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PAPER

Dynamic transmission line modeling and real-time fault analysis using ABCD parameters enhanced by equivalent π-model for accurate efficiency and voltage stability assessment

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Abstract

Efficient and reliable electricity transmission is a fundamental requirement for modern power systems, particularly for long-distance networks where transmission losses and voltage regulation challenges significantly impact overall system performance. This study proposes an enhanced ABCD parameter-based transmission line model, integrating an equivalent π-model, to improve the accuracy of power loss calculations, voltage regulation, and transmission efficiency. Unlike traditional models, this approach accurately captures the effects of temperature variations, aging infrastructure, and real-time load conditions, ensuring more precise power system analysis. Extensive simulations in MATLAB/Simulink validate the model's effectiveness, demonstrating an efficiency improvement of up to 88.8% for long transmission lines, ensuring compliance with IEEE standards. Furthermore, the model features an automated alert system that warns users if efficiency drops below 95%, making it a practical tool for grid operation and planning. These findings underscore the model's potential for optimizing transmission line design, particularly in rural electrification projects and renewable energy integration, where efficient power delivery is crucial.

Nomenclature

V_S	Sending-end voltage (line-to-neutral or line-to-line)
V_R	Receiving-end voltage
I_S	Sending-end current
I_R	Receiving-end current
R	Series resistance
L	Series inductance
C	Shunt capacitance
G	Shunt conductance
z	Series impedance $r + jX_L$ (per-unit-length or total)
y	Shunt admittance $j\omega C$ (per-unit-length or total)
l	Line length
f	System frequency
ω	Angular frequency $2\pi f$

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A	ABCD parameter (voltage ratio with input shorted)
B	ABCD parameter (voltage ratio with input open / series effect)
C	ABCD parameter (output current ratio with input shorted / shunt effect)
D	ABCD parameter (current transfer function / propagation factor)
γ	Propagation constant $\sqrt{yz}$
α	Attenuation constant (real part of γ)
β	Phase constant (imaginary part of γ)
Z_c	Characteristic impedance $\sqrt{z/y}$
$\cosh(\gamma l)$	Hyperbolic cosine term in ABCD model
$\sinh(\gamma l)$	Hyperbolic sine term in ABCD model
Z'	Equivalent series impedance in π-model
Y'	Equivalent shunt admittance in π-model
θ	Phase angle
P	Active (real) power
Q	Reactive power
S	Apparent power
PF	Power factor ($\cos\theta$)
η	Transmission efficiency
%VR	Percentage voltage regulation
P_S	Sending-end power
P_R	Receiving-end power
P_L	Power loss ($P_S - P_R$)
$V_{S(L-N)}$	Sending-end line-to-neutral voltage
$V_{S(L-L)}$	Sending-end line-to-line voltage
$V_{R(L-N)}$	Receiving-end line-to-neutral voltage
$V_{R(L-L)}$	Receiving-end line-to-line voltage
I_{fault}	Fault current
t	Time
Δx	Differential line segment length
T	Temperature
Age	Line aging (in years)
$R(T)$	Resistance as a function of temperature
$L(T)$	Inductance as a function of temperature
$C(T)$	Capacitance as a function of temperature
$G(T)$	Conductance as a function of temperature
R(Age)	Resistance as a function of aging
L(Age)	Inductance as a function of aging
$\eta(T)$	Efficiency as a function of temperature
η(Age)	Efficiency as a function of aging
Alert	Indicator for abnormal operating condition
VR	Voltage regulation
$\pi-$ model	Lumped parameter π-equivalent model
RMS	Root Mean Square
HVDC	High Voltage Direct Current
FACTS	Flexible AC Transmission Systems
SVC	Static VAR Compensator
IEEE	Institute of Electrical and Electronics Engineers

GUI	Graphical User Interface
SDL	Sequential Deep Learning
LSTM	Long Short-Term Memory
ML	Machine Learning
AI	Artificial Intelligence
DL	Deep Learning
DNN	Deep Neural Network
ANN	Artificial Neural Network
MATLAB	Matrix Laboratory
Simulink	MATLAB-based simulation environment
kV	Kilovolt
kW	Kilowatt
MVA	Mega Volt-Ampere
pu	Per unit

