WAVE PHENOMENA IN COMMUNICATION LINES AND THEIR ROLE IN CRITICAL INFRASTRUCTURE SECURITY

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Abstract: In this study, wave processes in multiconductor coupled transmission lines and their impact on the security of critical energy infrastructures are investigated. High-frequency electromagnetic disturbances can cause overvoltage, signal distortions, and malfunctions in control systems, which necessitates an accurate physical description of wave phenomena in such lines. Traditional modal approaches complicate practical analysis, as they do not directly represent the waves that physically exist in the conductors. The paper proposes a physically substantiated approach to the description of wave processes without the use of modal transformations. The concept of an equivalent wave impedance is introduced, defined in terms of the voltage and current of a physically existing wave; this parameter has a clear physical meaning and can be measured experimentally. It is shown that this impedance depends on electrical operating regimes and excitation conditions, which opens up the possibility of influencing wave processes without changing the geometry of the lines. The obtained results can be applied to the analysis of transient processes and to enhancing the electromagnetic resilience of communication channels and power systems within critical infrastructures.

Key words: infrastructure security, power system dependability, electromagnetic resilience, coupled transmission lines, integral wave impedance, transient electromagnetic effects.

1. INTRODUCTION

The security of critical energy infrastructures is today a fundamental prerequisite for national security, as these systems are increasingly exposed to natural hazards, high-frequency electromagnetic disturbances, cyberattacks, and deliberate electromagnetic impacts. Consequently, the protection of critical infrastructure is now regarded as a complex of interrelated measures aimed at ensuring the sustainable operation of power systems, telecommunications, information services, transport networks, water supply, financial and healthcare institutions, as well as public administration. Critical infrastructures form a highly integrated and interdependent system in which a failure in one component can trigger cascading failures across the entire system. A striking example is the large-scale blackout in Texas in 2021, when the failure of the power system left more than 4.5 million consumers without electricity, disrupted water supply, transport, and communication systems, and resulted in significant socio-economic losses [1]. As emphasised in [2], modern energy systems are becoming increasingly digitalised, which simultaneously enhances control efficiency and expands the scale of potential cyber threats.

A decisive role within these systems is played by computing technologies, as they provide automated control, monitoring, data processing, and the implementation of real-time decision-making algorithms. Energy systems, transport networks, telecommunications, financial platforms, and security systems, as highlighted for example in [3] and [4], operate exclusively due to the availability of high-performance computing complexes, whose architectures ensure both the processing of large volumes of information and the continuity of operation under external disturbances.

In classical descriptions of computer architecture, the set of basic subsystems is typically limited to the central processing unit, memory, input/output devices, and control interfaces. However, this list effectively omits the communication line system – a complex, multi-level network of conductive structures that physically enables signal transmission between all components. Its role is fundamental, as it determines the feasibility of real interaction between subsystems, constrains performance, defines latency, ensures signal integrity, and sets the electromagnetic operating conditions of the computing complex. Despite this, even authoritative textbooks and normative sources do not single out communication lines as a distinct subsystem of computer hardware architecture. Thus, even in seminal works on computer organisation, such as [5], internal conductive structures are mentioned only indirectly and are generically referred to as the system bus. Similarly, works on computer systems [6] describe the processor, memory, and input/output subsystems, yet the physical signal transmission lines are not identified as an independent element.

Despite this, the actual physical structure of computing hardware demonstrates that the total length of conductive lines in modern devices amounts to several kilometres in multilayer server-class motherboards equipped with multiple memory modules and expansion cards. Studies on high-speed board routing [7] clearly show that even a single printed circuit board may contain between two and six kilometres of communication lines, depending on the number of interfaces, the number of PCB layers, and the data bus architecture. At such scales, these lines can no longer be regarded merely as ordinary conductors that simply carry current. At the operating frequencies of modern computing systems, signal wavelengths are comparable to the lengths of the lines, and therefore each of them behaves as a transmission line with characteristic wave effects.

