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Travelling waves prospective in high voltages, propagation characteristics, faults location, and mitigation: A review

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Abstract

The reliability and efficiency of power transmission systems are essential for the functionality of modern electric grids. High-voltage systems, such as 220kV double circuit transmission lines, are integral in transmitting electricity over long distances, but they are prone to disturbances that generate transient phenomena known as traveling waves. These waves, resulting from sudden changes in voltage or current along the line, can significantly affect power stability, quality, and infrastructure. This review explores the effects of traveling waves in double-circuit transmission lines, with a focus on their propagation, interactions with system components, and impacts on system stability. The review findings are from recent studies, simulations, and practical examples, and offer insights into potential mitigation strategies for optimizing transmission line design and protective schemes.

1.0 Introduction

The reliability and efficiency of power transmission systems are critical factors in the operation of modern electric grids [1]. High-voltage transmission lines, such as 220kV double circuit systems, serve as vital links between power generation stations and the end-users, transporting electricity over vast distances with minimal losses [2]. However, these systems are frequently exposed to disturbances, both natural and artificial, that can give rise to transient phenomena known as traveling waves. These waves, which occur due to sudden changes in current or voltage along the transmission line, can significantly impact system stability, power quality, and the overall performance of the transmission infrastructure [3].

The phenomenon of traveling waves in high-voltage transmission lines is largely influenced by factors such as line impedance, fault conditions, switching operations, and environmental conditions like lightning strikes [4,5]. Understanding the behavior of these waves and their interaction with double-circuit configurations is crucial, as double circuits are designed to enhance reliability and improve the efficiency of power transmission [6]. Nonetheless, the presence of current traveling waves in such systems can lead to complications, including resonance, voltage surges, and over-voltages, which may compromise the protective schemes and lead to insulation failures [7].

This review investigates the effects of current traveling waves on a double circuit transmission line, focusing on the propagation characteristics, interaction with system components, and the subsequent impact on power system stability. By analyzing recent studies, simulation models, and practical case examples, this review aims to provide a comprehensive understanding of traveling waves within double circuit systems and highlight potential mitigation techniques. Enhanced insight into these dynamics is essential for optimizing transmission line design, improving protective measures, and ensuring uninterrupted power delivery in high-voltage networks.

2.0 Methodology

The review comprehensively surveys the literature on traveling waves in high-voltage transmission lines, such as tower parameters, clearance, span etc. The review included peer-reviewed journal articles, conference papers, and technical reports published between 2010 and 2024. Key databases such as IEEE Xplore, ScienceDirect, and SpringerLink were searched using relevant keywords to identify studies on wave propagation, fault location techniques, and mitigation strategies. The selection criteria focused on studies addressing traveling wave behaviors in transmission systems and their implications for design and protection.

3. Traveling Waves

A traveling wave is a type of wave that moves or propagates through a medium, carrying energy from one point to another without transporting matter. In electrical systems, particularly in high-voltage transmission lines, traveling waves are transient disturbances that result from sudden changes in voltage or current [8]. These waves can be caused by various events, such as lightning strikes, short circuits, switching operations, or other electrical faults

3. 1 Operation of Traveling Waves

In the operation of high-voltage transmission lines, the occurrence of faults or malfunctions often leads to abrupt changes in current and voltage levels. These disturbances generate a high-frequency electromagnetic pulse, known as a Traveling Wave (TW) [9]. This pulse propagates rapidly along the transmission line, moving away from the fault point towards both ends of the line at nearly the speed of light. Traveling waves are inherently transient, typically persisting for only a few microseconds to milliseconds [10]. Despite their brief duration, they carry energy across a wide frequency spectrum, generally ranging from 2 kHz to 10 MHz, which can impact the performance and integrity of the transmission line and connected equipment [11].

The significance of traveling waves extends beyond their immediate effect on current and voltage levels. Understanding the propagation and characteristics of these waves is essential for multiple aspects of transmission line engineering [12]. They play a critical role in defining the insulation requirements for lines and components and in the design of insulators and protective devices. These waves influence the insulation coordination process, ensuring that all equipment along the transmission line can withstand potential over-voltages without damage. Accurate knowledge of traveling waves is, therefore, pivotal for the specification of insulation levels and for safeguarding terminal equipment and protective systems [13].