1. Introduction

Transmission lines are a crucial component of modern power systems, enabling the efficient transfer of electrical energy over long distances. For example, the authors in [1] examined the role of transmission infrastructure in large-scale power delivery, while [2] highlighted its importance in maintaining system stability. Additionally, [3] emphasized the need for reliable long-distance transmission to support growing electricity demand. However, their analyses and design can be complex and computationally intensive. As stated by Gupta *et al* (1996), there isn't a single best way to handle all transmission line issues. It is suggested that distinct models and analysis be used for each kind of connection due to accuracy and efficiency concerns [4]. The increasing demand for reliable and efficient power transmission has highlighted the need for more accurate and efficient modeling techniques.

One of the traditional methods for modeling transmission lines is the use of lumped parameter models, such as the π-model. For instance, the π-model has been widely applied to short transmission lines in [5], and later extended to medium-length lines in [6] and [7] due to its simplicity. However, studies such as [8] and [9] have shown that the lumped parameter approach becomes increasingly inaccurate for long lines because it cannot adequately capture distributed effects.

In contrast, distributed parameter models have been proposed to more accurately represent the behavior of long transmission lines. For example, the studies in [10] and [11] developed distributed formulations to account for the continuous nature of line parameters, while [12] introduced refinements to improve accuracy over long distances. A common implementation of this approach is the ABCD constant method, where [13] applied the two-port network representation, [14] and [15] extended it for long-line modeling, and [16] and [17] analyzed its capability to capture voltage and current relationships. Although these methods provide high accuracy, they are often computationally intensive, making them less suitable for real-time studies.

Many safety-critical applications, including power grids and embedded systems, heavily rely on transmission lines. A widely used representation of these mathematical models is the two-port network, which uses ABCD parameters to relate sending-end and receiving-end voltages and currents. For example, the two-port formulation was first presented in [18] and further refined for transmission line analysis in [19]. In [20] and [21], the ABCD-based two-port model was applied to evaluate voltage and current relationships under different loading conditions, while [15] demonstrated its effectiveness in simplifying long-line performance analysis. In recent years, several researchers have focused on adapting the π-model for long transmission lines because it offers a balance between accuracy and computational efficiency. For instance, [22] introduced an improved π-model that accounts for long-line parameters, while [23] proposed simplifications to retain accuracy with reduced complexity. In addition, [24] demonstrated that modified π-models can approximate distributed effects more efficiently than fully distributed models.

However, existing methods for deriving equivalent π models are often limited in their applicability and accuracy [25, 26].

The ABCD constants are a set of four parameters commonly used to model transmission lines in a two-port network, allowing the sending-end voltage and current to be expressed in terms of the receiving-end values. Authors in [27] presented the mathematical foundation of the ABCD formulation, while [14] demonstrated its

application for long-line voltage and current analysis. Additionally, [16] investigated the effectiveness of ABCD parameters in representing transmission line behavior under different operating conditions. When the input is shorted, attenuation, or the voltage ratio, is represented by Constant A. B stands for the voltage ratio with the input open, or phase shift. With the input shorted, the output current ratio is represented by C. When the input is open, the output current ratio is shown by D. By using these constants, one can analyze properties of transmission lines, such as impedance and attenuation, based on electrical parameters and line dimensions; model segments of transmission lines connected in cascade configurations; simulate the entire transmission medium between the source and the load using two-port blocks; and use them as a versatile tool for network analysis when working with circuits, filters, measurements, and other two-port network-related applications.