In view of this, wave phenomena within internal interconnect systems directly affect the operability, performance, and reliability of computing equipment. Neglecting the effects of reflections, discontinuities, dispersion, losses, and impedance matching can lead to incorrect data transmission, signal degradation, or a complete halt of computational processes. Consequently, the inability of computing devices to perform their functions poses a threat to the operability of virtually all critical infrastructures, as they are intrinsically dependent on the stability of computing systems [4], [8]. Therefore, wave effects in internal communication lines should be regarded not as a secondary aspect of electronic design, but as a key factor in ensuring the resilience and security of critical infrastructures.

In distributed energy systems, particularly in Smart Grids, communication lines ensure the acquisition of data from a large number of sensors, the transmission of control commands, and the operational reconfiguration of networks. It is shown in [9] that software-defined Smart Grid networks remain vulnerable to various attacks on communication protocols and controllers and therefore require analysis not only at the logical but also at the physical level of signal transmission. Strategic studies, such as the OECD report [10], further emphasise that the physical resilience of communication infrastructure constitutes the foundation of the stability of public services, since communication channels underpin the operation of all other elements of critical infrastructures.

A significant proportion of infrastructural systems relies on data transmission over power lines (PLC), which creates specific threats at the physical level. Study [11] substantiates that PLC channels in the context of SCADA systems are characterised by high noise levels and vulnerability to external interference, which can lead to disruptions in the control of energy facilities. A broader survey [12] systematises the key security issues of PLC technologies, including bandwidth limitations, channel instability, and the possibility of malicious signal interference. These conclusions are consistent with the results of [13], which presents an analysis of the wave and frequency limitations of PLC channels caused by the non-uniformity of power networks, their topology, and electromagnetic characteristics.

At the same time, intelligent energy systems require rapid solutions for network reconfiguration, multi-criteria optimisation, and real-time processing of telemetry data. As shown in [14], communication lines are a critical factor in the operational controllability of Smart Grids, and their resilience determines the effectiveness of countering both cyber and physical threats. In addition, the analytical review in [15] demonstrates that the expanding use of IoT devices, digital sensors, and distributed data acquisition systems continuously increases the load on communication channels, thereby raising the requirements for the performance and reliability of methods used for their analysis.

Nevertheless, a substantial proportion of existing methods for modelling wave processes in coupled or strip line communication lines is based on the numerical solution of systems of differential equations, which is too slow for applications that require real-time computation. Thus, a contradiction arises: on the one hand, ensuring the security of critical infrastructure requires rapid analysis of wave regimes in conductive communication channels; on the other hand, existing algorithmic methods do not provide the required computational performance. This necessitates the development of new mathematical models and algorithms for forecasting wave processes that are capable of delivering sufficient accuracy and the required speed for practical application in critical infrastructure systems.

2. RELATED WORKS

Modern studies of the state of power networks, as presented in [16], show that the development of Smart Grids is accompanied by an increasing sensitivity to impulsive transient processes and high-frequency electromagnetic impacts, which in turn makes wave analysis a key element in ensuring their resilience. Particular attention is drawn to the impact of high-speed High-Altitude Electromagnetic Pulse (HEMP) events on multiconductor cables, which are capable of exciting multimode waves and causing dangerous overvoltage in equipment of critical importance. For example, the studies published in [17] demonstrate that a HEMP event induces extremely fast overvoltage in overhead transmission lines, with durations of several tens of nanoseconds and peak values reaching several megavolts. This indicates that multiconductor overhead lines exposed to HEMP can generate hazardous wave processes that give rise to significant overvoltage.

In critical energy infrastructures, coupled transmission lines constitute an integral component of multi-level technical systems. In power circuits, they appear in the form of individual overhead lines installed on common supports and exhibiting strong electromagnetic coupling between conductors. This is illustrated in [18], where it is shown that electromagnetic interaction between conductors mounted on a common support is a key factor determining the behaviour of the entire structure. In such lines, wave effects and modal interaction cannot be neglected, as they significantly influence the distribution of currents and voltages during transient processes and lead to substantial overvoltage in adjacent conductors, even when they are not electrically interconnected.

