus 3 station assumes the backup master position. The stations at buses 1, 2, and 3 perform active power control with references at -200 MW, -100 MW, and 150 MW, respectively. All the MMCs perform reactive power control on the $q$ axis. A detailed system description can be found in Santos (2021).

![High-level and low-level controllers diagram.](image)

Table 7.1: Electrical parameters for the transmission line.

<table>
<thead>
<tr>
<th></th>
<th>Aerial Mode</th>
<th>Ground Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$ ($\Omega$/km)</td>
<td>$L$ (mH/km)</td>
<td>$C$ ($\mu$F/km)</td>
</tr>
<tr>
<td>Aerial Mode</td>
<td>Ground Mode</td>
<td>Aerial Mode</td>
</tr>
<tr>
<td>0.00702</td>
<td>0.860602</td>
<td>0.0134166</td>
</tr>
</tbody>
</table>
7.5.1.2 Definition of the Faulty Section

All the buses are connected to more than one line for the HVDC meshed system under analysis. Thus, the traveling wave is transmitted to the other lines when propagating through a specific line and colliding with a bus. Therefore, the traveling wave can be detected through the voltage measurements of all lines. By defining the line from which the traveling wave originally arrived, it is possible to estimate the location of the fault more accurately. To do this, the method compares the intensity of the wavefront measured on all lines connected to the bus at the arrival time of the first alpha-mode wavefront. The wavefront with the highest intensity indicates the faulty section.

Fig. 7.5 depicts the wavelet transform coefficients for the alpha-mode voltage signals at buses 1 and 2 for a fault on line L12 located 50 km from bus 1. Fig. 7.5(a) depicts that the highest intensity traveling wavelet is detected on line L12 for bus 1. Although it cannot be determined if the fault occurred at line L12, it can be determined that the traveling wave propagated through that line. Fig. 7.5(b) depicts that for the bus 2, the method correctly detected that the wave propagated from line L12 as well. If there was communication between these two buses, it would be possible to determine that the fault occurred on line L12. However, since the method does not rely on telecommunication, it is not possible to determine the faulty line without first estimating the location of the fault.

![Wavelet Transform Coefficients for Buses 1 and 2](image1)

Fig. 7.5 depicts that for buses 3 and 4, the method correctly detected the faulty section. For

![Wavelet Transform Coefficients for Buses 3 and 4](image2)
bus 3, the traveling wave came from line L31. For bar 4, the wave came from line L24. For all 495 faults applied in the system, the method could correctly detect the faulty section. This was possible even for the pole-to-pole faults since they generate alpha-mode traveling waves.

### 7.5.1.3 Search Zone

Fig. 7.7 depicts the minimum sampling frequency as a function of the desired length for the search zone, considering the transmission line depicted on 7.2. The greater the sampling frequency the smaller the search zone. 7.7(a) depicts the sampling frequency required for search zones varying from 0 to 35 km. For instance, a sampling frequency of 100 kHz ensures a search zone of about 7 km. Fig. 7.7(b) depicts the search zone for a sampling frequency within a range traditionally adopted in real HVDC systems. For example, for a sampling frequency of 25 kHz, the search zone is approximately 28 km. On the other hand, for higher sampling frequencies and commercially available for HVAC systems, Fig. 7.7(c) depicts a search zone between 1 and 7 km. For 1 MHz, the search zone is 700 meters, which represents an error for the mean fault location close to a typical tower span, approximately 300 m.

![Wavelet Transform Coefficients](image)

Figure 7.6: Wavelet transform coefficients for a fault on line L12 for the alpha-mode voltages of all lines connected to: (a) bus 3; (b) bus 4.
Figure 7.7: Minimum sampling frequency as a function of the desired length for the search zone, which varies from: (a) 0 to 35 km; (b) 20 to 70 km; (c) 0 to 8 km.
7.5. PERFORMANCE ASSESSMENT

7.5.1.4 Fault Location Estimation

Fig. 7.8 depicts the Lattice diagram for a positive pole to ground fault on line L12, distanced 50 km from bus 1. The adopted sampling frequency was 100 kHz. The difference in samples between the arrival times of the alpha and zero mode waves measured on bus 1 was 15 samples. The range for the fault location estimation on bus 1 given by (7.21) is from 48.92 to 55.90 km. The mean fault location estimation on bus 1 given by (7.22) is 52.41 km.