Power factor and the ABCD line parameter determine the quality of power transmitted [28]. Transmission line performance, including transmission line current, voltage regulation, and critical voltage, is impacted by the load situation at the transmission feeder. Transmission lines are represented by a comparable model that contains the proper circuit characteristics for each phase. The model that determines power flow, voltages, and currents is dependent on line length. A precise representation of the transmission line with ABCD parameters using simple mathematics has allowed for the analytical calculation of both real and complex power. Transmission lines are typically classified into short, medium, and long categories based on their physical length and operating voltage. Authors in [29] defined the standard boundaries for each category, while [30] analyzed the electrical characteristics associated with different line lengths. In addition, [31] discussed how operating voltage influences the choice of modeling approach for each line type. All of these factors associated with the transmission system are determined by a number of characteristics, including the resistance (R), capacitance (C), and inductance (L) of the transmission line. It is assumed that the line's length has an equal distribution of the parameters R, L, and C associated with each transmission.

The allowed percentage voltage variation in transmission and distribution lines can vary by region and regulatory standards. However, a common guideline is that transmission lines' voltage regulation is typically allowed within $\pm 5\%$ of the nominal voltage [32, 33]. These variations help to ensure reliable power delivery while minimizing the risk of damage to electrical equipment. A system's capacity to deliver almost constant voltage is referred to as voltage regulation.

In most developing countries, connecting households to the grid requires large investments in transmission lines [34, 35], because the majority of citizens live in rural and remote areas, spread-out over the country. There is therefore a need to consider long transmission of electricity. To improve reliability and power transfer capability, multiple transmission lines are often interconnected or cascaded to form long-distance transmission corridors. However, long lines introduce several operational challenges. Authors in [34] reported that under light-load or no-load conditions, the receiving-end voltage can rise above acceptable limits due to the Ferranti effect. Similarly, [36] and [37] showed that voltage regulation becomes difficult to maintain over long distances, particularly when reactive power is not properly managed. In addition, [38] demonstrated that during heavy-load conditions, the receiving-end voltage may drop below nominal levels, potentially leading to instability. Excessive phase shift in long transmission lines can lead to stability issues, and if reactive power is not properly compensated, the no-load current may become significantly high. In transmission line analysis, it is typically assumed that the voltage, current, and line parameters at one end of the line are known in order to determine the unknown quantities at the other end. For accurate computation, it is therefore essential to have precise knowledge of both the line characteristics and the sending-end voltage and current. Authors in [39] emphasized the importance of accurate parameter estimation for reliable voltage calculations, while [15] demonstrated that small parameter deviations can lead to significant errors in current prediction. Similarly, [40] highlighted the need for precise modeling in long-line performance evaluation, and [41] showed that improved parameter identification enhances the accuracy of transmission line simulations. As a result, accurate transmission line parameters improve the quality of various power system analyses, including state estimation, load flow studies, and transient stability assessments. For example, [26] demonstrated that parameter precision significantly enhances state estimation performance, while [42] showed that accurate line models lead to more reliable load flow results. In addition, [43] highlighted that transient stability analysis is highly sensitive to parameter inaccuracies, particularly in long-distance transmission scenarios.

Recently, time-series behavior in transmission lines and other time-dependent systems has been successfully predicted using deep learning architectures like Long short-term memory (LSTM) and Transformer-based models [44, 45]. By automatically extracting pertinent temporal aspects and long-range relationships from the input data, these models are able to forecast the dynamic response of the system with great computational efficiency and accuracy.

In [46], authors explored full transient data from pre- and post-fault cycles to make reliable decisions. Sequential Deep Learning (SDL) was employed through Long Short-Term Memory (LSTM) to model spatio-temporal sequences of high-dimensional multivariate features to achieve accurate classification and prediction results of different transmission line faults. Table 1 compares the most relevant existing works in terms of

Table 1. Comparison of related literature and this work.