Modern power systems operate under conditions of increasing instability, a high penetration of renewable energy sources, and growing network loads, which makes fast monitoring and control critically important. Instantaneous measurement of parameters, detection of emergency operating conditions, and rapid decision-making, as shown in [19], are necessary to prevent cascading failures, ensure resilience, and maintain power quality indicators.

As shown in [20], the presence of coupling between lines leads to the emergence of undesirable electromagnetic phenomena such as crosstalk, modal dispersion, reflections from discontinuities, resonant amplification, and complex transient processes. These phenomena not only degrade signal transmission quality but also create potentially hazardous conditions for power networks; in particular, they may facilitate the propagation of overvoltage between phases, instability of relay protection schemes, and false triggering of monitoring systems.

Cybersecurity of critical infrastructures is inseparably linked to the physical reliability and correctness of signal transmission in communication lines that form the foundation of modern energy, transport, and telecommunication systems. Any control system relying on digital or analogue transmission channels can operate only if the accuracy, integrity, and timeliness of information are preserved. Violation of these characteristics due to physical and technical factors, as noted in [21], may lead to control failures, incorrect decisions by automated systems, or the complete shutdown of an installation.

In critical energy infrastructures, accounting for wave processes in electrical and information transmission lines is a mandatory condition for ensuring resilience and security. High-frequency electromagnetic impacts, impulsive transient processes, and modal interaction in coupled conductors are capable of causing dangerous overvoltage, signal distortions, and disruptions to the normal operation of equipment. In environments saturated with IoT devices and distributed sensor networks, these physical phenomena are particularly critical, since even minor signal distortions may result in data loss, erroneous telemetry, and loss of synchronisation [22]. This, in turn, increases the risk of incorrect decisions by automated control systems and enhances vulnerability to cyberattacks. Therefore, comprehensive wave analysis of both power and information channels, including IoT infrastructure, is a key prerequisite for ensuring the reliability and cyber-resilience of modern energy systems.

Thus, the analysis of wave processes is a necessary element in the design and assessment of the reliability of critical infrastructure equipment. Studies devoted to modelling transient processes in multiconductor lines demonstrate that accurate reproduction of high-frequency wave dynamics is essential for predicting network behaviour under fault conditions and external disturbances. At the same time, wave analysis in multiconductor lines is mathematically complex. Contemporary research shows that modal decomposition may be inaccurate or frequency-dependent for real cables characterised by asymmetry, non-uniformities, and complex conductor structures [23]. This complicates the determination of wave parameters such as modal impedances and propagation constants and necessitates the development of new approaches that allow analysis to be carried out in the physical conductor space, avoiding the limitations of modal analysis.

In this context, the development of methods capable of describing the wave behaviour of a real physical wave in multiconductor lines without the need for complex transformations and modal diagonalisation becomes particularly relevant. This is precisely the objective pursued by the approach proposed in this work, which is focused on ensuring the resilience and security of critical energy infrastructures.

3. GENERALIZED WAVE PARAMETER OF A COUPLED LINE

As shown in [24], the electromagnetic processes associated with the propagation of a sinusoidal signal in a system of two coupled lines are described by the equations:

$$\begin{cases} \dot{U}_1(x) = C_1 \cdot ch(\gamma_1 x) + C_2 \cdot ch(\gamma_2 x) + C_3 \cdot sh(\gamma_1 x) + C_4 \cdot sh(\gamma_2 x) \\ \dot{U}_2(x) = C_1 \cdot ch(\gamma_1 x) - C_2 \cdot ch(\gamma_2 x) + C_3 \cdot sh(\gamma_1 x) - C_4 \cdot sh(\gamma_2 x) \\ \dot{I}_1 = -\dfrac{1}{\underline{Z}_{C1}}\big(C_1 \cdot sh(\gamma_1 x) + C_3 \cdot ch(\gamma_1 x)\big) - \dfrac{1}{\underline{Z}_{C2}}\big(C_2 \cdot sh(\gamma_2 x) + C_4 \cdot ch(\gamma_2 x)\big), \\ \dot{I}_2 = -\dfrac{1}{\underline{Z}_{C1}}\big(C_1 \cdot sh(\gamma_1 x) + C_3 \cdot ch(\gamma_1 x)\big) + \dfrac{1}{\underline{Z}_{C2}}\big(C_2 \cdot sh(\gamma_2 x) + C_4 \cdot ch(\gamma_2 x)\big) \end{cases} \quad (1)$$