3.1.1 Specifications of Traveling Waves

Mathematically, traveling waves can be expressed in several forms. One of the most common representations is an infinite rectangular or step wave, often used in theoretical models to simplify analysis [14,15]. However, traveling waves on transmission lines are typically characterized by four primary specifications (Figure 1):

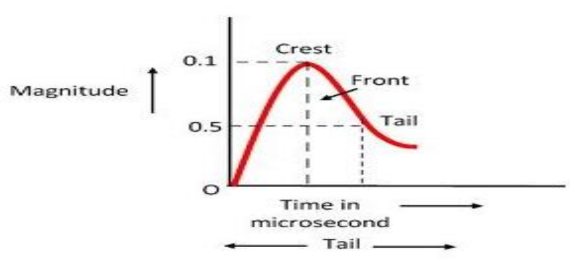

Figure 1: Specifications of travelling wave [14].

1. Amplitude: Amplitude represents the peak value of the wave, corresponding to the maximum over-voltage or overcurrent generated by a fault. This peak is indicative of the fault's severity and is influenced by the impedance characteristics of the transmission line. In high-voltage applications, amplitude assessment is essential for determining potential insulation breakdown and damage to equipment [16].

2. Frequency: Travelling waves consist of a range of frequencies, with higher-frequency components attenuating more rapidly as they propagate. The frequency spectrum is critical in designing line insulators and protective devices, as they must withstand rapid fluctuations and high-frequency transients that could otherwise lead to system failures [17].

3. Propagation Speed: The propagation speed of travelling waves along a transmission line approaches the speed of light in a vacuum. This speed is influenced by the line's physical properties, particularly inductance and capacitance, which vary based on the line's geometry and surrounding dielectric materials [18]. Accurate speed calculations are important for timing protection devices and synchronizing fault detection mechanisms.

4. Wavelength: Wavelength, the distance over which the wave repeats, is inversely proportional to the frequency. Understanding wavelength helps engineers estimate the extent of wave attenuation over a distance and is useful for identifying the reach of transient effects within the transmission line [19].

These parameters are fundamental to analyzing travelling waves, which is essential for the effective operation of a 220kV double-circuit transmission line. They help predict the behavior of traveling waves under various fault conditions, allowing for enhanced line design and improved resilience against transient disturbances [20]

Furthermore, when analyzing traveling waves on transmission lines, understanding additional wave characteristics is crucial. The crest represents the peak magnitude of the wave, measured in kiloamperes (kA) or kilovolts (kV), indicating the maximum voltage or current encountered during a transient event. Front refers to the segment leading up to the crest, capturing the rapid rise from the wave's initiation to its peak, which is often measured in microseconds (μs). Following the crest is the tail, a segment that extends from the initiation of the wave to the point where its magnitude has decreased to 50% of the crest value, providing insight into the wave's decay over time. Finally, polarity specifies whether the wave's crest is positive or negative, influencing how protective systems respond. For example, a wave with a crest of +200 kV, a front duration of 1 μs, and a tail duration of 25 μs would be represented as +200/1025 [21]. Understanding these characteristics helps in the precise analysis and design of protective measures, ensuring the transmission system can handle such transient disturbances effectively.

3.2 Fault Location Techniques Using Traveling Waves

In high-voltage transmission systems, traveling waves produced by faults cause abrupt voltage and current changes, which generate high-frequency electromagnetic impulses. These impulses travel bi-directionally from the fault point, and analysis of their modal components and arrival times at different locations enables precise fault location. Current traveling wave transients are preferred for fault location as they exhibit reduced distortion compared to voltage transients and can be accurately replicated using conventional current transformers [22].

3.2.1 Transmission Line Equations

Transmission lines transmit electromagnetic energy between two points. Heaviside's transmission line equations model these lines using resistance (R), conductance (G), inductance (L), and capacitance (C) per unit length, allowing for detailed analysis of electric flux (ψ) and magnetic flux (φ), which generate instantaneous current (i(X, t)) and voltage ($\boldsymbol{U}$(X, t)) as shown in equations (1) and (2) [23-26].