Author	Method/Model	Scope/Factors	Limitation/Gap
Bendjabeur *et al* [5]	π-model	Short transmission lines	Simple but cannot capture distributed effects
Xu *et al* [7]	Extended π-model	Medium-length lines; basic performance metrics	Accuracy decreases as line length increases
Shaikh *et al* [10]	Distributed parameter model	Long lines; continuous parameter representation	Accurate but mathematically complex for real-time use
Kanawade *et al* [14]	ABCD parameter model	Two-port network; long-line voltage/current analysis	Computationally intensive; limited environmental consideration
Safar [22]	Modified π-model	Long-line parameters considered; efficiency-accuracy balance	Still approximates distributed effects; limited validation
Parihar *et al* [28]	Performance analysis	Power factor, voltage regulation, feeder conditions	Doesn't address long-line distributed effects or aging
Chanda *et al* [36]	Long-line voltage studies	Load conditions, Ferranti effect, regulation challenges	Difficult to maintain voltage stability over long distances
Belagoune *et al* [46]	LSTM-based fault prediction	Time-series data; transient analysis	Data-driven only; lacks physical model interpretability
Proposed Work	Enhanced ABCD-π hybrid + MATLAB/Simulink	Short/medium/long lines; temperature, aging, load variation; normal & abnormal conditions; 95% efficiency alert	Balances accuracy and computational efficiency; improves long-line modeling (88.8% efficiency); enables real-time monitoring and fault detection

modeling method, operating conditions, and limitations, and illustrates the gap that motivates the approach proposed in this study.

In order to derive the equivalent π-model from the ABCD constants, a comprehensive technique is presented in this paper. This methodology accounts for the various transmission line characteristics, which are spread throughout the line and include resistance (R), capacitance (C), and inductance (L). Values of ABCD parameters, Real and Reactive power, transmission line efficiency and voltage regulation were obtained analytically. The proposed approach was tested and validated through extensive simulations using simulink in Matlab R2023b, demonstrating its accuracy and effectiveness in modeling long transmission lines. Additionally, a Matlab .m file (code) was created to determine a transmission line's ABCD characteristics and utilize them to determine voltage control and efficiency.

The main contributions of this study are as follows:

An enhanced transmission line modeling approach that integrates ABCD parameters with an equivalent π-model was developed, achieving a balance between accuracy and computational efficiency.

Real-world operating factors such as temperature variations, aging infrastructure, and dynamic load conditions were incorporated, which are often neglected in traditional models.

An efficiency-based monitoring and alert system that automatically triggers warnings when efficiency drops below 95% was designed, enabling proactive fault detection.

We validated the proposed model through extensive MATLAB/Simulink simulations under both normal and abnormal operating conditions for short, medium, and long transmission lines.

The proposed approach achieved up to 88.8% efficiency in long lines, outperforming the conventional *pi*-model and providing a practical tool for modern power system planning and renewable energy integration.

2. Methods

For short, medium, and long transmission lines, the performance of the lines is evaluated using a number of important metrics in this study. Some of these parameters are Power Loss, Voltage Regulation, Transmission Line Efficiency, Line Impedance, Capacitance, and Inductance, Sending-End Voltage and Current (V_s and I_s), Power Factor, Apparent Power, Active Power, and Reactive Power, and ABCD Parameters:

Figure 1 displays a transmission line's 2–port representation;

Three transmission lines are examined in this study: a 50 km short transmission line, a 150 km medium transmission line, and a 400 km long transmission line operating at 132 kV.

A long transmission line can only be correctly described in terms of the uniformly distributed properties r (series resistance), l (series inductance), and c (shunt capacitance). That is, if the parameters are not packed together but rather distributed uniformly over the length of the line. To achieve an ideal model, we will examine

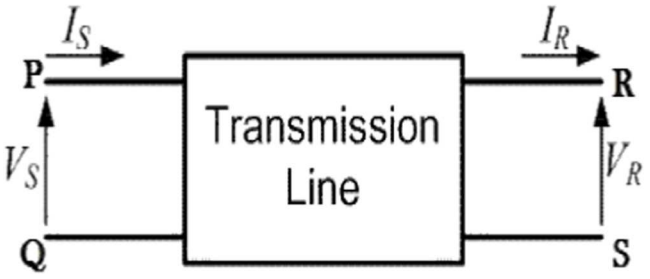


Figure 1. Two-port representation of a transmission network.