where $\dot{U}_1, \dot{U}_2, \dot{I}_1, I_2$ – the voltage and current phasors in each line at a distance x from their origin, γ_1 and γ_2 – are the propagation constants of the even and odd modes, respectively, $\underline{Z}_{C1}$ and $\underline{Z}_{C2}$ – the wave impedances, which represent the proportionality coefficients between the incident and reflected current and voltage waves of each mode. The constants C_1, C_2, C_3, and C_4 are determined from the initial conditions.

The even mode in a symmetrical two-conductor line is an eigenmode of wave propagation in which the voltages and currents in the conductors are determined by the energy sources connected to these conductors. The odd mode is formed by currents and voltages that arise in the given line as a result of electromagnetic coupling with a neighbouring line.

As can be seen, all currents and voltages mathematically consist of four components: two modes for the incident waves and two modes for the reflected waves. Each of these waves is formed by two oscillation modes, which gives rise to the appearance of two different wave impedances. However, these impedances do not have a direct physical meaning in the conductor, since the modes are merely mathematical eigen-solutions of the system of equations rather than real waves that exist in the line. Physical meaning is associated only with the wave impedances of the incident and reflected waves, as it is these that describe the actual relationships between voltage and current along the physical conductor, the energy flow, and the behaviour of the wave during propagation and reflection.

Therefore, the two separate wave impedances are purely mathematical quantities that simplify the solution of problems but do not reflect real wave processes. Instead, we introduce the concept of an equivalent wave impedance as the coefficient of proportionality between the currents and voltages of the physically existing incident and reflected waves:

$$\dot{U}^{(+)} = \underline{Z}_e \cdot \dot{I}^{(+)}. \tag{2}$$

Here, the symbols $\dot{U}^{(+)}$ and $\dot{I}^{(+)}$ denote the incident voltage and current waves.

Such an equivalent wave impedance for the incident and reflected waves has a clear physical interpretation, since it is directly related to the actual, experimentally observable regime of signal propagation in the conductor. It will be shown later that the same impedance $\underline{Z}_e$ is also characteristic of the reflected waves $\dot{U}^{(-)}$ and $\dot{I}^{(-)}$.

To calculate the equivalent wave impedance, system (1) is rewritten in terms of exponential functions:

$$\begin{cases} \dot{U}_1 = D_1 e^{\gamma_1 x} + D_2 e^{-\gamma_1 x} + D_3 e^{\gamma_2 x} + D_4 e^{-\gamma_2 x} \\ \dot{U}_2 = D_1 e^{\gamma_1 x} + D_2 e^{-\gamma_1 x} - (D_3 e^{\gamma_2 x} + D_4 e^{-\gamma_2 x}) \\ \dot{I}_1 = -\dfrac{1}{\underline{Z}_{C1}}(D_1 e^{\gamma_1 x} - D_2 e^{-\gamma_1 x}) - \dfrac{1}{\underline{Z}_{C2}}(D_3 e^{\gamma_2 x} - D_4 e^{-\gamma_2 x}). \\ \dot{I}_2 = -\dfrac{1}{\underline{Z}_{C1}}(D_1 e^{\gamma_1 x} - D_2 e^{-\gamma_1 x}) + \dfrac{1}{\underline{Z}_{C2}}(D_3 e^{\gamma_2 x} - D_4 e^{-\gamma_2 x}) \end{cases} \tag{3}$$