The change in electric flux ($d\psi(t)$) is comparable to the outcome of the instantaneous voltage (U(X, t), capacitance (C), and line segment length (dx), as represented in Equation (1).

$$d\psi(t) = U(X,t)Cdx \qquad (1)$$

The change in magnetic flux (d φ (t) equals the product of sudden current (i(X, t), inductance (L), and length of the line segment (dx), as expressed in Equation (2).

$$d\varphi(t) \ = \ i(X,t)Ldx \qquad (2)$$

The voltage decrease in the positive x-direction over the distance dx is shown in equation (3)

$$U(X,t) - U(X+dx,t) = -dU(X,t) = \frac{\partial U(X,t)}{dx}dx \qquad (3)$$

Differentiation of equation (3) yields equation (4)

$$\frac{\partial U(X,t)}{dx} = -L\frac{\partial i(X,t)}{dx} = Ri(X,t) \qquad (4)$$

Applying Kirchhoff's current law of analysis, equations (5) and (6) were obtained [27].

$$\mathrm{i}\,(\mathrm{X},\mathrm{t}) - \mathrm{i}(\mathrm{X}+\mathrm{dx},\mathrm{t}) = -\mathrm{di}(\mathrm{X},\mathrm{t}) - \frac{\partial \mathrm{i}(\mathrm{X},\mathrm{t})}{\mathrm{dx}}\mathrm{dX}$$
$$= \left(\mathrm{G} + \mathrm{C}\frac{\partial}{\partial \mathrm{t}}\right)\mathrm{U}(\mathrm{X},\mathrm{t})\mathrm{dx} \qquad (5)$$

Eliminating dx from both sides of equation (5) results in equation (6)

$$\frac{\partial i(X,t)}{dx} = -C\frac{\partial u(X,t)}{dt} - GU(X,t) \qquad (6)$$

The negative sign in the equation indicates that as the wave propagates in the positive x-direction, the amplitude of u(x,t) decreases with increasing x. This reduction in amplitude is observed when the current and voltage waves propagate, and the behavior of i(x,t) (current) is substituted into the analysis.

$$Z = R + \frac{\partial L(X,t)}{\partial t} \ and \ Y = G\frac{\partial C(X,t)}{\partial t} \qquad (7)$$

By further differentiating with respect to x, we can derive the second-order partial differential equations from this expression (MA Akbar, 2021).

$$\frac{\partial^2 i(X,l)}{\partial x^2} = -Y\frac{\partial U(X,t)}{\partial t} = YZi(x,t) = Y^2 i(X,t) \qquad (8)$$

$$\frac{\partial^2 i(X,l)}{\partial x^2} = -Z\frac{\partial U(X,t)}{\partial t} = YZu(x,t) = Y^2 i(X,t) \qquad (9)$$

The complex quantity referred to as propagation constant is defined as shown in equation (10)

$$Y = \sqrt{ZY} = a + j\beta \qquad (10)$$

Here, $\boldsymbol{\alpha}$ is constant of attenuation influencing the amplitude of the traveling wave, β is phasing constant affecting phase shift of the traveling wave. Equation (8) and (9) can be resolved using two methods, transform or classical, yielding two arbitrary functions that satisfy the partial differential equations. It is important to note that the solution can take any form, as long as both unconventional variables, t and x, emerge in a way where second derivatives of functions of current i and voltage v with respect to x and t are directly proportional to each other [24].

$$\mathrm{U(x.t)} = \mathrm{A_1,(t)} \quad (11)$$

$$\mathrm{i(x.t)} = \frac{1}{\mathrm{Z}}\mathrm{A_1,(t)e^{YX} + A_2(t)e^{YX}]} \quad (12)$$

where Z. which stands for the line's characteristic impedance, is determined by.

$$Z = \left(\frac{\left(R + \frac{L\partial}{\partial t}\right)}{G + \frac{C\partial}{\partial t}}\right) \quad (13)$$

where A_l and A_2 are arbitrary functions [29]

3.3 Double circuit transmission lines

Double-circuit transmission lines play a critical role in ensuring the reliable and efficient distribution of electricity over vast distances in modern power systems. These lines feature two parallel circuits that carry electric power independently, typically at high voltages, such as 220 kV, 275kV, 330kV, 400kV and 500kV. As a cost-effective solution, double-circuit transmission lines help meet the rising demand for electricity while maintaining system reliability. By accommodating two circuits on a single tower structure, these lines offer increased power transfer capacity and provide redundancy, enabling one circuit to operate if the other fails. This redundancy enhances system reliability and stability, making double circuit transmission lines particularly valuable in urban areas and regions where reliability is paramount [30].