![Lattice diagram](image)

Table 7.2 summarizes the fault location estimations and their respective errors at all buses for this specific fault. The faulty transmission line is connected to buses 1 and 2. Considering only the fault location estimated by these two buses, the maximum error was 5.9 km. This value is below the mathematically predicted search zone, which is 7 km. Similarly occurs for bus 4. However, for bus 3, the maximum error was 8.9 km. Thus bus is 250 km from the fault point and is not connected to a faulty line. Thus, the traveling wave detection becomes less accurate, which influences the accuracy of the fault location estimation. However, even less precise, this is still relevant information since it was estimated without communicating with the other buses in the system.

<table>
<thead>
<tr>
<th>Bus</th>
<th>Estimation (km)</th>
<th>Error (km)</th>
<th>Superior Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48.92</td>
<td>-1.08</td>
<td>55.90</td>
</tr>
<tr>
<td>2</td>
<td>48.92</td>
<td>-1.08</td>
<td>55.90</td>
</tr>
<tr>
<td>3</td>
<td>241.1</td>
<td>-8.90</td>
<td>248.08</td>
</tr>
<tr>
<td>4</td>
<td>146.75</td>
<td>-3.25</td>
<td>153.74</td>
</tr>
</tbody>
</table>

Table 7.2: Fault location estimation for a fault on line L12 at 50 km from bus 1.
7.5. PERFORMANCE ASSESSMENT

### 7.5.1.4.1 Variation of Fault Location on Line L12

Fig. 7.9 depicts the error in fault location estimation for a positive pole to ground faults applied on line L12 and estimations made on buses 1 and 2. The faults were applied from 5 to 95 km from bus 1, at steps of 5 km. Additionally, faults were applied at 3 and 97 km so that the boundary of the search zone could be checked. This makes a total of 21 fault cases. Both buses 1 and 2 performed equally well in fault location estimation. Fig. 7.10 depicts the fault location estimation on bus 1 as a function of the fault location for the same fault cases.

![Graph showing error in fault location estimation as a function of fault location for bus 1 and bus 2.](image)

Figure 7.9: Error in the fault location estimation as a function of the fault location for faults on the line L12 for: (a) estimation on bus 1; (b) estimation on bus 2.

All wavefronts were correctly detected so that all faults were estimated within the mathematically predicted search zone. The fault applied at 3 km had its mean location estimated at 0 km, with the search zone outside the L12 line. The fault applied at 97 km had its mean estimated location within line L12 but with a search zone extending to line L24. For these fault cases, the previous detection of the faulty line would be fundamental for the correct fault location estimation and eventual protection operation.

Fig. 7.11 depicts the fault location estimation for the faults applied on line L12 and estimations performed on buses 3 and 4. For both buses, several faults were located slightly outside the search zone. This is due to incorrect detection of the wavefronts. Wavefronts are attenuated when they reach the line terminals and are transmitted to an adjacent line. In addition, the
greater the distance from the fault point, the greater the attenuation of the wave. These factors make it difficult to detect the correct arrival sample of the wavefront. Thus, the estimation of the fault location performed by buses not connected to the faulty line can be used efficiently to determine whether the fault is internal or external to the lines connected to these buses. However, the buses connected to the faulty line can estimate more accurately the fault location due to the lower attenuation of the wavefronts arriving at these buses.

**7.5.1.4.2 Variation of Fault Location on Line L13**

Positive pole-to-ground faults were applied on the L13 line from 5 to 195 km, at steps of 5 km. Additionally, faults were applied at 3 and 197 km. Thus totaling 41 fault cases. Fig. 7.12 depicts the error in fault location estimation as a function of the fault point for buses 1 and 3. All fault locations were estimated within the mathematically defined search zone.

Fig. 7.13 depicts the fault location estimation as a function of the fault location for measurements taken at bus 2. This bus is not directly connected to the faulty line. Therefore, the traveling waves arrived at bus 2 with higher attenuation. This resulted in inaccuracy in detecting the correct sample arrival of the waves. Thus, in some cases, the fault was located slightly outside the search zone stipulated by the method.

