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Received: 22 April 2026

Accepted: 18 August 2026

Published online: 21 August 2026

Cite this article as: Mugabe R., Atim M.R., Obungoloch J. *et al.* Fault–responsive hybrid analytical–simulation framework for electric power transmission performance monitoring. *Sci Rep* (2026). <https://doi.org/10.1038/s41598-026-67869-0>

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Fault–Responsive Hybrid Analytical–Simulation Framework for Electric Power Transmission Performance Monitoring

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Abstract—Continuous monitoring of electric power transmission systems is essential for maintaining reliable power transfer under increasingly dynamic operating conditions. Although analytical and simulation-based approaches have individually advanced transmission-system analysis, comparatively fewer studies have integrated their complementary strengths within a unified monitoring framework. This paper proposes a fault-responsive hybrid analytical–simulation framework that combines distributed-parameter transmission-line modelling based on the ABCD parameter formulation with an equivalent π -model implemented in MATLAB/Simulink for continuous assessment of transmission-line performance. The framework evaluates transmission efficiency, voltage regulation, and voltage-drop index under normal and abnormal operating conditions, including voltage sag, overload, low power factor, and balanced and unbalanced faults. Validation is performed against a benchmark distributed-parameter simulation using waveform comparison together with root mean square error (RMSE) and mean absolute error (MAE). The proposed hybrid framework consistently achieved the lowest prediction errors, reducing the average transmission-efficiency MAE from approximately 0.62% for the analytical ABCD model and 0.05% for the equivalent π -model to approximately 0.01%. Similarly, the average voltage-regulation MAE decreased from approximately 1.05% and 0.65% to approximately 0.07%, while accurately reproducing transmission-line behaviour during fault initiation, fault clearing, and post-fault recovery. These results demonstrate that integrating analytical modelling with dynamic simulation provides a practical, computationally efficient, and scalable framework for continuous transmission-line performance monitoring and decision support.

Index Terms—Power transmission, hybrid modelling, ABCD parameters, π -model, performance monitoring, fault analysis.

I. INTRODUCTION

The reliable operation of electric power transmission systems is fundamental to ensuring the secure, efficient, and continuous delivery of electrical energy from generating stations to distribution networks and end users [1]–[3]. As modern power systems continue to expand through long-distance transmission corridors, increasing penetration of renewable energy resources, growing electricity demand, and more dynamic loading conditions, transmission networks are required to operate under a wider range of operating scenarios than ever before [4], [5]. These evolving operating conditions introduce significant technical challenges, including increased transmission losses, voltage deviations, power quality deterioration, and a higher likelihood of abnormal events that may compromise system reliability and operational security [6]–[9].

Continuous monitoring of transmission-line performance has therefore become an essential component of modern power system operation [10], [11]. Accurate and timely assessment of key transmission performance indicators enables system operators to detect abnormal operating conditions at an early stage, evaluate the severity of disturbances, support operational decision-making, and implement appropriate corrective actions before minor disturbances develop into widespread system failures [12]–[15]. Consequently, the development of reliable monitoring frameworks capable of assessing transmission-line performance under both normal and abnormal operating conditions remains an important research area in electric power transmission engineering [16]–[18].

Several analytical and simulation-based approaches have

been developed to model and evaluate the performance of electric power transmission systems [19]–[21]. Among the most widely adopted analytical techniques are distributed-parameter transmission-line models based on the ABCD parameter formulation, which provide an accurate representation of voltage and current relationships over long transmission distances [22], [23]. Equivalent π -models have also been extensively employed to simplify distributed transmission-line behaviour into practical circuit representations suitable for steady-state analysis, protection studies, and numerical simulation. In parallel, electromagnetic transient (EMT) programs and MATLAB/Simulink-based implementations have become indispensable tools for investigating transmission-system dynamics under both normal and disturbed operating conditions [24]–[26]. These approaches have significantly advanced the understanding of transmission-line behaviour and continue to serve as fundamental tools for system analysis, design, and operational studies.

Early transmission-line studies mainly relied on lumped-parameter representations suitable for short lines [27], [28], whereas distributed-parameter formulations provide more accurate modelling of long transmission lines and transient behaviour [29], [30].

Recent advances in transmission-line monitoring have extended beyond conventional analytical and simulation techniques to include measurement-driven and intelligent monitoring frameworks [31]–[33], [35]. Phasor Measurement Unit (PMU)-based monitoring systems provide synchronized, high-resolution measurements that support wide-area situational awareness, dynamic state estimation, and disturbance analysis [34], [36]. Supervisory Control and Data Acquisition (SCADA) systems remain the backbone of operational monitoring by enabling centralized data acquisition and control across large transmission networks [37], [38]. Electromagnetic transient (EMT) simulation platforms offer detailed representations of fast transient phenomena, while travelling-wave and impedance-based methods have demonstrated high accuracy in fault detection and fault-location applications [39], [40]. More recently, digital twin technologies and machine learning approaches have emerged as promising solutions for predictive maintenance, anomaly detection, and intelligent decision support by exploiting large volumes of operational data [41]–[43].

Although these approaches have significantly advanced transmission-line analysis and monitoring, they are generally developed to address specific aspects of transmission-system operation, such as detailed electromagnetic simulation, synchronized measurement analysis, fault location, or data-driven anomaly detection. Comparatively fewer studies have focused on integrating established analytical transmission-line models with dynamic simulation and continuous performance-index evaluation within a unified monitoring architecture. Consequently, there remains a need for practical frameworks capable of combining the

physical interpretability of analytical models with the dynamic behaviour captured by simulation while continuously assessing transmission performance under both normal and abnormal operating conditions using multiple complementary performance indicators.

To address this need, this paper proposes a Fault-Responsive Hybrid Analytical–Simulation Framework for Electric Power Transmission Performance Monitoring. The proposed framework integrates distributed-parameter analytical modelling based on the ABCD transmission-line formulation with an equivalent π -model implemented in MATLAB/Simulink to establish a unified monitoring architecture for transmission-system performance assessment. Rather than introducing a new transmission-line model, the framework combines complementary analytical and simulation capabilities to continuously evaluate key transmission performance indices, including transmission efficiency, voltage regulation, and voltage-drop index, under both balanced and unbalanced operating conditions. In addition, the framework incorporates fault-responsive monitoring, threshold-based anomaly detection, and comprehensive validation using multiple operating scenarios to support reliable assessment of transmission-line performance.

The main contributions of this work are summarized as follows:

- 1) A fault-responsive hybrid analytical–simulation framework is developed for continuous performance monitoring of electric power transmission systems by integrating distributed-parameter analytical modelling with dynamic simulation within a unified monitoring architecture.
- 2) An analytical transmission-line formulation based on ABCD parameters is integrated with an equivalent π -model implemented in MATLAB/Simulink to enable complementary analytical prediction and dynamic simulation of transmission-line behaviour under normal and abnormal operating conditions.
- 3) A comprehensive performance-monitoring methodology is presented for the continuous evaluation of transmission efficiency, voltage regulation, and voltage-drop index together with threshold-based anomaly detection under multiple operating scenarios, including voltage sag, overload, low power factor, and balanced and unbalanced faults.
- 4) The proposed framework is extensively validated using multiple transmission-line operating conditions through waveform analysis, root-mean-square error (RMSE), mean absolute error (MAE), and comparative performance assessment against conventional analytical modelling approaches.
- 5) The proposed framework is critically discussed in the context of contemporary transmission-line monitoring approaches, highlighting its applicability, advantages, limitations, and potential integration with future PMU-, SCADA-, and digital-twin-based monitoring environments.

The remainder of this paper is organized as follows. Section II presents the proposed hybrid analytical–simulation framework, including the analytical transmission-line formulation, equivalent π -model representation, fault modelling strategy, performance-monitoring methodology, MATLAB/Simulink implementation, and validation procedure. Section III presents the simulation results, comparative performance evaluation, robustness analysis, and discussion under normal and abnormal operating conditions. Finally, Section IV concludes the paper and outlines directions for future research.

To further position the proposed framework within the context of existing transmission-line monitoring approaches, Table 1 presents a conceptual comparison between representative analytical, simulation-based, measurement-based, and data-driven techniques. The comparison highlights their principal characteristics in terms of computational complexity, data requirements, monitoring capability, and practical deployment considerations, thereby providing a clearer understanding of the research gap addressed in this work. Existing approaches generally emphasize either high-fidelity simulation, measurement-based monitoring, or data-driven analysis. In contrast, the proposed hybrid analytical–simulation framework combines analytical modelling with dynamic simulation to provide a physics-based, computationally efficient, and interpretable solution for continuous transmission-line performance monitoring without requiring large labelled training datasets or specialized wide-area synchronized measurement infrastructure.

II. METHODOLOGY

A. Framework Architecture

Figure 1 presents the architecture of the proposed framework for electric power transmission performance monitoring. The framework integrates analytical transmission-line modelling, dynamic simulation, continuous performance evaluation, and decision support within a unified architecture to enable systematic assessment of transmission-line operating conditions under both normal and abnormal scenarios. Rather than introducing a new transmission-line model, the framework combines established analytical and simulation techniques to exploit their complementary strengths for continuous monitoring and performance assessment.

The framework is organised into four interconnected functional components. The analytical modelling component establishes the mathematical representation of the transmission line using distributed-parameter theory and computes the transmission-line parameters required for analytical performance evaluation. The dynamic simulation component implements an equivalent π -model within MATLAB/Simulink to reproduce the time-domain behaviour of the transmission line under normal operation and fault conditions. The performance monitoring component continuously evaluates transmission efficiency, voltage regulation, voltage-drop

index, and other electrical quantities to assess the operational state of the transmission system. Finally, the decision support and validation component performs threshold-based performance assessment together with quantitative validation using waveform comparison and statistical error metrics.

The interaction between these components enables the framework to combine analytical prediction with dynamic simulation while providing continuous monitoring of transmission-line performance. The following subsections describe the development of each component and its contribution to the overall monitoring framework.