However, deploying double circuit transmission lines involves a range of technical and environmental considerations. Designers must account for factors such as voltage levels, conductor materials, insulation, and tower configurations, as these elements influence the lines' performance and reliability. Despite their advantages, double circuit lines can pose challenges, such as increased electromagnetic interference and maintenance complexity due to the proximity of two circuits. Moreover, while these lines reduce the need for additional right-of-way and land acquisition, they can still have visual and ecological impacts, especially in environmentally sensitive areas. Therefore, careful planning is needed to minimize their footprint and mitigate potential environmental effects [31].

Double circuit transmission lines are especially beneficial in densely populated regions or areas with limited available land, as they maximize the use of existing infrastructure while limiting new land requirements. Additionally, technological advancements, such as improved conductor materials and innovative tower designs, enable these lines to support higher voltage levels and improve efficiency. By addressing both the technical and environmental aspects, double circuit transmission lines as shown in Figure 2 remain a practical and efficient solution for modern power distribution needs, balancing increased demand, system reliability, and environmental considerations [32].

Figure 2. 220kV Double circuit transmission tower and line [33,34]

3.4 Mutual coupling

Mutual coupling in transmission lines refers to the electromagnetic interaction between two or more adjacent circuits or conductors, wherein the magnetic field generated by current flowing through one circuit induces a voltage or current in the nearby circuits [35]. This phenomenon is especially prevalent in double-circuit transmission lines, where the close proximity of conductors leads to a significant level of interaction. When current flows through one circuit, it produces a magnetic field that can induce voltage and, subsequently, current in the adjacent circuit [36]. This effect is commonly referred to as mutual inductance.

Mutual inductance quantifies the extent to which the magnetic field from one circuit affects another. In double-circuit transmission lines, mutual inductance occurs between the conductors of the two circuits due to their physical closeness. The degree of mutual inductance depends on several factors, including the distance between conductors, the magnitude of the current, and the transmission line configuration. This phenomenon can impact the behavior and performance of the transmission line, as it can lead to unwanted coupling, signal interference, and cross-talk between circuits [35,36].

To analyze and model mutual coupling, we can employ the telegrapher's equations, which are used to describe the voltage and current behavior in each circuit. The telegrapher's equations account for the effects of resistance, inductance, capacitance, and mutual inductance between conductors [37]. By incorporating mutual inductance terms, these equations provide a comprehensive framework for understanding and managing the effects of mutual coupling on transmission line performance.

In practical applications, reducing mutual coupling effects can involve the physical separation of conductors, using transposition techniques, or employing shielding measures to minimize electromagnetic interactions. Understanding and mitigating mutual coupling is essential for maintaining the efficiency, reliability, and safety of transmission line systems as shown in equations (15)-(18) [37].

For Circuit 1:

$$\frac{\partial V_1}{\partial z} = -L_1 \frac{\partial I_1}{\partial t} - (R_1 + R_M)I_1 + \left(M_1 \frac{\partial V_2}{\partial t}\right) \quad (15)$$

$$\frac{\partial I_1}{\partial z} = -C_1 \frac{\partial V_1}{\partial t} \quad (16)$$

For Circuit 2:

$$\frac{\partial V_2}{\partial z} = -L_2 \frac{\partial I_2}{\partial t} - (R_2 + R_M)I_2 + \left(M_1 \frac{\partial V_2}{\partial t}\right) \quad (17)$$

$$\frac{\partial I_2}{\partial z} = -C_2 \frac{\partial V_1}{\partial t} \quad (18)$$

Where V_1 and V_2 are the voltages in circuits 1 and 2. respectively, I_1 and I_2 appear as currents along circuits I and 2, respectively, z is the distance along the transmission line, t is time. In these equations, the terms involving M_1 and M_2 represent the mutual coupling between the circuits. R_m represents mutual resistance, but it's typically neglected in transmission line analysis unless the coupling is extremely tight [37].