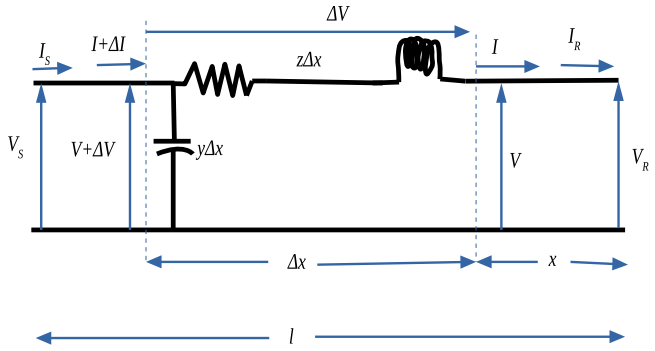


Figure 2. Long transmission line representation.

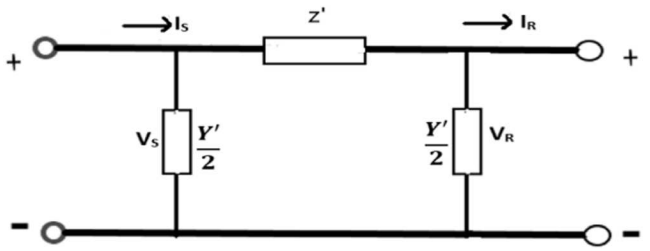


Figure 3. π Model equivalent for a long transmission line.

a tiny strip ($\triangle x$), which represents the complete transmission line. Figure 2 illustrates the line under consideration.

A series impedance is linked at the line's center, and two shunt admittances are connected at either end for an equivalent π-network. For a long line we can draw the equivalent π–network as shown in figure 3.

Now that we have a two port model, we can effectively transform the distributed parameter system into a lumped parameter π-equivalent model. The two lumps representing the total capacitance are at the beginning and the end of the line, respectively. The sending-end voltage V_S can be expressed as the receiving-end voltage V_R modified by the shunt admittance and series impedance effects, as shown in equation (1).

$$\mathrm{V_S} = \left(1 + \frac{\mathrm{Y'Z'}}{2}\right)\mathrm{V_R} + \mathrm{Z'I_R} \tag{1}$$

The sending-end current I_S can be expressed in terms of the receiving-end current and voltage, incorporating the shunt admittance effect, as shown in equation (2).

$$\mathrm{I_S} = \mathrm{Y'}(1 + \frac{\mathrm{Y'Z'}}{4})\mathrm{V_R} + (1 + \frac{\mathrm{Y'Z'}}{2})\mathrm{I_R} \tag{2}$$

For a long transmission line, ABCD parameter equations can be found by following the steps below;

$$\mathrm{V_S} = \mathrm{V_R}cosh(\gamma l) + \mathrm{I_R Z_c}\sinh(\gamma \mathrm{l}) \tag{3}$$

$$I_S = \frac{V_R}{Z_c}\sinh(\gamma l) + I_R\cosh(\gamma l) \tag{4}$$

Here, γ represents the propagation constant, defined as

$$\gamma = \sqrt{yz}$$

and Z_C represents the characteristic impedance given by

$$Z_C = \sqrt{\left(\frac{z}{y}\right)}$$

where y is the shunt admittance per unit length and z is the series impedance per unit length. The hyperbolic functions $\cosh(\gamma l)$ and $\sinh(\gamma l)$ represent wave propagation in lossy systems, accounting for both attenuation and phase shift.

comparing (1) with (3) and (2) with (4) we have

$$1 + \frac{Y'Z'}{2} = \cosh(\gamma l) \tag{5}$$

$$Z' = Z_c\sinh(\gamma l) \tag{6}$$

$$Y'\left(1 + \frac{Y'Z'}{4}\right) = \frac{sinh(\gamma l)}{Z_c} \tag{7}$$

from (6);

$$\begin{aligned} Z' &= Z_c sinh(\gamma l) \\ Z' &= \sqrt{\frac{z}{y}}.\frac{sinh(\gamma l)}{l.\sqrt{yz}}(l.\sqrt{yz}) \\ Z' &= zl\frac{sinh(\gamma l)}{\gamma l} \end{aligned}$$