The constant $D_1 - D_4$ can be calculated as follows:

$$D_1 = \frac{C_1 + C_3}{2};\; D_2 = \frac{C_1 - C_3}{2};\; D_3 = \frac{C_2 + C_4}{2};\; D_2 = \frac{C_2 - C_4}{2}. \tag{4}$$

Then, the equivalent wave impedance for the incident wave in the first conductor can be written as:

$$\underline{Z}_{e1}^{(+)} = \frac{D_2 e^{-\gamma_1 x} + D_4 e^{-\gamma_2 x}}{\dfrac{D_2}{\underline{Z}_{C1}} e^{-\gamma_1 x} + \dfrac{D_4}{\underline{Z}_{C2}} e^{-\gamma_2 x}}.$$

This equation is valid for any point along the line, including the case *x=0*. Thus, we obtain:

$$\underline{Z}_{e1}^{(+)} = \frac{D_2 + D_4}{\dfrac{D_2}{\underline{Z}_{C1}} + \dfrac{D_4}{\underline{Z}_{C2}}}. \tag{5}$$

The coefficient D_2 in the first equation of system (3) corresponds to the even mode of oscillation, which is determined by the intrinsic energy source connected to this line. The coefficient D_4, which corresponds to the odd mode (it multiplies the exponential term with the exponent γ_2), characterises the influence of the neighbouring conductor. Let us denote the ratio

$$\frac{D_4}{D_2} = k^{(+)}. \tag{6}$$

This ratio represents the specific influence of the second conductor on the first and can be regarded as a measure of electromagnetic coupling between the conductors. We refer to this quantity as the influence coefficient. Taking (6) into account, the final expression can be written as

$$\underline{Z}_{e1}^{(+)} = \frac{\underline{Z}_{C1} \cdot \underline{Z}_{C2} \cdot \left(1 + k^{(+)}\right)}{\underline{Z}_{C2} + k^{(+)} \cdot \underline{Z}_{C1}}. \tag{7}$$

For the ratio of voltage to current of the reflected wave, introducing the influence coefficient

$$\frac{D_3}{D_1} = k^{(-)},$$

we obtain the expression for the equivalent wave impedance of the reflected wave:

$$\underline{Z}_{e1}^{(-)} = \frac{\underline{Z}_{C1} \cdot \underline{Z}_{C2} \cdot \left(1 + k^{(-)}\right)}{\underline{Z}_{C2} + k^{(-)} \cdot \underline{Z}_{C1}}. \tag{8}$$

For the second line, there also exist two equivalent wave impedances, which can be calculated in an analogous manner.

4. DISCUSSION

The introduction of the equivalent wave impedance into the practice of electrical engineering calculations creates new opportunities for controlling electromagnetic processes in multiconductor structures used in critical infrastructure systems. Unlike the traditional approach, in which wave properties are described by the characteristic impedances of the even and odd modes, the proposed parameter directly relates the voltage and current of a physically existing wave in a specific conductor. This is fundamentally important, since these quantities can be directly measured and monitored by hardware means for control and regulation purposes, whereas modal components exist only as mathematical abstractions, are not amenable to direct measurement, and cannot be used in practical systems without prior mathematical processing.

However, another unexpected aspect is of particular significance. Since traditional modal impedances are determined exclusively by the primary parameters of the line – inductances, capacitances, and mutual couplings – they remain constant during system operation. Consequently, within classical theory, wave impedances are fixed constants that can be adjusted only through physical modification of the line geometry, such as changing the spacing between conductors, conductor widths, or the dielectric properties of the substrate. This means that the traditional approach does not conceptually allow for dynamic control of wave impedance and therefore does not reveal the potential controllability of wave processes in coupled structures.