3.5 Improved Fault Mitigation Techniques in Travelling Waves for High Voltage Systems

Fault mitigation in high-voltage systems, particularly when dealing with travelling waves, requires robust and adaptive strategies to ensure system reliability and prevent cascading failures. Travelling waves, generated by sudden disturbances such as lightning strikes, switching actions, or insulation breakdowns, propagate through the transmission network and can severely impact system stability [38]. The following advanced techniques improve fault detection, isolation, and mitigation in high-voltage networks:

1. Advanced Signal Processing for Traveling Wave Analysis

Modern Digital Signal Processing (DSP) techniques, including wavelet transform, Hilbert-Huang transform, and empirical mode decomposition, have revolutionized the analysis of high-frequency components in traveling waves. These advanced methodologies enable the precise decomposition of signals into time-frequency domains, allowing for enhanced fault localization and characterization [39]. By leveraging these tools, significant improvements can be achieved in real-time fault detection, the discrimination between transient disturbances and actual faults, and the resolution of multiple fault locations within complex network environments. This level of precision ensures more reliable and efficient fault analysis in power systems and other critical infrastructures [40].

2. Wide-Area Monitoring Systems (WAMS) for Traveling Wave

The integration of Wide-Area Monitoring Systems (WAMS) with synchronized Phasor Measurement Units (PMUs) significantly enhances fault mitigation and system reliability. WAMS enable real-time tracking of traveling waves and their interactions across the power network by utilizing time-synchronized measurements from geographically dispersed PMUs. This integration provides several key advantages, including accurate fault localization through time-stamped data correlation, the implementation of early warning mechanisms using predictive analytics, and rapid decision-making based on system-wide wave propagation analysis. These capabilities make WAMS an essential tool for maintaining grid stability and improving operational efficiency [41].

3. High-Speed Protective Relaying

High-speed protective relays, leveraging traveling wave-based algorithms, provide unparalleled fault detection capabilities by analyzing initial wavefronts within microseconds. These advanced relays enhance the reliability of power systems by offering improved sensitivity to transient events, ensuring rapid identification of disturbances. Their ability to minimize fault-clearing times significantly reduces the risk of equipment damage, while selective fault isolation helps maintain overall system stability. These features make high-speed protective relaying a critical component in modern power system protection strategies [42].

4. Adaptive Thresholding and Machine Learning Approaches

The integration of machine learning algorithms into fault mitigation frameworks enhances the accuracy, adaptability, and intelligence of modern protection systems. Advanced techniques such as artificial neural networks (ANNs), support vector machines (SVMs), and deep learning models enable dynamic adjustment of fault detection thresholds in response to changing system conditions. These algorithms excel in pattern recognition, facilitating the differentiation between fault types and locations with high precision. Additionally, their self-learning capabilities allow continuous performance improvement, making them invaluable for evolving power system demands and complex operational scenarios [43].

5. Traveling Wave Fault Locators

Traveling wave-based fault locators offer exceptional accuracy by measuring the time of arrival (TOA) of wavefronts at various points in the network. These devices utilize advanced techniques such as double-ended and single-ended fault location methods to determine fault positions with high precision. Integration with GPS ensures precise timing synchronization, enabling accurate correlation of wavefront data across multiple locations. Furthermore, real-time data sharing with centralized control systems enhances situational awareness and facilitates rapid decision-making, making traveling wave fault locators a cornerstone of modern fault detection and mitigation strategies [44].

6. Surge Arrester Coordination

Effective surge arrester coordination plays a vital role in mitigating the adverse effects of traveling waves caused by lightning strikes or switching surges. Advanced surge arresters equipped with energy-dissipating capabilities provide robust protection against over voltages, safeguarding sensitive equipment. They also dampen wave propagation, minimizing the impact on downstream components and improving overall system resilience. By effectively limiting voltage magnitudes, coordinated surge arresters enhance the reliability and stability of power systems, ensuring optimal performance under transient conditions [45].