B. Analytical Modelling Layer

The analytical modelling layer establishes the physical and mathematical foundation of the proposed framework. Its primary objective is to accurately represent the electrical behaviour of a long transmission line using distributed-parameter transmission-line theory. By accounting for the continuous distribution of the electrical parameters along the transmission line, this layer provides the analytical relationships required to evaluate voltage, current, power transfer, and other operating quantities before dynamic simulation is performed.

The analytical modelling layer consists of four sequential stages. First, the transmission line is represented as a distributed electrical system. Second, the distributed electrical parameters are used to formulate the governing transmission-line equations. Third, the propagation constant and characteristic impedance are determined to describe wave propagation along the transmission line. Finally, the ABCD transmission parameters are derived and subsequently transformed into an equivalent π -model for implementation within the dynamic simulation layer.

1) Distributed Representation of the Transmission Line:

The proposed framework represents the transmission line as a distributed-parameter system in which the series resistance (R), series inductance (L), shunt capacitance (C), and shunt conductance (G) are continuously distributed along the entire line length. This representation provides a realistic description of long transmission lines where the electrical characteristics cannot be accurately approximated using lumped circuit elements.

Distributed-parameter modelling enables accurate characterization of voltage and current propagation while accounting for attenuation, phase shift, reactive power exchange, and charging effects that become increasingly significant as transmission-line length increases. Consequently, this representation provides the physical basis for deriving the transmission-line equations employed within the analytical modelling layer of the proposed framework.

2) Distributed-Parameter Transmission-Line Formulation:

The distributed transmission-line model is developed using the electrical parameters summarized in Table 2. These parameters describe the electrical characteristics per unit length of the transmission line and form the basis for deriving the governing analytical equations.

TABLE 1
CONCEPTUAL COMPARISON OF REPRESENTATIVE TRANSMISSION-LINE MONITORING APPROACHES

Method		Accuracy	Computational Cost	Data Requirement	Real-Time Capability	Remarks
EMT-based [24]–[26]	simulation	High	High	Detailed network parameters	Limited	Highly accurate but computationally intensive for continuous monitoring.
Traveling-wave detection [42]	fault	Very High	Moderate	High-frequency synchronized measurements	High	Excellent fault-location accuracy but requires high-speed measurement hardware.
Frequency-dependent transmission-line model [58]	model	High	High	Detailed frequency-dependent line parameters	Moderate	Accurately represents wide-band electromagnetic transient behaviour but requires more detailed parameterization and increased computational effort.
PMU/SCADA monitoring [34], [36], [37]		Moderate–High	Low	Wide-area synchronized measurements	High	Suitable for operational monitoring but depends on communication infrastructure.
Impedance-based methods [57]		Moderate	Low	Voltage and current measurements	High	Simple implementation but accuracy decreases under varying operating conditions.
Digital twin approaches [38], [49]		High	High	Real-time measurement and communication infrastructure	High	Provides comprehensive system representation but requires continuous model updating.
Machine-learning methods [34], [38]		High	Moderate–High	Large labelled training datasets	High	Good adaptive capability but dependent on training data quality and model generalization.
Proposed hybrid analytical–simulation framework		High	Moderate	Analytical parameters and simulation data	Offline (current study)	Integrates analytical modelling, dynamic simulation and continuous performance monitoring within a unified framework.

TABLE 2
DISTRIBUTED TRANSMISSION-LINE PARAMETERS EMPLOYED IN THE ANALYTICAL MODELLING LAYER.

Symbol	Description	Unit
R	Series resistance per unit length	Ω/km
L	Series inductance per unit length	H/km
C	Shunt capacitance per unit length	F/km
G	Shunt conductance per unit length	S/km
l	Transmission-line length	km
f	System frequency	Hz
ω	Angular frequency, $\omega = 2\pi f$	rad/s
j	Imaginary operator, $j = \sqrt{-1}$	Dimensionless

The distributed electrical parameters are combined to determine the series impedance and shunt admittance per unit length of the transmission line according to

$$z = R + j\omega L \quad (1)$$

$$y = G + j\omega C \quad (2)$$

The series impedance represents the combined effects of conductor resistance and inductive reactance, whereas

the shunt admittance represents the combined influence of dielectric leakage and capacitive charging. For overhead transmission lines operating under normal conditions, the leakage conductance is generally very small ([44], [45]) and is therefore assumed to be negligible in the present study, resulting in $G \approx 0$ for all simulation cases considered.

3) *Propagation Constant and Characteristic Impedance:*
The propagation characteristics of the transmission line are determined from the distributed series impedance and shunt admittance. These quantities describe the manner in which voltage and current waves propagate along the transmission line and therefore constitute fundamental parameters within the analytical modelling layer.

The propagation constant is determined as

$$\gamma = \sqrt{zy} \quad (3)$$

where γ (km^{-1}) is the complex propagation constant, whose real component represents the attenuation constant and whose imaginary component represents the phase constant.

The characteristic impedance is given by

$$Z_c = \sqrt{\frac{z}{y}} \quad (4)$$

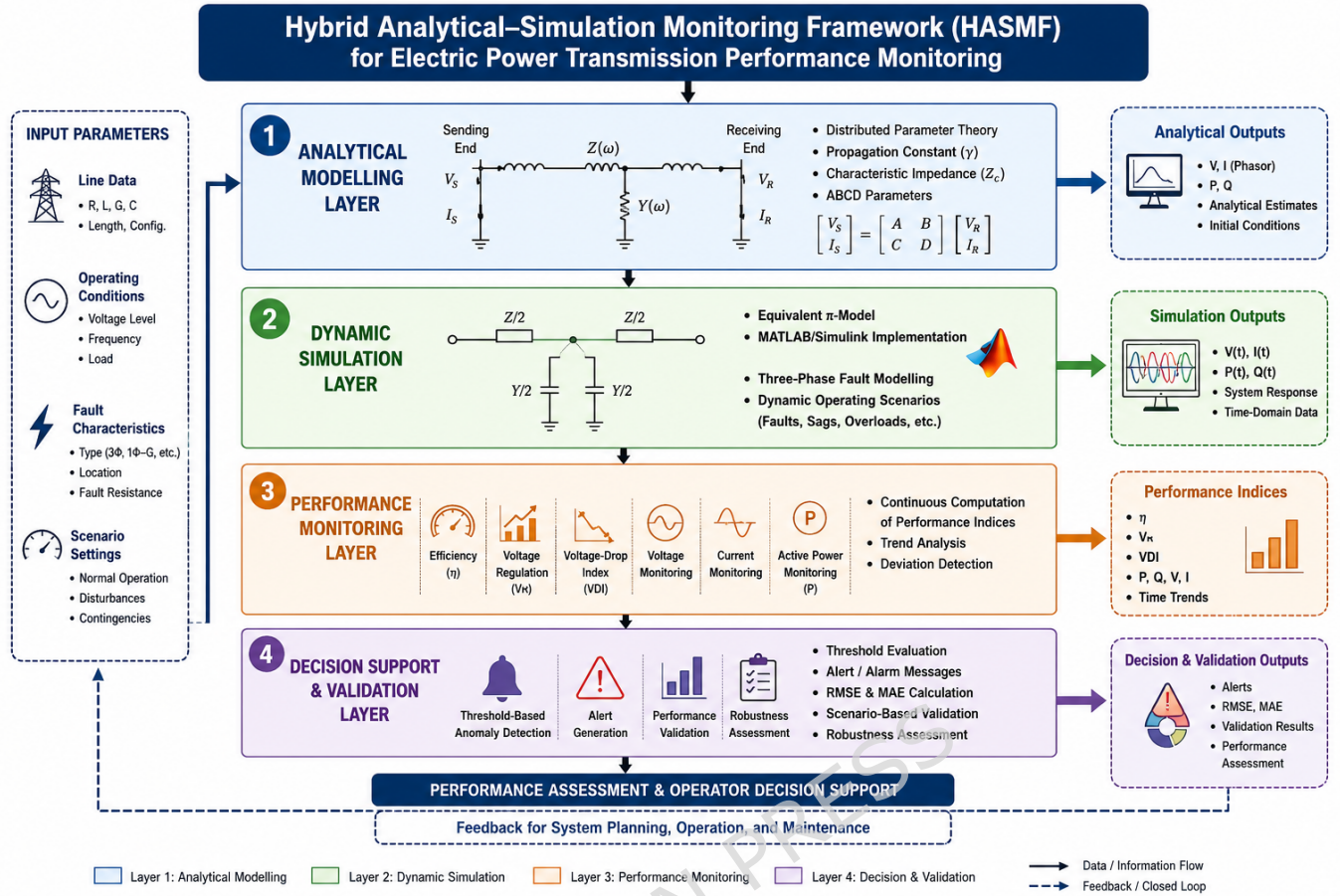


Fig. 1. Architecture of the proposed Hybrid Analytical-Simulation Monitoring Framework (HASMf) for electric power transmission performance monitoring.

where Z_c (Ω) denotes the characteristic impedance of the transmission line.

The propagation constant and characteristic impedance provide a complete analytical description of wave propagation in distributed transmission systems and are subsequently employed in the computation of the ABCD transmission parameters. These quantities also establish the analytical reference against which the dynamic simulation results obtained from the equivalent π -model are evaluated.

4) ABCD Transmission Parameters: The ABCD transmission parameters establish the relationship between the sending-end and receiving-end electrical quantities of a distributed transmission line. These parameters provide a compact mathematical representation of transmission-line behaviour and constitute the analytical foundation upon which the subsequent equivalent π -model is developed.