Fig. 7.14 depicts the fault location estimation as a function of the fault location for measurements performed at bus 4. Fig. 7.14(a) depicts the estimation performed for waves that arrived at bus 4 from line L41. Whereas Fig. 7.14(b) depicts the estimation for waves coming from line L43. This is because, for the first half of the faults applied on line L13, the shortest path to bus 4 is through line L41, which is 200 km long. For faults applied on the second half of line
Figure 7.11: Fault location estimation as a function of the fault location for faults on the line L12 for: (a) estimation on bus 3; (b) estimation on bus 4.
L13, the shortest path for traveling waves is through line L43, which is also 200 km long. This way, even varying the fault point on line L13 with a range of approximately 200 km, the fault location at bus 4 was correctly estimated with a range of approximately 100 km.

7.5.1.4.3 Variation of Fault Location on Lines L14, L24, and L34

The same methodology was applied for pole-to-ground faults on lines L14, L24, and L34. Therefore, 41 faults were applied on lines L14, 21 on L24, and 41 on L34. This makes a total of 103 additional fault cases. The proposed method performed similarly to the results presented for the faults in lines L12 and L13. For all cases, the buses connected to the faulty line estimated the fault location within the previously calculated search zone. For the other buses, in some cases, the traveling wave arrival samples were not detected with complete accuracy, which resulted in an estimation of the fault location slightly outside the search zone.
7.5. PERFORMANCE ASSESSMENT

7.5.1.5 Negative Pole-to-Ground and Pole-to-Pole Fault Cases

All the fault cases mentioned so far were repeated for negative pole-to-ground and pole-to-pole faults. Thus, 165 negative pole-to-ground and 165 inter-pole faults were applied on lines L12, L13, L14, L24, and L34. For the negative pole-to-ground faults, the results were the same as for the positive pole-to-ground faults. The method could not estimate the faults’ location for the inter-pole faults since there was no detection of zero-mode waves.

7.5.1.6 Protection Operation Time

The distance protection was parameterized to operate for faults with a location range of less than 90% of the line length. The operation time of the protection corresponds to the time between the fault inception time and the arrival of the zero-mode traveling wave, added to a sampling time of the IED.

Fig. 7.15 depicts the operation time of the protection as a function of the fault location for positive pole-to-ground faults. The faults were applied on line L12. The protection functions on buses 1 and 2 were sensitized. Fig. 7.15(a) depicts the operation time of the protection at bus 1. Fig. 7.15(b) depicts the operation time of the protection at bus 2 with the fault location taking as reference bus 1. All faults up to 80 km were detected as internal for both buses. The fault applied at 85 km was estimated at 83.86 and 90.85 km. Thus, above 90 km of the defined protection zone. The maximum operation time was 0.54 ms.

Fig. 7.16 depicts the operation time of the protection for fault applied on line L13. Only the protections on buses 1 and 3 were sensitized. All applied faults up to 175 km were correctly detected as internal. From 180 km onwards, all faults were correctly detected outside the defined...
Figure 7.14: Fault location estimation as a function of the fault location for faults on the line L13 and estimation on bus 4 for traveling waves coming from the line: (a) L41; (b) L43.
7.5. PERFORMANCE ASSESSMENT

Figure 7.15: Protection operation time as a function of the fault location referred to bus 1 for faults on the line L12 and protection function on: (a) bus 1; (b) bus 2.

Similar results were found for the faults applied to lines L14, L24, and L34. The same operating times for the positive pole-to-ground faults were also performed for the negative pole-to-ground faults. The method was not able to detect any pole-to-pole faults.

The method can detect the fault in both terminals connected to the faulty line only when the fault is within the protection zone for both buses. Otherwise, only one of the line terminals can detect the fault as internal. In this situation, it would not be possible to have full protection selectivity without communication between the terminals.

A DTT protection scheme could be achieved for the proposed distance protection. In this way, getting full protection selectivity with only local measurement data would be possible. However, in this situation, communication between the terminals would still be required for a direct trip transfer signal to be sent to the remote terminal.