7 Fault-Tolerant System Designs

Fault-tolerant system designs are essential for maintaining operational continuity in the face of system disturbances. By incorporating redundant transmission paths, power flow is sustained even during line outages, ensuring uninterrupted service. Self-healing grid technologies further enhance resilience by automatically detecting and reconfiguring the network to restore normal operations after disturbances. Additionally, modular power electronic systems enable selective isolation of faulty modules, preventing disruptions from escalating and ensuring the rest of the system functions efficiently. These innovative design strategies contribute significantly to the robustness and reliability of modern power networks [46].

8. Integration

Integrating renewable energy sources, such as solar and wind, into power systems introduces complexity due to their variable and intermittent nature. To address these challenges, coordination with traveling wave protection schemes is essential. Energy storage systems play a critical role in buffering transient surges, ensuring stability during fluctuations. Dynamic control of inverters enables seamless fault ride-through, maintaining system continuity even under fault conditions. Additionally, hybrid protection systems, designed specifically for mixed-generation networks, provide tailored solutions that enhance fault detection and isolation. These measures ensure the reliable and efficient operation of renewable energy-integrated power systems [47].

9. Simulation and Digital Twin Technology

Advanced simulation tools and digital twin technology provide powerful resources for enhancing fault mitigation strategies in high-voltage systems. By creating virtual replicas of transmission networks, operators can simulate traveling wave behavior under a variety of fault scenarios, allowing for more precise fault analysis and planning. These models enable the optimization of protection settings tailored for real-world conditions, ensuring more efficient and responsive fault detection. Additionally, digital twins help identify potential vulnerabilities within the system before they lead to failures, improving overall system reliability and enabling proactive maintenance strategies [48].

3.6 Review of Related Research Works

A fault location scheme using composite traveling waves was proposed by [49] to enhance the accuracy of fault detection on transmission lines and to reduce error rates in fault location, particularly for newly added lines. This research analyzed the refraction and reflection characteristics of traveling waves at busbars with multiple lines, a critical consideration for systems with adjacent, fault-free lines. A study by [49] introduced a fault location method based on a time-frequency matrix for adjacent lines not directly linked to traditional traveling wave fault locators. The findings offer insights into mitigating the refraction and reflection effects of traveling waves in transmission systems, thus improving fault location accuracy.

A related study by [50] focused on a high-pass filter-based traveling wave fault location method for voltage-source converter (VSC) interfaced high-voltage direct current (HVDC) systems. Given the speed of traveling waves along HVDC lines, often in overhead configurations, the researcher developed a new algorithm utilizing high-pass filtering to more precisely distinguish traveling wave peaks by minimizing oscillations in the signal. This approach was validated through simulations conducted in PSCAD, using a double-ended method to ensure greater accuracy. This study contributes significantly to understanding traveling wave dynamics in HVDC systems, and the methodologies could be adapted to enhance HVAC transmission line reliability and efficiency [50].

Furthermore, other researchers have also investigated the broader effects of traveling waves on transmission systems. The scholar in [51] explored the behavior of current traveling waves, assessing their impact on transmission line performance and stability. This study likely employed a mix of theoretical analysis, simulations, or experiments to comprehend wave propagation and its implications for system operation. Insights from the research may inform strategies to mitigate negative effects of traveling waves, enhancing transmission system optimization.

The researcher in [52] extended this inquiry by providing a comprehensive analysis of current traveling waves, possibly using theoretical models, numerical simulations, and experimental validations. The findings likely offered a detailed understanding of traveling wave propagation characteristics and underscored potential strategies for mitigating adverse impacts on transmission system performance.

The scholar in [53] focused on developing mathematical models and computational simulations to explore how traveling waves propagate and interact within transmission lines. This research examined factors such as line parameters, load conditions, and system topology. Through simulations, the researcher evaluated various mitigation techniques aimed at managing traveling wave effects, thus enhancing system reliability.