For a long transmission line, the ABCD parameters are obtained from

$$\begin{aligned} A &= D = \cosh(\gamma l) \\ B &= Z_c \sinh(\gamma l) \\ C &= \frac{1}{Z_c} \sinh(\gamma l) \end{aligned} \quad (5)$$

The corresponding sending-end and receiving-end voltage-current relationship is expressed as

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \quad (6)$$

The ABCD transmission parameters preserve the distributed electrical characteristics of the transmission line while providing a computationally efficient analytical representation of the voltage-current relationship between the sending and receiving terminals. Within the proposed framework, these parameters constitute the analytical output of the analytical modelling layer and provide the information required for developing the equivalent π -model implemented within the dynamic simulation layer.

C. Dynamic Simulation Layer

The dynamic simulation layer provides the computational component of the proposed framework by transforming the analytical transmission-line representation into an equivalent circuit suitable for time-domain simulation. While the analytical modelling layer accurately characterizes the steady-state behaviour of the transmission line using distributed-parameter theory, dynamic simulation enables the investigation of transient phenomena and the evaluation

of transmission-line performance under changing operating conditions and network disturbances.

To preserve the distributed electrical characteristics while facilitating efficient simulation, the analytically derived ABCD transmission parameters are transformed into an equivalent π -model. This equivalent circuit retains the steady-state characteristics of the distributed transmission line while providing a practical representation for implementation within MATLAB/Simulink. Consequently, the analytical and simulation components remain mathematically consistent while enabling complementary evaluation of transmission-line behaviour.

1) Development of the Equivalent π -Model: The equivalent π -model is developed directly from the distributed transmission-line parameters to establish an equivalent circuit representation that preserves the electrical characteristics of the original transmission line. The model consists of a series impedance representing the longitudinal impedance of the transmission line together with two equal shunt admittances that represent the distributed charging effects at both terminals.

The equivalent series impedance is obtained as

$$Z' = \frac{Z \sinh(\gamma l)}{\gamma l} \quad (7)$$

where Z' (Ω) denotes the equivalent series impedance of the transmission line.

The equivalent shunt admittance is determined by

$$Y' = 2 \frac{\tanh\left(\frac{\gamma l}{2}\right)}{Z_c} \quad (8)$$

where Y' (S) represents the total equivalent shunt admittance distributed equally between the sending and receiving terminals.

The series impedance reproduces the distributed impedance of the transmission line, whereas the equivalent shunt admittances represent the cumulative capacitive charging effects occurring along the transmission-line length. Consequently, the resulting equivalent π -model preserves the steady-state electrical characteristics of the distributed transmission line while providing a computationally efficient circuit representation suitable for dynamic simulation.

Although the equivalent π -model represents a simplified circuit realization of the distributed transmission line, its parameters are derived directly from the distributed-parameter formulation through the propagation constant and characteristic impedance. Consequently, the equivalent circuit remains analytically consistent with the underlying transmission-line theory while providing the flexibility required for dynamic simulation under varying operating conditions [46], [47].

The derived equivalent π -model constitutes the simulation component of the proposed framework and forms the basis for implementing the transmission line within the MATLAB/Simulink environment.

2) Modelling of Normal and Abnormal Operating Conditions: The proposed framework is designed to evaluate transmission-line performance under both normal and abnormal operating conditions to assess its capability for continuous monitoring and fault-responsive analysis. The investigated operating scenarios are summarized in Table 3. These scenarios were selected to represent practical transmission-system conditions that significantly influence transmission efficiency, voltage regulation, and overall network performance. Normal operating conditions correspond to steady-state operation under rated transmission-line parameters without externally imposed disturbances. These operating conditions provide the reference case against which all abnormal operating scenarios are evaluated.

Abnormal operating conditions are introduced by applying controlled disturbances within the dynamic simulation environment. Voltage sag conditions are simulated by reducing the sending-end voltage magnitude to emulate upstream supply disturbances and network voltage depressions. Overload conditions are generated by progressively increasing the receiving-end load demand beyond its nominal operating level while maintaining the transmission-line configuration unchanged. Low power factor conditions are established by increasing the reactive power demand of the receiving-end load, thereby reducing the load power factor while maintaining the specified active power demand.

Fault conditions are represented using balanced and unbalanced short-circuit disturbances applied at predefined locations along the transmission line. The investigated fault scenarios include three-phase (LLL) faults, single-line-to-ground (SLG) faults, line-to-line (LL) faults, and double-line-to-ground (DLG) faults. Each fault is characterized by its location, fault resistance, initiation time, clearing time, and grounding configuration to reproduce representative transmission-system disturbances.

Following fault inception, each disturbance is maintained for a predetermined duration before being cleared to emulate protective relay operation and circuit-breaker action. The subsequent post-fault recovery period enables evaluation of the proposed framework during system restoration and facilitates assessment of its capability to continuously monitor transmission-line performance before, during, and after fault events.

The operating conditions described above were systematically implemented within the dynamic simulation environment to evaluate the proposed framework under representative transmission-system scenarios. The resulting simulation architecture enables consistent comparison between the analytical predictions and the corresponding dynamic responses obtained under each operating condition.

3) MATLAB/Simulink Implementation: The equivalent π -model together with the proposed monitoring framework is implemented within the MATLAB/Simulink environment, as can be seen in Figure 2, to enable dynamic simulation under the operating conditions. MATLAB is employed for the analytical computation of the distributed transmission-line

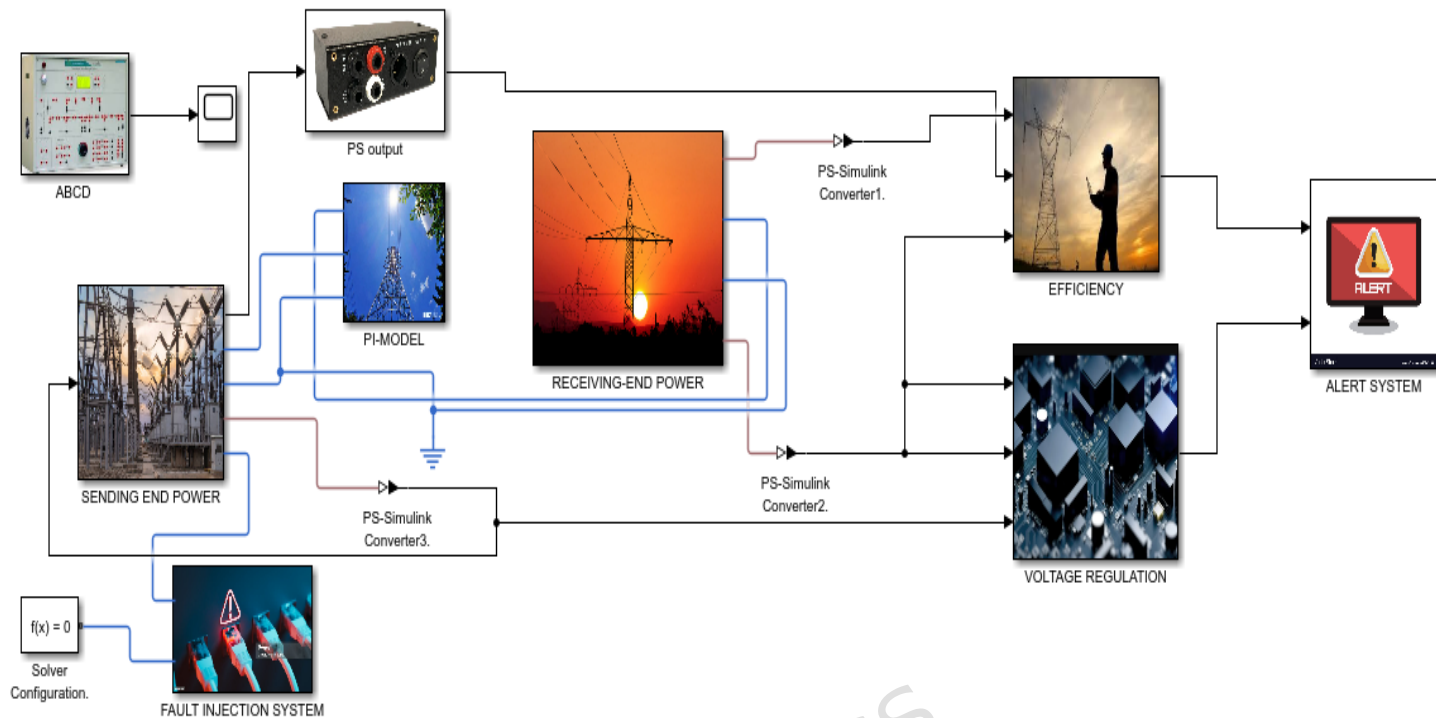


Fig. 2. Simulink schematic for fault-responsive transmission line modeling and performance monitoring.

TABLE 3
OPERATING CONDITIONS CONSIDERED IN THE PROPOSED FRAMEWORK

Operating Condition	Physical Representation
Normal operation	Rated transmission-line operation without an externally imposed disturbance.
Voltage sag	Temporary reduction of the source-voltage magnitude to represent an upstream voltage depression.
Overload	Increase in the receiving-end load demand beyond the nominal operating level.
Low power factor	Increase in receiving-end reactive power demand while maintaining the specified active power demand.
Three-phase fault	Simultaneous short circuit involving phases A, B, and C.
Single-line-to-ground fault	Short circuit between one phase conductor and ground.
Line-to-line fault	Short circuit between two phase conductors.
Double-line-to-ground fault	Short circuit involving two phase conductors and ground.

parameters, while Simulink provides the dynamic simulation environment for reproducing steady-state and transient transmission-line behaviour.

The simulation model incorporates the equivalent π -model together with configurable source, transmission-line, load, and fault subsystems to reproduce representative transmission-system operating conditions. The modular implementation enables systematic investigation of voltage sag, overload, low power factor, balanced faults,

and unbalanced faults while maintaining consistent transmission-line parameters throughout all simulation cases.

During each simulation, the sending-end and receiving-end voltages, currents, active power, and reactive power are continuously monitored to evaluate the transmission-line operating condition. These measured electrical quantities are subsequently employed to compute the transmission efficiency, voltage regulation, and voltage-drop index, which constitute the principal performance indicators used throughout this study. The analytical and simulated responses are further utilized during the validation stage to assess the consistency and accuracy of the proposed framework under both normal and abnormal operating conditions.