Therefore

$$\boxed{Z' = Z_{eq} = Z\frac{sinh(\gamma l)}{\gamma l}} \tag{8}$$

from (5);

$$\begin{aligned} 1 + \frac{Y'Z'}{2} &= cosh\gamma l \\ \frac{Y'}{2} &= \frac{cosh\gamma l - 1}{Z_c sinh\gamma l} \\ &= \frac{1 + 2sinh^2\frac{\gamma l}{2} - 1}{Z_c(2sinh\frac{\gamma l}{2}cosh\frac{\gamma l}{2}} \end{aligned}$$

Therefore

$$\boxed{\frac{Y'}{2} = Y_{eq} = \frac{tanh\frac{\gamma l}{2}}{Z_c}} \tag{9}$$

The full derivations are provided in appendix A.

2.1. Efficiency-based monitoring and alert system

To ensure effective real-time monitoring of transmission line performance, an efficiency-based alert system is incorporated into the proposed approach. This system continuously evaluates transmission efficiency and triggers an alert whenever efficiency drops below 95%, signalling potential abnormal operating conditions.

The 95% efficiency threshold is derived from theoretical transmission line models and empirical data from high-voltage power systems. Under normal conditions, transmission efficiency ranges between 95% and 99% in well-optimized networks. A drop below 95% typically indicates increased power losses, excessive loading, or potential fault conditions. This threshold ensures early detection of abnormal conditions, allowing operators to take corrective actions before efficiency deteriorates further.

The alert system operates using a rule-based detection mechanism, where efficiency is continuously computed based on the ABCD parameters of the transmission line. The system follows these steps:

1) Efficiency Calculation: At each time step, transmission efficiency is determined using the modeled ABCD parameters.

2) Threshold Comparison: If efficiency falls below 95%, an alert is triggered.

3) Alert Generation: The system logs the alert and notifies operators, enabling timely interventions.

The alert system is embedded within the computational model used for efficiency and voltage regulation analysis. This ensures that every scenario: normal operation, faults, overloads, voltage sags, and reactive power variations is evaluated, and alerts are triggered accordingly. The integration allows for tracking efficiency deviations in real-time without additional computational burden, providing instant alerts for potential grid instability conditions, and facilitating early intervention before transmission efficiency degrades significantly.

This methodology ensures that the efficiency alert system is seamlessly incorporated into the overall transmission line analysis, improving fault detection and enhancing power system reliability.

2.2. MATLAB implementation and key computational steps

To ensure reproducibility, the study utilises a structured MATLAB script for analysing transmission line performance under various conditions. The code in the script performs the following key computational steps:

1) Defining Transmission Line Parameters. Resistance, inductance, capacitance, voltage, and power factor are initialised to match real-world systems.

2) ABCD Parameter Computation. The transmission line's ABCD parameters are derived using hyperbolic function approximations to accurately model voltage and current transformations.

3) Modelling Abnormal Conditions. The script introduces fault impedance variations to simulate single-phase and three-phase faults, line overloads, voltage sags, and reactive power variations.

4) Efficiency and Voltage Regulation Computation. The efficiency is calculated as the ratio of output power to input power, while voltage regulation is determined based on sending and receiving end voltage differences.

5) Visualisation of Results. The script generates bar charts and line plots for comparative analysis of efficiency and voltage regulation across different conditions.

The full MATLAB script could not be added to the manuscript due to length constraints, but it is available for access at:https://drive.google.com/file/d/1wZ0ZucwzXQbuATG76BpW70XW489Wc2DI/view?usp=sharing

The logical flow of the proposed research methodology is presented in the flowchart in figure 4, which outlines the sequence of analytical modeling (ABCD and π-model), MATLAB implementation, Simulink simulations, and result validation.