Earlier experimental studies by [54], involved physical experiments to observe current traveling waves on laboratory-scale transmission lines. By generating traveling waves and analyzing propagation data, the researcher validated theoretical models and provided practical insights into managing wave effects. Similarly, researchers in [55] investigated how traveling waves impact transmission line performance, combining theoretical and numerical approaches to analyze the dynamic behavior of waves. The research work offered strategies for mitigating adverse effects on system operation, reinforcing the importance of managing traveling wave phenomena in optimizing transmission line reliability and efficiency.

Collectively, these studies contribute to a more nuanced understanding of traveling wave behaviors in transmission systems, informing fault location methods and strategies to enhance the performance and reliability of both HVAC and HVDC transmission networks. This review will build on these findings to further elucidate traveling wave dynamics in HVAC systems and develop practical approaches for mitigating associated challenges.

Table 1 highlights the focus of each study, the methods used, and the specific research gaps, providing a concise overview of the current state of research on traveling waves in transmission lines.

Table 1: Summary of the Related Review

Author	**Topic**	**Methods**	**Research Gap**
P. Cao, *et al* (2024) [59]	A fault location scheme based on composite traveling wave with transients in adjacent fault-free lines	Analyzed refraction and reflection characteristics; Time-frequency matrix method	Need for more accurate fault location schemes to handle refraction/reflection effects in multi-line systems
Javaid, et *al* (2024) [50]	High pass filter-based traveling wave method for fault location in VSC-Interfaced HVDC system	High-pass filter algorithm; PSCAD simulations	Application of TW fault location in HVAC systems, and further enhancement of accuracy
Kumar, et *al* (2024) [51]	Exploring dynamic behaviors of diverse electrical soliton pulses in lossy nonlinear electrical transmission lines.	Theoretical analysis, simulations, experimental investigations	Mitigation strategies for the negative effects of traveling waves on transmission stability
Mazibuko, et *al* (2024) [52]	A Review on the Impact of Transmission Line Compensation and RES Integration on Protection Schemes	Theoretical modelling, numerical simulations, experimental validation	Broader understanding of traveling wave propagation and impact on system performance
Rouhi, et *al* (2024) [53]	Parametric modeling of serpentine waveguide traveling wave tubes.	Mathematical modeling, computational simulations	Optimization of traveling wave control techniques based on line parameters and system topology
Reck & Aksel (2013) [54]	Experimental study of current traveling waves	Physical experiments on laboratory-scale transmission lines	Need for practical insights and validation of theoretical models for traveling waves
Davis, et *al* (2020) [55]	Spontaneous traveling cortical waves gate perception in behaving primates	Theoretical analysis, numerical simulations	Identification and mitigation of adverse traveling wave impacts on line reliability and efficiency

4. Review Findings

Traveling waves are high-frequency electromagnetic pulses generated by disturbances like faults or switching operations. These waves can persist for milliseconds but carry energy across a wide frequency range, potentially impacting transmission line performance. Key parameters, such as amplitude, frequency, propagation speed, and wavelength, are crucial in analyzing the impact of these waves on system stability and equipment integrity. Faults in transmission systems induce traveling waves, enabling accurate fault location through time-of-arrival analysis. Techniques like modal analysis of current transients have been developed for precise fault detection. Simulation models and algorithms, such as those utilizing high-pass filtering for peak detection, have shown promise in enhancing fault location accuracy in both HVAC and HVDC systems.

Double circuit configurations enhance power capacity and reliability but introduce complexities like mutual coupling, where electromagnetic interactions between circuits can lead to issues like crosstalk and interference. Understanding mutual inductance and using transposition and shielding techniques are key to managing these effects. Effective mitigation strategies for traveling waves involve improving line insulation and incorporating advanced protective devices. Recent research suggests approaches like using composite traveling waves and high-pass filtering in fault location algorithms to reduce the impact of wave transients.

5. Conclusion

Traveling waves in 220kV double circuit transmission lines present significant challenges but also offer opportunities for improving system resilience and fault location accuracy. The findings underscore the need for continuous advancements in modeling and simulation of traveling waves to enhance protective schemes and infrastructure design. Future research should focus on refining mitigation techniques and exploring emerging technologies to optimize transmission line performance amidst transient disturbances.

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