The proposed framework is evaluated using MATLAB and Simulink as an offline simulation environment ([48], [49]) to investigate transmission-line behaviour under controlled operating conditions. The objective of the study is to develop and validate a fault-responsive monitoring methodology rather than to demonstrate hardware-based real-time implementation. Consequently, the analytical computations and dynamic simulations are performed within the MATLAB/Simulink platform to enable systematic evaluation of normal operation, voltage disturbances, overload conditions, and balanced and unbalanced faults. This implementation provides a flexible environment for validating the proposed framework prior to future deployment within real-time digital simulation or hardware-assisted monitoring platforms.

The simulation model consists of:

- Three-Phase source as shown in Figure 3 and Figure 4, voltage and current measurement blocks,

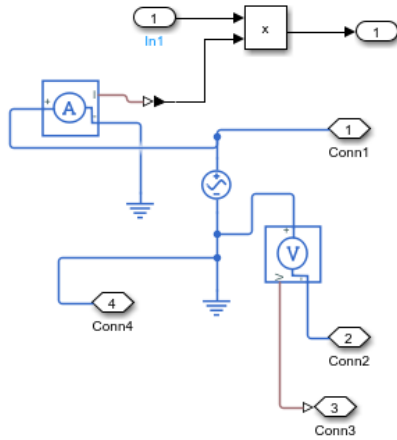


Fig. 3. Sending-end power block

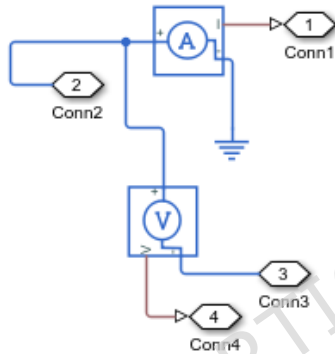


Fig. 4. Receiving-end power block

- RLC load and distributed line model
- Subsystems for ABCD, Figure 5, and π -model, Figure 6, calculation using MATLAB function blocks

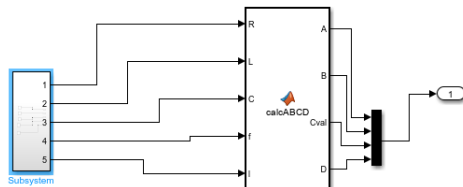


Fig. 5. ABCD parameter computation subsystem.

- Computation blocks for active power (P), apparent power (S), efficiency (η), Figure 7, and voltage regulation (VR), Figure 8

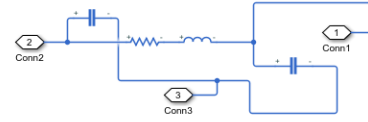
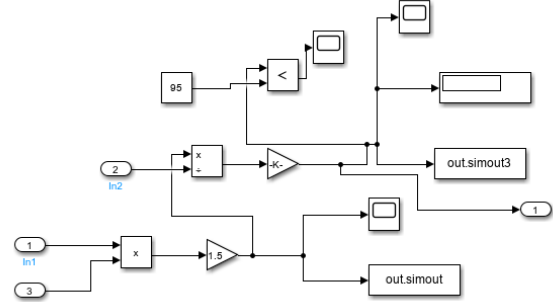
Fig. 6. π -model block.

Fig. 7. Efficiency computation block.

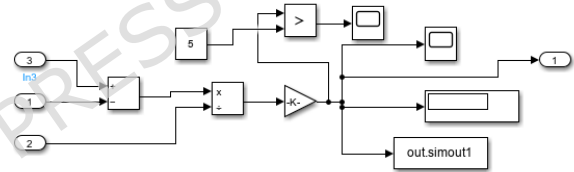


Fig. 8. Voltage regulation computation block.

To support reproducibility, extend the analytical modeling, and enable further experimentation, a MATLAB code was developed for this study, using MATLAB R2023b, and has been provided as supplementary material. The source code is available and can be accessed at :<https://drive.google.com/file/d/1gtedv2xvxQsnQwBuSnBgAFivygbyTyqdR/view?usp=sharing>

The MATLAB script operationalizes the core framework described in this paper by simulating a three-phase transmission line under various fault and abnormal conditions. It integrates all major theoretical components, including distributed line modeling, ABCD parameter derivation, and π -model transformation, into a dynamic simulation environment. This complements the Simulink model presented in the manuscript and supports the objectives of the study regarding dynamic fault response and performance evaluation.

D. Performance Monitoring Layer

The performance monitoring layer constitutes the operational component of the proposed framework by continuously evaluating the electrical state of the transmission line using the quantities acquired from the analytical and dynamic simulation layers. During each simulation, the

sending-end and receiving-end voltages, currents, active power, and reactive power are continuously monitored and processed to assess the transmission-line operating condition under both normal and abnormal scenarios.

Unlike the preceding analytical and simulation layers, which establish the mathematical and computational representation of the transmission line, the performance monitoring layer focuses on interpreting the measured electrical quantities to quantify transmission-line performance. This evaluation is achieved through continuous computation of transmission efficiency, voltage regulation, and the voltage-drop index. These performance measures provide complementary information regarding power transfer capability, voltage quality, and overall transmission-line operating condition, thereby enabling systematic assessment of network performance under changing operating conditions.

The computed performance measures also provide the basis for threshold-based assessment and subsequent validation of the proposed framework. Consequently, the performance monitoring layer establishes the link between the dynamic behaviour of the transmission line and the decision support process developed in the following section.

1) *Transmission Efficiency*: Transmission efficiency represents the effectiveness with which electrical power is transferred from the sending end to the receiving end of the transmission line. It provides a direct measure of transmission losses and serves as one of the principal indicators of transmission-line operating performance.

The transmission efficiency is determined from the ratio of the receiving-end active power to the sending-end active power according to

$$\eta = \frac{P_R}{P_S} \times 100 \quad (9)$$

where η (%) denotes the transmission efficiency, P_S (W) is the sending-end active power, and P_R (W) is the receiving-end active power.

Under normal operating conditions, transmission efficiency remains close to unity [50], [51], indicating that only a small proportion of the transmitted power is lost along the transmission line. During overload conditions and fault disturbances, increased line losses reduce the transmission efficiency, thereby providing an effective indicator of deteriorating transmission-line performance.

2) *Voltage Regulation*: Voltage regulation quantifies the ability of the transmission line to maintain the receiving-end voltage as the loading condition varies. It provides an important measure of voltage quality and indicates the extent to which voltage drops occur along the transmission line due to the combined effects of line impedance and load current.

The percentage voltage regulation is computed as

$$VR = \frac{|V_S| - |V_R|}{|V_R|} \times 100 \quad (10)$$

where VR (%) denotes the voltage regulation, V_S (V) is the sending-end voltage magnitude, and V_R (V) is the receiving-end voltage magnitude.

Low values of voltage regulation indicate satisfactory voltage control and efficient power delivery, whereas higher values signify increased voltage drops caused by heavy loading, excessive reactive power demand, or fault conditions [52]. Consequently, voltage regulation provides an effective indicator for assessing transmission-line operating performance and identifying abnormal operating conditions.

3) *Voltage-Drop Index*: The voltage-drop index provides a normalized measure of the voltage reduction experienced along the transmission line and complements the voltage-regulation analysis by directly quantifying the percentage voltage loss between the sending and receiving terminals.

The voltage-drop index is determined as

$$VDI = \frac{|V_S| - |V_R|}{|V_S|} \times 100 \quad (11)$$

where VDI (%) denotes the voltage-drop index.

Unlike voltage regulation, which expresses the receiving-end voltage deviation relative to the receiving-end voltage itself, the voltage-drop index normalizes the voltage difference with respect to the sending-end voltage. Consequently, the two indices provide complementary information for evaluating transmission-line voltage performance under different loading conditions and fault disturbances.

4) *Threshold-Based Performance Assessment*: Continuous monitoring alone is insufficient unless the measured performance indicators can be interpreted to distinguish between acceptable and abnormal operating conditions. For this reason, threshold-based performance assessment is incorporated within the proposed framework to provide automated evaluation of the monitored transmission-line parameters.

During each simulation, the computed transmission efficiency, voltage regulation, and voltage-drop index are continuously compared with predefined operational limits. Whenever one or more monitored quantities exceed their respective thresholds, the operating condition is classified as abnormal and an alert is generated for further investigation.

The threshold values adopted in this study are selected based on widely accepted transmission-system operating practices. Transmission efficiency values below 95% indicate excessive transmission losses [53], [54], while voltage regulation values exceeding 5% indicate unacceptable voltage deviations requiring operational attention [55], [56]. These thresholds provide practical criteria for distinguishing satisfactory operating conditions from degraded transmission-line performance.

The threshold-based assessment does not replace conventional protection systems. Instead, it provides a supplementary monitoring mechanism that continuously evaluates transmission-line operating performance and assists

operators in identifying deteriorating system conditions before they develop into severe operational problems.

E. Decision Support and Validation Layer

The decision support and validation layer constitutes the final stage of the proposed framework. It integrates the monitored transmission-line performance indicators with quantitative validation techniques to evaluate the consistency of the analytical and simulation models and to support engineering decision-making under both normal and abnormal operating conditions.

The monitored electrical quantities and performance indicators obtained from the analytical and dynamic simulation layers are systematically analysed to determine whether the transmission line operates within acceptable performance limits. In addition, quantitative comparison between the analytical predictions and the corresponding simulation responses provides an assessment of the consistency of the proposed modelling approach. The validation methodology adopted in this study combines waveform comparison with statistical error analysis to evaluate the agreement between both modelling approaches under the investigated operating scenarios.