The proposed equivalent wave impedance depends not only on the primary parameters but also on the electrical operating regimes, in particular on the ratio of the even and odd modal components in the physical wave, which is determined by the excitation conditions, phase relationships, and the load state. Our approach demonstrates that wave impedance is not a purely geometrical characteristic, but a dynamic parameter that can be influenced by controlling the electrical quantities within the line. Thus, it becomes possible to modify the effective wave impedance without any physical alteration of the line, solely by adjusting the excitation parameters or the voltage in the coupled conductor. This important conceptual result is unattainable within the framework of classical modal theory.

In the theory of distributed-parameter circuits, the concept of a matched load regime is well known. This regime is achieved when the load resistance of a line is equal to its wave impedance. Under such conditions, the reflected wave is absent, and all electromagnetic energy carried by the line is transferred to the load. In single transmission lines, achieving this regime in practice is very difficult. However, the controllability of the wave impedance of a coupled line revealed in this study makes it possible to realise dynamic matching between the line and its load. This ensures a minimal reflection coefficient and maximum energy transfer efficiency, transforming the coupled line into an adaptive structure capable of autonomously maintaining optimal operating regimes.

In the context of high-speed telecommunication systems of critical infrastructure, this opens a pathway to the formation of wave states in which interference can be compensated, transmission distortions reduced, and devices matched under changing load characteristics and signal source conditions. In systems with strong mutual electromagnetic coupling, dynamic adjustment of the ratio of modal components may allow control of electromagnetic interaction between lines, ensure electromagnetic compatibility, and maintain the stability of communication channels even under conditions of intense disturbances.

Thus, the introduction of the equivalent wave impedance not only refines the physical understanding of wave processes in coupled lines but also, in practical terms, unlocks the potential for controlling these processes. The coupled line is transformed from a passive element into a dynamically controlled structure whose parameters can be modified in real time without changing its geometry. This creates new prospects for enhancing the reliability, adaptability, and efficiency of information and energy channels within critical infrastructures.

5. CONCLUSION

This work proposes a well-substantiated approach to the analysis of wave processes in coupled lines that overcomes the limitations of traditional modal theory and makes it possible to reveal the interdependencies between physically existing incident and reflected waves in real conductors. On the basis of this approach, a new parameter – the equivalent wave impedance – is introduced. It is defined through the relationship between the voltage and current of a real wave and has a direct physical meaning. Unlike modal characteristic impedances, which are mathematical constructs and cannot be measured directly, the equivalent wave impedance can be determined experimentally.

It is shown that the equivalent wave impedance is not a constant determined solely by the geometry of the line but depends on the electrical operating regimes within the lines. This creates the possibility of dynamic control of wave processes, adaptive real-time matching of lines, and active suppression of undesirable electromagnetic effects such as reflections, transient overvoltage, cross-modal interference, or resonant phenomena. This reveals a fundamental property of coupled lines – their ability to exhibit controllable wave behaviour without any change in geometry, solely through active influence on the electrical parameters of the system.

The practical significance of the obtained results is multifaceted. First, in critical infrastructures where wave effects can cause maloperation of relay protection, erroneous telemetry, signal degradation, and loss of resilience of communication channels, the new wave parameters may be used as indicators of network state. Second, equivalent wave impedances enable the development of digital twins of transmission lines, that is, models capable of accurately reproducing the wave properties of real lines in real time. Such digital twins can be employed to forecast emergency operating conditions, assess the impact of HEMP events, analyse anomalies and IoT telemetry, and test stress scenarios without risk to real equipment. This provides developers with a unique tool for virtual testing, early detection of line degradation, optimisation of communication channels, and enhancement of the cyber-physical resilience of critical systems.

The obtained results open up opportunities for further interpretation of wave processes in lines in terms of equivalent wave impedances, thereby creating prerequisites for the formation of digital twins of communication lines and the analysis of their behaviour without intervention in the physical infrastructure. Future research may focus on extending this approach to asymmetric and non-uniform structures, as well as on its interpretation in the context of cyber-physical systems and digital monitoring of critical infrastructures. Such developments will make it possible to integrate theoretical insights into wave processes with practical tasks of analysis, observation, and control of the states of power supply and information transmission systems.

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Manuscript received on 01 December 2025