Fig. 7.17 depicts the cumulative frequency of the protection operation time for the cases in which the protection tripped. Among the 330 cases of pole-to-ground faults applied in the system, the distance protection tripped for 284 cases. All were correctly detected as internal faults. Thus, defined for a protection zone of 90% in each line, the protection operated in 86% of the grounded faults. All faults were correctly detected by at least one of the buses in less than 1.2 ms. Thus, it is evident that traveling wave-based distance protection applied to HVDC meshed systems is fast. Furthermore, such protection can be of great relevance in the context
of the need for total selectivity of protection in the occurrence of faults on transmission lines when there is no communication between the system terminals.

Figure 7.16: Protection operation time as a function of the fault location referred to bus 1 for faults on the line L13 and protection function on: (a) bus 1; (b) bus 3.

Figure 7.17: Cumulative frequency for the protection operation time.
7.5. PERFORMANCE ASSESSMENT

7.5.2 Test System 2

Fig. 7.18 depicts the simplified topology of the LCC-HVDC transmission system used to assess the performance of the proposed protection system. This benchmark model is based on the Madeira River system of ±600 kV and 3150 MW/pole (LUZ; JUNIOR; JUNIOR, 2014). It is modeled on the EMTP/ATPDraw software and is available for download in (LUZ, 2016). The protected DC transmission line is 500 km long and modeled with the JMarti frequency-dependent distributed parameter line model according to its geometrical parameters shown in Fig. 7.3. Additionally, the adjacent AC transmission lines are 100 km long and modeled with the JMarti model. The geometrical parameters of the AC transmission lines are based on an actual 230-kV system and are depicted in Fig. 7.19.

![Diagram](image)

Figure 7.18: Point-to-point LCC-HVDC test system.

![Diagram](image)

Figure 7.19: Geometrical parameters for the AC transmission line.

In the JMarti frequency-dependent model, the traveling wave speed is unknown, so it needs to be estimated. In the design of real HVDC transmission lines, the system is completely modeled in an EMTDC (Electromagnetic Transients including DC) software. The modeling is done with high accuracy since all data for all components of the real system to be implemented is known. In addition, the entire control and protection design is implemented based on simulations of the modeled system. Thus, a viable strategy for estimating the modal traveling wave speeds would be through simulation. Additionally, the estimation could be performed on a real system employing an energization procedure. This procedure has been adopted before for real HVAC systems (SCHWEITZER et al., 2016) and has been proven to be suitable in simulations for estimating modal wave speeds (FRANÇA et al., 2020).

For test system 2, modal wave speeds were estimated from the simulation of a pole-to-ground fault at the end of the protected DC line at the remote station connection. The modal wave propagation time was measured from the fault inception time to the instants of modal wave arrival at the local station. The modal wave speeds were estimated as $v_\alpha \approx 2.9429 \times 10^5$ (0.9921$c$) and $v_0 \approx 2.6042 \times 10^5$ (0.8681$c$).
Simulations were performed with a simulation step-size equal to 1 µs. The adopted relay sampling frequency was 25 kHz. Positive pole-to-ground faults were applied by varying the fault location at a 5 km step from 0 to 500 km of the protected DC line. In total, 101 faults were applied. The following performance assessment methodology was adopted:

1. a discussion about the sampling frequency to be adopted depending on the search zone was addressed in subsection 7.5.2.1;
2. the performance assessment of the proposed fault location method, as addressed in subsection 7.5.2.2;
3. the evaluation of the protection operation time for all faults detected as internal ones, as addressed in 7.5.2.3.

7.5.2.1 Search Zone

Fig. 7.20 depicts the minimum sampling frequency as a function of the desired length for the search zone, considering the system depicted in Fig. 7.18. In test system 2 the zero-mode wave speed is considerably higher than in test system 1. This is because the transmission line is modeled with the JMarti frequency-dependent model. As a consequence, the length of the search zone becomes larger, according to 7.25. For the sampling frequency of 25 kHz, the search zone now becomes approximately 166 km. A sampling frequency of 1 MHz would result in a search zone of approximately 4 km.

Since in actual HVDC systems, the sampling frequency is 25 kHz, the 166 km search zone given by the proposed method would need to be more accurate for fault location estimation. However, with the proposed mathematics, it would still be possible to determine a maximum range of the distance protection in order to guarantee the selectivity of the protection, even with the lack of communication between the stations. This is further discussed in the following sections.