3. Results and analysis

The ABCD parameters are calculated using hyperbolic functions that consider the distributed effects over the line's length. By using equations (6) and (??), we found the equivalent π-model values of I_s, V_s, transmission line efficiency and voltage regulation of short, medium and long transmission lines as shown in tables 2–4.

3.1. For short transmission lines

Table 2 compares the results obtained by using the two methods; Using the derived ABCD parameters, and the equivalent π-model for a short transmission line, length of 50 km.

The sending-end voltage and current are nearly identical between the ABCD parameters and the π-model, reflecting the fact that short lines can be accurately modeled by the proposed ABCD model. Both models show high efficiency, with only a slight difference between them. The voltage regulation is very close in both models. So for a short transmission line, the equivalent π-model and the ABCD model can both be used to analyze a transmission line with almost identical results.

Figure 5 presents a comparative analysis of transmission line efficiency for short, medium, and long transmission lines using both the ABCD model and the equivalent π-model. The results indicate that while both models perform similarly for short transmission lines, significant discrepancies emerge as line length increases. For long transmission lines (400 km), the π-model predicts a low efficiency, highlighting its limitations in capturing distributed effects. In contrast, the ABCD model maintains a reasonable efficiency of 88.8%, aligning with industry expectations. This confirms that ABCD modeling is essential for long-distance power transmission, where the lumped-parameter assumption of the π-model may lead to inaccurate predictions.

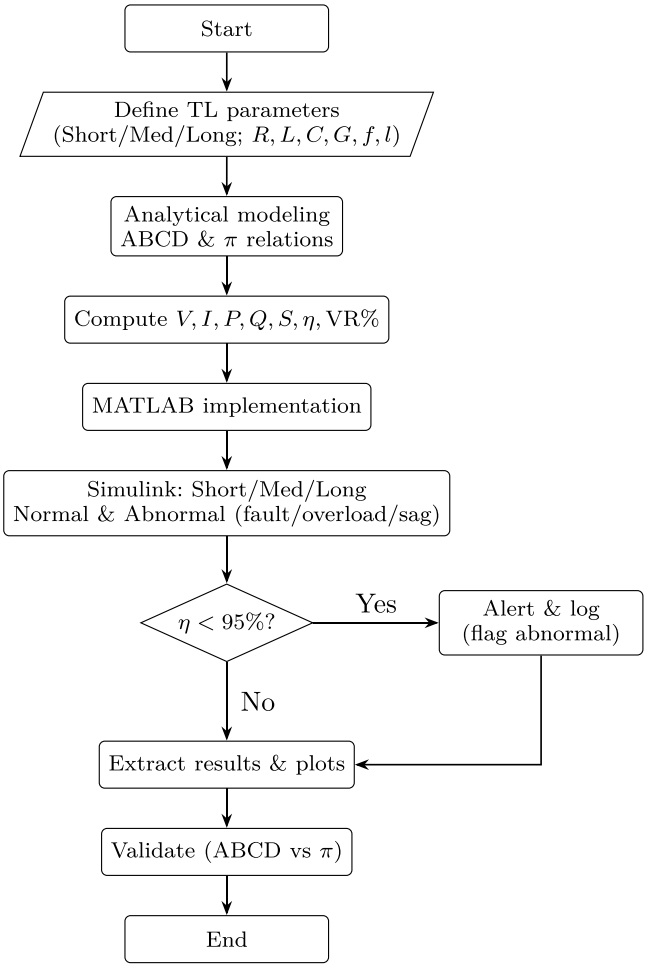


Figure 4. Flowchart of the research methodology.

Table 2. Comparison of results obtained by ABCD parameters and the equivalent π-model for a short line, 50km.

	Derived ABCD	equivalent π-model
I_S	391.47 A	391.40 A
V_S	103479.50 V	103451.72 V
Line Efficiency	97.53%	97.52%
Voltage regulation	4.35%	4.34%

Table 3. Comparison of results obtained by ABCD parameters and the equivalent π-model for a medium line of length 150 km.