1) *Performance Validation*: To evaluate the accuracy and consistency of the proposed hybrid analytical–simulation framework, a benchmark solution was established as the reference against which all performance metrics were assessed. In this study, the benchmark corresponds to the high-fidelity distributed-parameter transmission-line simulation implemented in the MATLAB/Simulink environment. This reference solution preserves the complete distributed electrical characteristics of the transmission line and provides the expected system response under both normal and abnormal operating conditions. The analytical distributed-parameter formulation and the equivalent π -model are evaluated relative to this benchmark using the root mean square error (RMSE) and mean absolute error (MAE), thereby demonstrating the accuracy and consistency of the proposed hybrid framework.

Performance validation is performed by evaluating the proposed hybrid analytical–simulation framework through comparison of the analytical distributed-parameter formulation and the equivalent π -model relative to the benchmark solution under identical operating conditions.

The objective of this comparison is not merely to demonstrate mathematical consistency between the two modelling approaches, but also to verify that the equivalent π -model accurately reproduces the electrical behaviour predicted by the distributed-parameter analytical formulation while remaining suitable for dynamic fault simulation and continuous performance monitoring.

2) *Error Metrics*: To quantify the agreement between the analytical and simulation results, statistical error metrics are employed. The Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) are selected because they provide complementary measures of the deviation between

the analytical predictions and the corresponding simulation responses.

The RMSE is computed as

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \hat{x}_i)^2} \quad (12)$$

where x_i denotes the analytical result, $\hat{x}_i$ denotes the corresponding simulation result, and N represents the total number of observations.

The MAE is determined as

$$MAE = \frac{1}{N} \sum_{i=1}^N |x_i - \hat{x}_i| \quad (13)$$

Lower values of RMSE and MAE indicate closer agreement between the analytical and simulation models, thereby demonstrating the consistency of the proposed framework.

3) *Framework Robustness Assessment*: The robustness of the proposed framework is assessed by evaluating its performance under a diverse range of transmission-line operating conditions, including normal operation, voltage sag, overload, low power factor, and balanced and unbalanced fault scenarios. The framework is considered robust if it consistently maintains close agreement between the analytical and simulation results while accurately identifying changes in transmission-line operating performance across the investigated scenarios.

Rather than relying on a single operating condition, the robustness assessment considers the framework's ability to provide reliable performance monitoring over a broad range of practical transmission-system disturbances. This approach demonstrates the applicability of the proposed framework for continuous transmission-line performance assessment under varying network conditions.

III. RESULTS AND DISCUSSION

A. Validation of the Proposed Hybrid Analytical–Simulation Framework

The first stage of the validation process evaluates the accuracy of the proposed hybrid analytical–simulation framework relative to the conventional analytical ABCD model and the equivalent π -model. Rather than considering a single operating condition, the comparison is performed over a representative set of normal and abnormal transmission-line operating scenarios, including voltage sag, overload, low power factor, and balanced and unbalanced fault conditions. This comprehensive evaluation provides an overall assessment of the modelling accuracy achieved by each approach.

The primary objective of this validation is to determine whether integrating the distributed-parameter analytical model with the equivalent π -model improves the accuracy of transmission-line performance estimation while preserving the computational advantages of simplified analytical and simulation models. Validation is therefore performed using statistical error metrics computed from the transmission

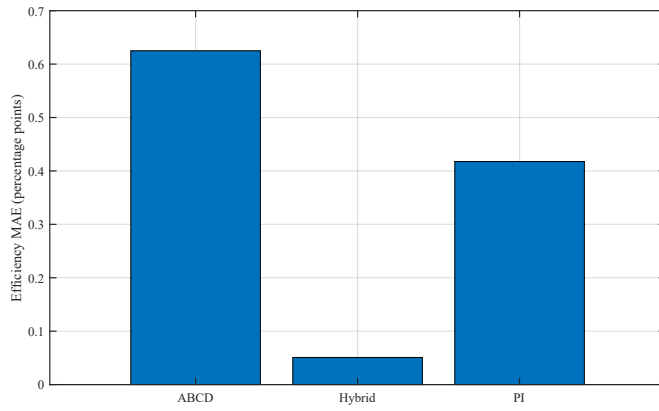


Fig. 9. Comparison of the average transmission-efficiency mean absolute error (MAE) obtained using the analytical ABCD model, the equivalent π -model, and the proposed hybrid analytical–simulation framework across all investigated operating conditions.

efficiency, voltage regulation, voltage-drop index, voltage, and current responses obtained under identical operating conditions.

Figure 9 compares the average transmission-efficiency MAE obtained using the three modelling approaches. The analytical ABCD model exhibits the largest average error, whereas the equivalent π -model significantly improves the overall accuracy. The proposed hybrid analytical–simulation framework achieves the lowest average MAE, demonstrating that combining the analytical and simulation models substantially reduces the discrepancy between the predicted and reference transmission efficiencies.

The observed reduction in efficiency error indicates that the proposed framework effectively exploits the complementary strengths of the distributed-parameter analytical formulation and the equivalent circuit representation. Whereas the ABCD formulation accurately represents the distributed electrical characteristics of the transmission line and the π -model facilitates efficient dynamic simulation, their integration produces a more accurate representation of transmission-line behaviour over a broad range of operating conditions.

This result provides the first quantitative evidence supporting the proposed hybrid framework and demonstrates that the improvement is not limited to a single disturbance scenario but is maintained across all operating conditions investigated in this study.

The validation is further extended by comparing the average voltage-regulation MAE for the three modelling approaches, as presented in Figure 10. A similar trend is observed, with the proposed hybrid framework consistently producing the smallest prediction error. The analytical ABCD model exhibits the highest deviation from the benchmark solution, while the equivalent π -model provides intermediate performance.

The consistent reduction in both transmission-efficiency and voltage-regulation errors demonstrates that the proposed framework improves modelling accuracy across multiple performance indicators rather than optimizing only a single

evaluation metric. This consistency provides strong evidence that the hybrid analytical–simulation strategy enhances the overall reliability of transmission-line performance monitoring under diverse operating conditions.

B. Dynamic Performance Under Fault Conditions

The dynamic behaviour of the proposed framework is investigated by analysing the temporal responses of the principal transmission-line performance indicators before, during, and after fault occurrence. Unlike the aggregate statistical comparisons presented previously, the time-domain responses provide insight into the ability of the proposed framework to continuously monitor transmission-line performance throughout the fault evolution process. The investigated performance indicators include transmission efficiency, voltage regulation, and the voltage-drop index, each of which reflects a different aspect of transmission-line operating behaviour during transient disturbances.

Figure 11 illustrates the variation of transmission efficiency during a single-line-to-ground fault. Prior to fault initiation, all three approaches predict nearly identical steady-state transmission efficiencies, indicating consistent operation under normal conditions. Following fault inception, the transmission efficiency decreases abruptly as the fault introduces additional losses and disrupts power transfer between the sending and receiving ends.

Although both the analytical ABCD model and the benchmark solution capture the general reduction in efficiency, the proposed hybrid framework follows the benchmark response more closely throughout the disturbance and post-fault recovery intervals. Following fault clearing, the transmission efficiency gradually returns to its pre-fault value, demonstrating the capability of the proposed framework to continuously monitor the restoration of normal transmission-line operating conditions.

Figure 12 presents the corresponding voltage-regulation response during the same fault event. The application of the fault produces an immediate increase in voltage regulation due to the reduction in receiving-end voltage and the increased voltage drop along the transmission line. The proposed hybrid framework reproduces both the transient increase and the subsequent recovery more accurately than the standalone analytical model, thereby providing improved estimation of transmission-line voltage performance throughout the disturbance.

Figure 13 shows the evolution of the voltage-drop index during the fault event. As expected, the fault causes a significant increase in the voltage-drop index, reflecting the deterioration of transmission-line voltage performance. The proposed hybrid framework exhibits close agreement with the benchmark response during both the fault and recovery periods, whereas the analytical model shows comparatively larger deviations. The results demonstrate that the proposed framework provides accurate continuous monitoring of transmission-line voltage behaviour during transient disturbances.

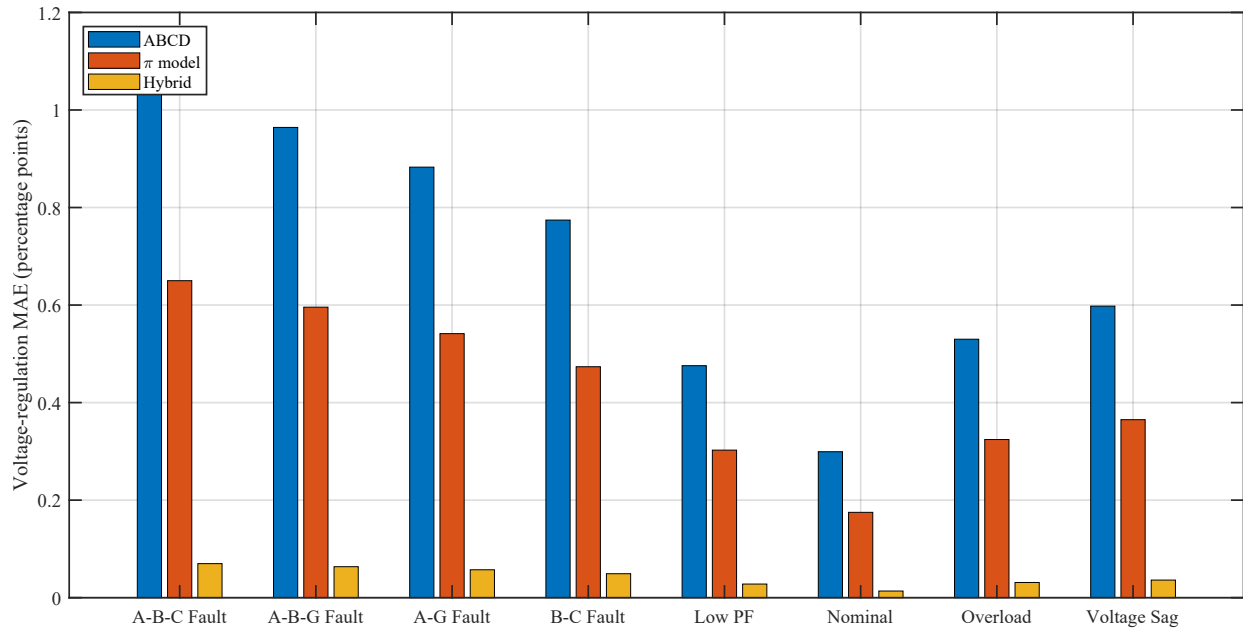


Fig. 10. Comparison of the average voltage-regulation mean absolute error (MAE) obtained using the analytical ABCD model, the equivalent π -model, and the proposed hybrid analytical–simulation framework.