7.5.2.2 Fault Location Estimation

For systems with transmission lines modeled with frequency-dependent models, as in real systems, there is expected to be greater uncertainty in the estimation of the traveling wave speed. This occurs especially with the zero-mode wave. The greater the distance from the fault to the measuring point, this mode suffers greater propagation attenuation. Thus, there is a higher dependency between the fault point and the real speed of the zero-mode traveling wave (LIU et al., 2012). This can influence the estimation of the fault location. This is an important motivation for the need to know the uncertainty in fault location estimation precisely due to the effect of sampling frequency in order to minimize uncertainties in distance protection.

Fig. 7.21 depicts the error in fault location estimation. Fig. 7.22 depicts the fault location estimation as a function of the fault location for the same fault cases. Among the 101 faults applied, 6 presented an estimated search zone with an error above the theoretically predicted one. These six faults were applied at points 85, 170, 180, 265, 275, and 335 km. The errors for the search zone’s theoretical limit were approximately 1.6, 3.3, 13.3, 15, 25, and 1.6 km. These errors are due to the error in estimating modal wave speeds.

There is expected to be a greater error between the value of the estimated zero-mode wave speed and the actual value of the speed for faults closer to the local station. This is because the modal wave speeds have been estimated from the application of a fault at the remote terminal. Thus, the closer the fault is to the remote terminal, the closer the zero-mode wave speed will be to the previously estimated value. Consequently, the fault search zone estimation should
be more accurate for faults closer to the remote station. The results presented reinforce this statement, since all faults applied from 340 km were located within the theoretical search zone. This represents 68% of the line length.

![Diagram](image-url)

Figure 7.20: Minimum sampling frequency as a function of the desired length for the search zone for: (a) 0 to 1000 kHz; (b) 20 to 100 kHz; (c) 100 to 1000 kHz.
7.5. PERFORMANCE ASSESSMENT

Figure 7.21: Error in the fault location estimation as a function of the fault location.

7.5.2.3 Protection Operation Time

The distance protection was parameterized to operate for faults with a location range of less than 90% of the line length, 450 km. The operation time of the protection corresponds to the time between the fault inception time and the arrival of the zero-mode traveling wave, added to a sampling time of the IED.

Fig. 7.23 depicts the operation time of the protection as a function of the fault location. All
faults applied up to 375 km were detected as internal. This represents 75% of the line length. The faults applied at 385 and 395 km were also detected as internal. 395 km represents 79% of the line length. All the remaining faults were detected as outside of the protection zone of 90% of the line. The fault at 385 km presented a search zone estimation ranging from 250 to 416 km. This is less than 90% of the line length. On the other hand, the fault at 380 km had a search zone estimation ranging between 333 and 500 km, which is more than 450 km. For this reason, this fault was detected as external. Similarly occurred for the remaining faults detected as external ones.

Therefore, even with the definition of a high search zone for the fault location, the method is reliable for defining a protection zone. This ensures selectivity of protection for most faults when communication fails between stations. In addition, the method presented a maximum operation time of less than 1.6 ms, representing a very fast operation time.

![Figure 7.23: Protection operation time as a function of the fault location.](image)

### 7.6 Conclusion

This chapter evaluated the applicability of traveling wave-based distance protection for meshed HVDC systems. A distance protection method was proposed for earth faults in overhead transmission lines. A thorough investigation of the effect of sampling frequency was performed.

The method defines a mathematical equation for defining the minimum sampling frequency as a function of the search zone to estimate the fault location. Therefore, the fault location presents greater reliability for its application in distance protection since the error in estimating the fault location is mathematically predicted. In addition, there is a paradigm breaking concerning the need for a high sampling frequency for traveling wave-based fault location. For example, a sampling frequency of 25 kHz, which is commercially adopted in actual systems, could be used in distance protection.

Two systems were modeled for the assessment of the proposed method. The first system contains four terminals interconnected by five transmission lines modeled by the Bergeron distributed parameter model. Thus, the traveling waves’ modal speeds are known, enabling the accurate evaluation of the mathematics presented. The method was able, at each terminal, to correctly distinguish internal faults from external faults for faults applied on all system lines.
For the terminals connected to the faulty line, the method was able to locate 100% of the faults within the mathematically predicted search zone. For the other terminals, some faults were located slightly outside the search zone due to lower accuracy in wavefront detection.