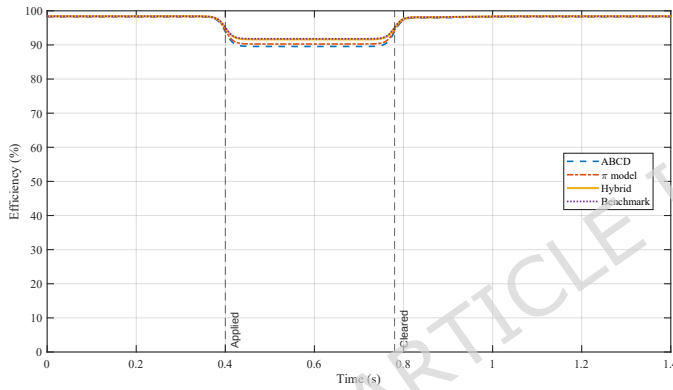


Fig. 11. Dynamic response of transmission efficiency during a single-line-to-ground (A-G) fault. The responses obtained using the analytical ABCD model, the benchmark solution, and the proposed hybrid framework are compared before, during, and after fault clearing.

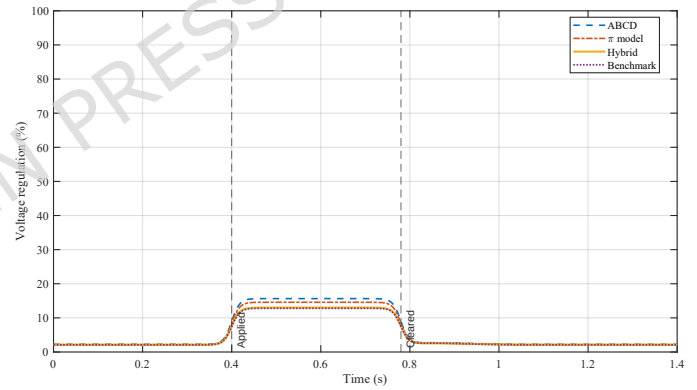


Fig. 12. Dynamic variation of voltage regulation during a single-line-to-ground (A-G) fault.

C. Three-Phase Fault Waveform Validation

The capability of the proposed framework to reproduce the electrical behaviour of the transmission line under different fault conditions is further evaluated by examining the corresponding three-phase voltage and current waveforms. Unlike the performance indices discussed previously, the phase-domain waveforms provide a direct representation of the transient electrical response and therefore enable assessment of the framework under practical transmission-system fault conditions. Representative balanced and unbalanced faults are considered to evaluate the ability of the proposed framework to capture the characteristic voltage collapse, current rise, and post-fault recovery associated with each disturbance.

Figure 14 presents the three-phase voltage and current

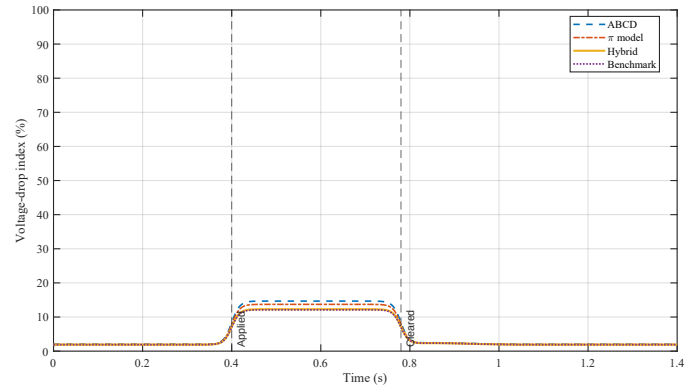


Fig. 13. Dynamic response of the voltage-drop index during a single-line-to-ground (A-G) fault.

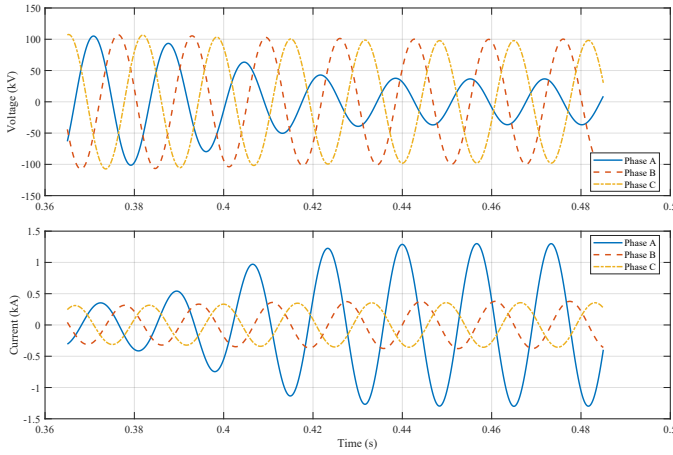


Fig. 14. Three-phase voltage and current waveforms during a single-line-to-ground (A-G) fault.

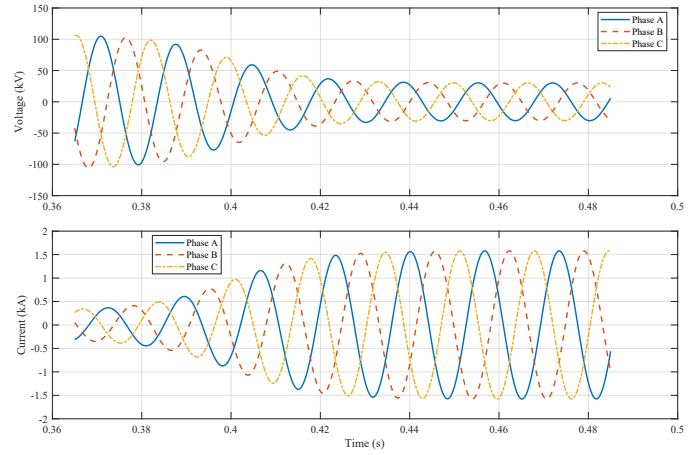


Fig. 16. Three-phase voltage and current waveforms during a balanced three-phase (A-B-C) fault.

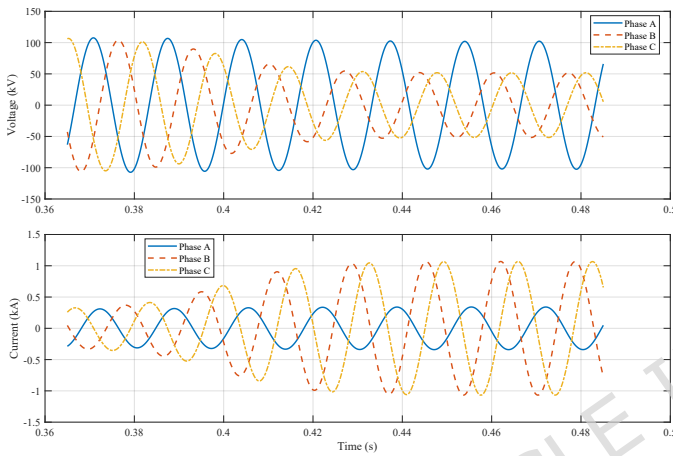


Fig. 15. Three-phase voltage and current waveforms during a line-to-line (B-C) fault.

responses during a single-line-to-ground fault. Following fault initiation, the faulted phase experiences a pronounced voltage depression accompanied by a substantial increase in fault current, whereas the remaining healthy phases continue to operate with comparatively smaller disturbances. After fault clearing, the voltages and currents gradually recover to their pre-fault operating conditions. The obtained responses are consistent with the expected behaviour of single-line-to-ground faults and demonstrate the capability of the proposed framework to reproduce realistic phase-domain fault dynamics.

Figure 15 illustrates the transient response during a line-to-line fault involving phases B and C. Immediately after fault application, the voltages of the faulted phases decrease significantly while their corresponding currents increase rapidly because of the reduced fault-path impedance. The unfaulted phase remains comparatively unaffected, illustrating the asymmetric nature of the disturbance. The simulated responses confirm that the proposed framework accurately reproduces the transient characteristics associated

with line-to-line faults.

Figure 16 shows the voltage and current waveforms during a balanced three-phase fault. In contrast to the previous unbalanced fault scenarios, all three phase voltages collapse simultaneously while the fault currents increase uniformly across the three phases. Following fault clearance, the voltages and currents recover synchronously toward their steady-state operating values. The balanced nature of the disturbance is clearly reflected in the symmetry of the measured waveforms, confirming the ability of the proposed framework to accurately represent both balanced and unbalanced transmission-line faults.

The waveform responses presented in Figures 14–16 demonstrate that the proposed framework consistently reproduces the characteristic electrical behaviour associated with representative transmission-line faults. The close agreement between the simulated phase-domain responses and the expected physical characteristics of balanced and unbalanced disturbances provides additional validation of the proposed hybrid analytical–simulation framework prior to the quantitative error analysis presented in the following subsection.

D. Performance Under Practical Operating Conditions

The proposed framework is further evaluated under representative transmission-line operating conditions that commonly occur during practical system operation but do not necessarily correspond to short-circuit faults. These operating scenarios include voltage sag and overload conditions, both of which influence transmission efficiency, voltage regulation, and power transfer capability. Evaluating the framework under these disturbances demonstrates its ability to continuously monitor gradual performance degradation in addition to abrupt fault events.