The second is a point-to-point LCC system with transmission lines modeled with the frequency-dependent JMarty model. In this way, it was possible to evaluate the proposed method in a more real-world scenario, where the traveling wave speed is unknown and needs to be estimated. As expected in an actual system, in this line model, the speed of the zero-mode wave approaches the speed of the alpha-mode wave. Hence, the search zone predicted by the proposed method becomes larger. The search zone for the test system used was approximately 166 km for a 500 km line, which is significantly long. However, the precise evaluation of the effect of the sampling frequency made it possible to guarantee with high reliability the search zone as a function of the sampling frequency. This has made distance protection more reliable. By defining a protection zone of 90% of the line, the method detected all faults up to 75% of the line.

The proposed method showed a maximum operation time below 1.6 ms for all detected internal faults. This value is below the 2 ms maximum trip time requirement of the protection for meshed HVDC systems (CIGRÉ, 2018). This operation time is also achieved by the overcurrent protection that monitors the converter, the OCD. However, the OCD protection does not have any selectivity. Thus, the proposed method can act selectively and ensure greater selectivity to the system below 2 ms since additional communication delays do not affect it. Thus, the method shows promise for its applicability in meshed HVDC systems.

### 7.7 Chapter Synthesis

This chapter evaluates the applicability of traveling wave-based distance protection for earth faults for meshed HVDC systems. A distance protection method was proposed from the analysis of the effect of sampling frequency on fault location. The method presented selectivity and operation time below 2 ms, without the need for communication between stations, for a 4-terminal system interconnected by five transmission lines.
Chapter 8

Conclusions

8.1 Conclusions

This thesis investigated the application of traveling waves for developing protection and fault location methods for transmission lines. Three one-terminal methods have been proposed. The proposed methods assume that the system needs to guarantee the protection’s reliability, fast operation, and selectivity in the context of a lack of communication between stations. The first method is based on modal wave detection for earth faults in HVAC systems. The second method is also applied to HVAC systems and is based on detecting the reflected wave at the fault point. The third method is a distance protection applied to meshed HVDC systems. The development of all the proposed methods has in common the thorough investigation of the sampling frequency effects on the protection.

The first proposed method is a traveling wave-based earth fault transmission line distance protection, which only requires arrival instants of the first incident modal traveling waves at one line terminal and the estimation of modal propagation velocities with uncertainties. Therefore, the proposed protection overcomes traditional limitations of one-terminal traveling-wave-based methods, which require detecting reflected waves and accurate wave propagation velocity estimations. The proposed function setup procedure is straightforward, facilitating practical implementation.

A thorough investigation of the sampling frequency effect allowed the definition of error margins for the modal wave velocity estimations, ensuring the reliability of the protection in well-defined protection zones. The proposed function provides a protection reach, considering the adopted error margins for the modal wave velocity estimations, wherein all the internal faults will always be detected. This facilitates the application of the proposed function in real-world systems. Reach values greater than 60% in the worst evaluated cases were achieved. A greater portion of the transmission line may be protected, depending on the error in velocity estimations. Therefore, unitary protection, where 100% of the transmission line is inside the protected zone, may be achieved via a DTT scheme whether a relay is connected at each line terminal of the protected line, considering the additional cost of applying a communication channel.

When associated with other existing auxiliary protection functions, the proposed function presented an ultra-fast operation time well below those presented by a commercially existing time domain distance protection. Errors in the wave velocity estimations and inaccuracies in line parameters were evaluated. The effect of the fault location was also evaluated. The proposed method accelerated the evaluated time-domain distance element available in the analyzed actual relay for all detected earth faults. The presented maximum operation time was smaller than 2 ms for all detected internal faults, without misoperations in cases of external faults. In addition, it was demonstrated that the proposed distance protection has the potential to speed up earth-
fault protection, even considering existing ultra-fast two-terminal methods. This represents an important contribution since fast fault detection provides greater stability to the electrical system and reduces the risk of damage to its components. The results have also demonstrated that the method presents good dependability, even considering errors in the wave velocity estimations.