Figure 17 illustrates the transmission-line response under a balanced voltage-sag condition. Unlike the fault scenarios presented previously, the three phase voltages remain balanced while their magnitudes are uniformly reduced, resulting

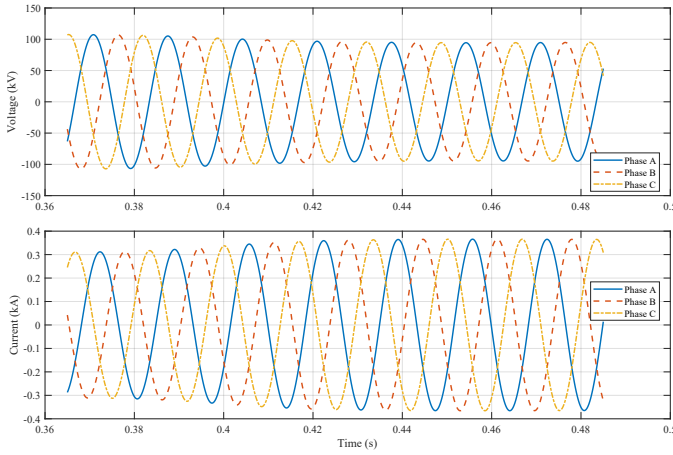


Fig. 17. Three-phase voltage and current waveforms under a balanced voltage-sag operating condition.

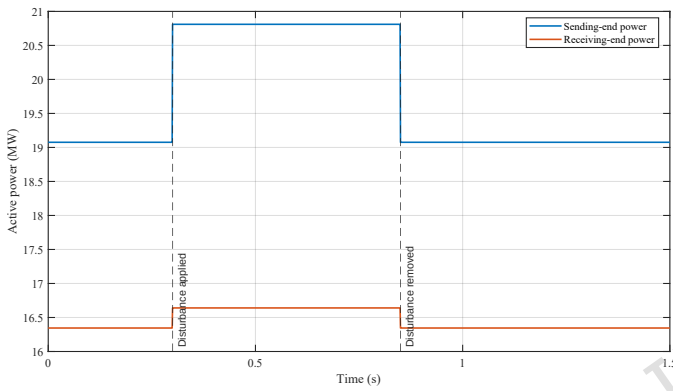


Fig. 18. Active-power response of the transmission line during an overload operating condition.

in a corresponding reduction in transmitted power. The phase currents remain approximately balanced throughout the disturbance, indicating that the network continues operating without the large current surges associated with short-circuit faults.

The balanced nature of the voltage sag demonstrates that the proposed framework can distinguish between voltage-quality disturbances and genuine fault conditions. This capability is particularly important for continuous transmission-line performance monitoring because corrective actions associated with voltage regulation differ significantly from those required for protective fault isolation.

Figure 18 presents the active-power response during an overload condition. As the receiving-end load demand increases beyond its nominal operating level, the transmitted active power rises accordingly while the associated transmission losses also increase. The resulting operating condition produces higher voltage drops and reduced transmission efficiency compared with normal operation.

The proposed hybrid framework continuously tracks these changes in power transfer capability, thereby enabling early identification of deteriorating operating conditions before

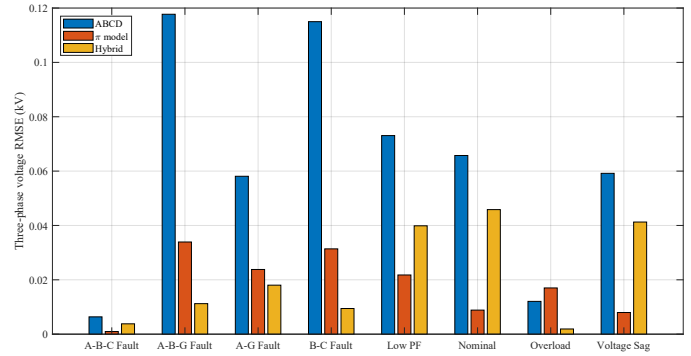


Fig. 19. Comparison of the voltage root mean square error (RMSE) obtained using the analytical ABCD model, the equivalent π -model, and the proposed hybrid analytical-simulation framework under the investigated operating conditions.

they develop into more severe network disturbances. This demonstrates that the proposed framework is suitable not only for fault-responsive monitoring but also for continuous assessment of transmission-line operating performance under varying loading conditions.

E. Quantitative Validation of the Proposed Framework

To further quantify the performance of the proposed hybrid analytical-simulation framework, statistical error metrics were computed by comparing the responses obtained from the analytical ABCD model, the equivalent π -model, and the proposed hybrid framework under all investigated operating conditions. The validation was performed using the Root Mean Square Error (RMSE) and Mean Absolute Error (MAE), thereby providing an objective assessment of the modelling accuracy achieved by each approach.

Unlike the waveform comparisons presented in the preceding subsections, the statistical validation enables quantitative evaluation of the overall modelling performance across multiple operating conditions and performance indices. Consequently, the following results provide the principal evidence supporting the effectiveness of the proposed hybrid framework.

Figure 19 compares the voltage RMSE produced by the three modelling approaches. The analytical ABCD model exhibits the largest voltage error across the investigated operating conditions, whereas the equivalent π -model provides improved agreement with the benchmark response. The proposed hybrid analytical-simulation framework consistently achieves the smallest voltage RMSE, demonstrating its improved capability to reproduce transmission-line voltage behaviour under both normal and disturbed operating conditions.

Figure 20 presents the corresponding current RMSE comparison. Similar to the voltage results, the proposed hybrid framework consistently produces the smallest prediction error, indicating improved representation of transmission-line current behaviour during both steady-state and transient operating conditions. The close agreement achieved by the hybrid

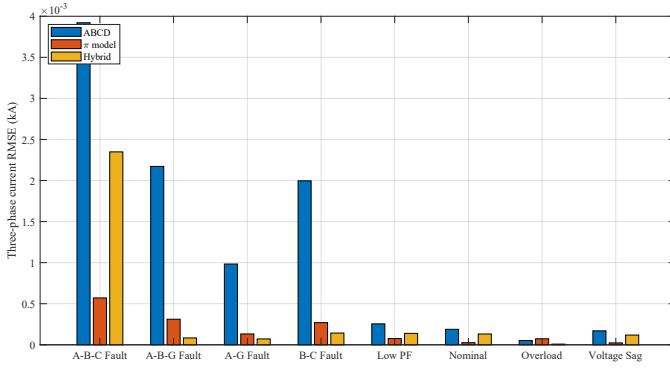


Fig. 20. Comparison of the current root mean square error (RMSE) obtained using the analytical ABCD model, the equivalent π -model, and the proposed hybrid analytical–simulation framework.

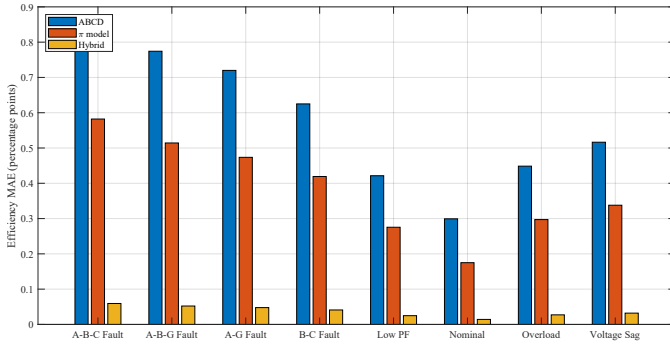


Fig. 21. Transmission-efficiency mean absolute error (MAE) for the investigated operating conditions.

framework confirms that the proposed modelling strategy accurately captures both voltage and current dynamics.

Figure 21 presents the transmission-efficiency MAE obtained under the investigated operating conditions. The proposed hybrid framework consistently achieves lower prediction errors than the analytical ABCD and equivalent π -models, demonstrating that the improvement observed during the aggregate validation is maintained across individual operating scenarios rather than being limited to a single disturbance condition.

F. Performance Under Practical Operating Conditions

Figure 22 presents the variation of the sending-end and receiving-end three-phase active power during the investigated operating conditions. Under normal operating conditions, the transmitted active power remains relatively constant, indicating stable power transfer along the transmission line. During abnormal operating conditions, including overload and voltage sag, noticeable deviations occur in both the sending-end and receiving-end active power, reflecting the influence of the disturbance on the power transfer capability of the network.

The reduction in receiving-end active power during disturbed operating conditions is accompanied by an increase in transmission losses, thereby contributing to the observed reduction in transmission efficiency discussed previously. Following disturbance clearance, both power traces gradually

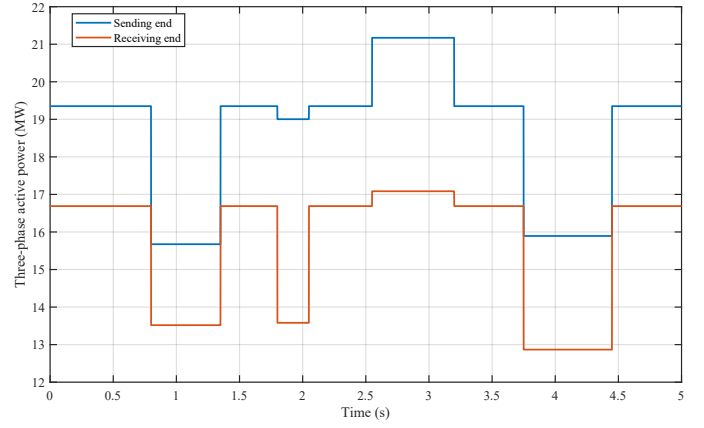


Fig. 22. Variation of sending-end and receiving-end three-phase active power under representative transmission-line operating conditions.

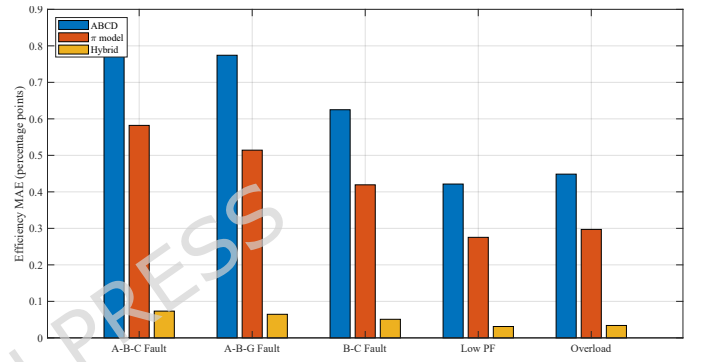


Fig. 23. Transmission-efficiency mean absolute error (MAE) obtained for the individual operating conditions using the analytical ABCD model and the proposed hybrid analytical–simulation framework.

return towards their steady-state values, demonstrating the capability of the proposed hybrid framework to continuously monitor the dynamic evolution of power transfer during both normal and abnormal transmission-line operation.

These results further confirm that the proposed framework captures not only voltage and current variations but also the corresponding changes in active power transfer, thereby providing a comprehensive assessment of transmission-line operating performance.

1) Performance Consistency Across Individual Operating Conditions: Although the aggregate validation results presented earlier demonstrate the overall superiority of the proposed hybrid framework, it is equally important to verify that this improvement is consistently maintained across the individual operating conditions investigated in this study. The following results therefore present the prediction errors obtained for each operating condition separately.

Figure 23 compares the transmission-efficiency MAE obtained under the individual operating conditions considered in this study, including balanced three-phase faults, single-line-to-ground faults, line-to-line faults, overload conditions, and low power-factor operation. For every investigated scenario, the proposed hybrid

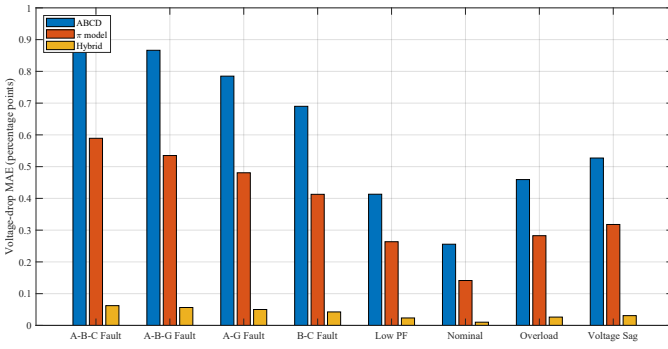


Fig. 24. Voltage-drop-index mean absolute error (MAE) obtained for the investigated operating conditions.

analytical–simulation framework consistently produces lower prediction errors than the conventional analytical ABCD model.

The largest improvements are observed during the fault conditions, where the dynamic behaviour of the transmission line becomes increasingly difficult to represent using a purely analytical formulation. By combining the distributed-parameter ABCD model with the equivalent π -model implemented in MATLAB/Simulink, the proposed framework more accurately reproduces the transient electrical behaviour associated with these disturbances.

An important observation from Figure 23 is that the improvement achieved by the proposed framework is not limited to a particular disturbance type. Instead, the hybrid framework consistently maintains lower transmission-efficiency prediction errors across all investigated operating conditions, thereby demonstrating the robustness and general applicability of the proposed modelling strategy.

Figure 24 illustrates the MAE associated with the voltage-drop index. The proposed hybrid analytical–simulation framework consistently provides the lowest prediction error over the investigated operating conditions, thereby confirming the reliability of the framework for continuous monitoring of transmission-line voltage performance. The observed improvement further demonstrates that integrating the analytical and simulation models enhances the overall accuracy of transmission-line performance estimation.

Overall, the statistical validation demonstrates that the proposed hybrid analytical–simulation framework consistently outperforms the standalone analytical ABCD model and the equivalent π -model across multiple electrical quantities and performance indices. The consistent reduction in RMSE and MAE obtained throughout the investigated operating conditions provides quantitative evidence supporting the improved accuracy and robustness of the proposed framework for transmission-line performance monitoring.

G. Discussion

The results presented throughout this study consistently demonstrate that the proposed hybrid analytical–simulation framework provides improved transmission-line performance

estimation compared with the standalone analytical ABCD model and the equivalent π -model. The improvement is evident across both steady-state and transient operating conditions and is consistently reflected in the reduced RMSE and MAE values obtained for voltage, current, transmission efficiency, voltage regulation, and voltage-drop index.

The improved performance of the proposed framework can be attributed to the complementary characteristics of its two constituent modelling approaches. The distributed-parameter ABCD formulation provides an accurate analytical representation of the electrical characteristics of long transmission lines, including propagation effects and distributed line parameters. However, its application is primarily analytical and therefore less convenient for continuous dynamic assessment under changing operating conditions. Conversely, the equivalent π -model provides an efficient circuit representation that is well suited for time-domain simulation within MATLAB/Simulink, although it introduces approximation errors when used independently.

By integrating these complementary modelling approaches, the proposed framework combines the physical accuracy of the distributed-parameter analytical model with the flexibility of dynamic simulation. Consequently, the hybrid framework is capable of maintaining improved modelling accuracy while simultaneously supporting continuous evaluation of transmission-line behaviour during voltage sag, overload, balanced faults, and unbalanced faults.

Unlike conventional validation studies that compare analytical and simulation models solely under steady-state operating conditions, the proposed framework demonstrates consistent performance over a broad range of representative transmission-line disturbances. This capability is particularly important for transmission-line performance monitoring because practical power systems operate under continually changing loading conditions and are periodically subjected to both transient disturbances and fault events.

1) Comparison with Existing Transmission-Line Monitoring Approaches: The proposed framework differs from conventional transmission-line monitoring approaches in both its modelling philosophy and intended application. Electromagnetic transient (EMT) simulations provide highly detailed representations of fast transient phenomena but generally require greater computational resources and detailed network models. PMU-based monitoring systems depend on synchronized field measurements and communication infrastructure, whereas impedance-based fault-location methods primarily estimate fault location rather than continuously assessing overall transmission-line performance.

More recent machine-learning and digital-twin approaches have demonstrated considerable potential for anomaly detection and predictive maintenance. However, these methods frequently require extensive historical datasets for model training, significant computational resources, and periodic retraining to maintain prediction accuracy under evolving network conditions. In contrast, the proposed hybrid framework is physics-based and therefore does not depend

upon historical fault datasets or training procedures. Instead, it combines established transmission-line theory with dynamic simulation to provide interpretable and computationally efficient continuous performance monitoring.

Consequently, the proposed framework should not be viewed as a replacement for advanced protection algorithms, travelling-wave fault-location techniques, or learning-based monitoring systems. Rather, it provides a complementary monitoring methodology capable of supporting transmission-line performance assessment, operational decision support, and engineering analysis under both normal and abnormal operating conditions.

2) *Practical Implications and Limitations:* The results indicate that the proposed hybrid analytical–simulation framework is suitable for engineering studies involving transmission-line performance assessment, educational simulation, operational planning, and offline analysis of abnormal operating conditions. The framework provides improved modelling accuracy while maintaining a computational structure that can be readily implemented within widely available engineering software.

Nevertheless, the present study has several limitations. The proposed framework has been validated using MATLAB/Simulink simulations rather than field measurements or hardware-in-the-loop implementation. Furthermore, although representative balanced and unbalanced faults have been investigated, practical transmission systems may exhibit additional complexities arising from measurement uncertainty, communication delays, protection-system interactions, and renewable-energy integration. Future work will therefore focus on experimental validation using real-time digital simulation platforms and field measurement data to further evaluate the applicability of the proposed framework under practical operating conditions.

IV. CONCLUSION

This paper presented a fault-responsive hybrid analytical–simulation framework for continuous performance monitoring of electric power transmission lines. The proposed framework integrates the distributed-parameter analytical ABCD model with an equivalent π -model implemented in MATLAB/Simulink to provide a unified methodology for evaluating transmission-line performance under both normal and abnormal operating conditions.

The proposed framework was validated through comprehensive simulation studies involving voltage sag, overload, balanced faults, and unbalanced fault scenarios. In addition to reproducing the expected transient voltage and current behaviour, the framework continuously evaluated transmission efficiency, voltage regulation, and voltage-drop index throughout each operating condition. Quantitative validation using RMSE and MAE demonstrated that the hybrid framework consistently achieved lower prediction errors than the standalone analytical ABCD model and the equivalent π -model across the investigated performance indices.

The results further demonstrated that integrating the complementary strengths of analytical distributed-parameter modelling and dynamic simulation improves the overall accuracy of transmission-line performance estimation while maintaining computational simplicity suitable for engineering analysis. Consequently, the proposed framework provides an effective physics-based methodology for transmission-line performance assessment, fault-responsive monitoring, and engineering decision support without requiring historical training data or complex data-driven models.

Although the proposed framework has been validated using MATLAB/Simulink simulations, future work will focus on experimental validation using hardware-in-the-loop platforms, real-time digital simulation, and field measurements. The framework will also be extended to support multi-line and meshed transmission networks and integrated with SCADA and PMU-based monitoring systems. In addition, adaptive monitoring strategies and machine-learning-assisted fault classification will be investigated to further enhance automated decision support and practical deployment in modern electric power transmission systems.

DECLARATIONS

Funding Statement: No funding was received for this research.

Ethical statement: The work presented in this manuscript is original and has not been published elsewhere in any form or language. Proper acknowledgment of other works was done where necessary.

Conflict of Interest statement: The authors have no relevant financial or non financial interests to disclose.

Data Availability: Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Authors' contribution: Robert Mugabe designed the system, Michael Robson Atim and Johnes Obungoloch guided and revised the manuscript, Jimmy Nabende Wanzala guided with the simulation.

Acknowledgment: Not applicable.

Clinical trial: Not applicable.

Ethics and Consent to Participate declarations: Not applicable.

Consent to Publish declaration: All authors read and approved the final manuscript for publication.

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