The second proposed method is an one-terminal protection for transmission lines. An extensive mathematical investigation of the effect of sampling frequency and error on estimating the traveling wave speed was performed.

The method establishes a clear mathematical parameter for defining a minimum sampling frequency, which makes it possible to adopt low sampling frequencies. Such a mathematical definition is unprecedented for one-terminal traveling wave-based methods. This also represents a paradigm break since traveling wave-based methods require high sampling frequencies in the order of hundreds of kHz. The method is also independent of the estimation of the traveling wave velocity. This also represents a paradigm break for traveling wave-based methods, especially those based on one terminal.

The proposed method achieved 100% accuracy for the protected zone defined by the adopted sampling frequency, regardless of the line’s electrical parameters. The operation time of the method was well below those presented by traditional methods. It also performed well when compared to traveling wave-based two-terminal methods.

This thesis has not investigated the correct and reliable distinction between the reflected wave from the fault point and reflected waves at line terminals when adjacent lines occur. Thus, this is still an open issue for the scientific community. Therefore the method is only valid for point-to-point lines, not connected to adjacent lines. Furthermore, the method only applies to transmission lines where the actual speed of the traveling wave is between 90 and 100% percent of the speed of light. This covers almost all overhead lines, whose wave speed is around 98% of the speed of light.

The last chapter of this work evaluated the applicability of traveling wave-based distance protection for meshed HVDC systems. A distance protection method was proposed for earth faults in overhead transmission lines. A thorough investigation of the effect of sampling frequency was performed.

The method defines a mathematical equation for defining the minimum sampling frequency as a function of the search zone for the estimation of the fault location. Therefore, the fault location presents greater reliability for its application in distance protection since the error in estimating the fault location is mathematically predicted. In addition, there is a paradigm breaking concerning the need for a high sampling frequency for traveling wave-based fault location. For example, a sampling frequency of 25 kHz, which is commercially adopted in actual systems, could be used in distance protection.

Two systems were modeled for the assessment of the proposed method. The first system contains four terminals interconnected by five transmission lines modeled by the Bergeron distributed parameter model. Thus, the traveling waves’ modal speeds are known, enabling the accurate evaluation of the mathematics presented. The method was able, at each terminal, to correctly distinguish internal faults from external faults for faults applied on all lines of the system. For the terminals connected to the faulty line, the method was able to locate 100% of the faults within the mathematically predicted search zone. For the other terminals, some faults were located slightly outside the search zone due to lower accuracy in wavefront detection.

The second test system is a point-to-point LCC system with transmission lines modeled with the frequency-dependent JMarty model. In this way, it was possible to evaluate the proposed method in a more real-world scenario, where the traveling wave speed is unknown and needs to be estimated. As expected in an actual system, in this line model, the speed of the zero-mode
wave approaches the speed of the alpha-mode wave. Hence, the search zone predicted by the proposed method becomes larger. The search zone for the test system used was approximately 166 km for a 500 km line, which is significantly long. However, the precise evaluation of the effect of the sampling frequency made it possible to guarantee with high reliability the search zone as a function of the sampling frequency. This has made distance protection more reliable. By defining a protection zone of 90% of the line, the method could detect all faults up to 75% of the line.

The proposed method showed a maximum operation time below 1.6 ms for all detected internal faults. This value is below the 2 ms maximum trip time requirement of the protection for meshed HVDC systems (CIGRÉ, 2018). This operation time is also achieved by the overcurrent protection that monitors the converter, the OCD. However, the OCD protection does not have any selectivity. Thus, the proposed method can act selectively and ensure greater selectivity to the system below 2 ms since it is not affected by additional communication delays. Thus, the method shows promise for its applicability in meshed HVDC systems.

Finally, this thesis demonstrates the applicability of using modal traveling waves and traveling wave reflection detection in fault location and protection of HVAC and HVDC transmission lines. In doing so, it proposes the commercial use of one-terminal traveling wave-based methods to increase the speed of operation, reliability, and higher protection selectivity even in communication loss between stations. In addition, this thesis also demonstrates the potential application of traveling waves for ultra-fast protection operation in HVDC meshed systems, whose protection operation times are expected to be much lower than current HVAC and HVDC systems.
Bibliography


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