	Derived ABCD	equivalent π-model
I_S	240 A	239 A
V_S	120500 V	120300 V
Line Efficiency	93%	92.8%
Voltage regulation	7.5%	7.3%

3.2. Medium transmission lines

A comparison of the two approaches' findings is shown in table 3, which makes use of the equivalent π-model and the resulting ABCD parameters for a medium-length, 150 km transmission line.

The voltage regulation and line efficiency values are very close between the two models, reflecting that either model can be used effectively for medium transmission lines.

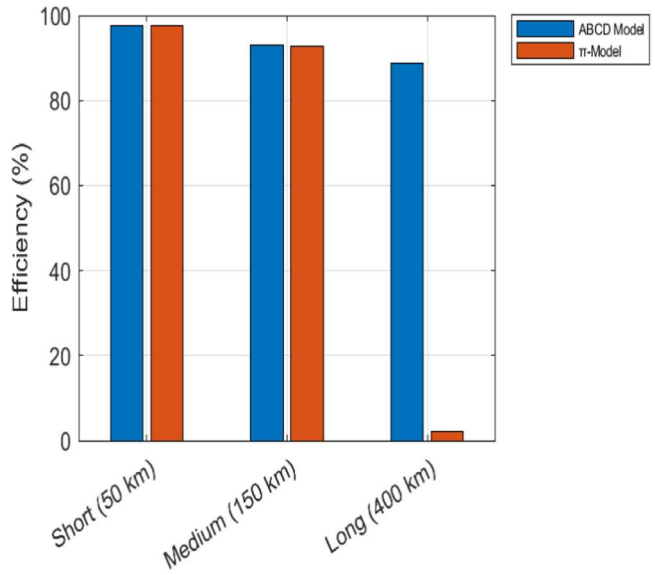


Figure 5. Comparison of transmission line efficiency.

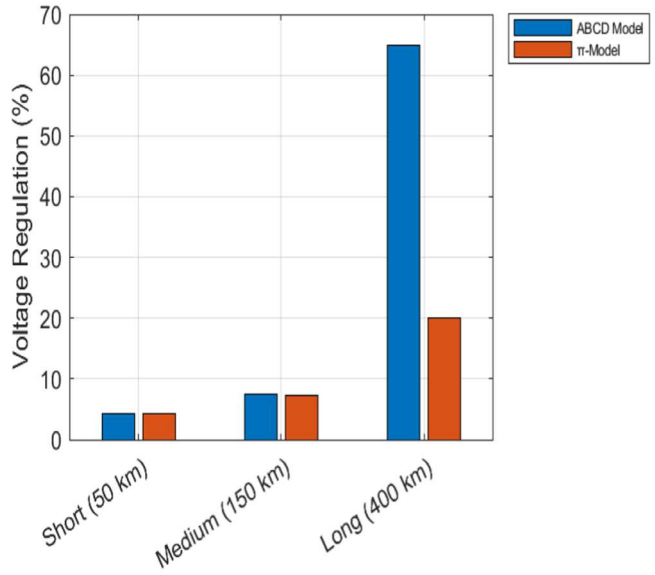


Figure 6. Comparison of voltage regulation.

Figure 6 illustrates the comparison of voltage regulation for short, medium, and long transmission lines using both the ABCD model and the equivalent π-model. The results indicate that while both models produce similar voltage regulation values for short and medium transmission lines, the discrepancy between the models becomes highly pronounced for long transmission lines. The ABCD model predicts a significantly higher voltage regulation, reflecting the increased impedance and reactive power effects over long distances, whereas the π-model underestimates these effects. This highlights the limitation of the lumped-parameter approximation in capturing the full behavior of long transmission lines and reinforces the necessity of using distributed-parameter models for accurate voltage regulation predictions.

3.3. For Long transmission lines

The outcomes of the two methods are contrasted in table 4, which uses the equivalent π-model and the resulting ABCD parameters for a 400 km transmission line.

Table 4 illustrates that, over a long line, the voltage regulation and transmission line efficiency change significantly between the ABCD parameters and the equivalent π-model. The dispersed character of the line's resistance, capacitance, and inductance over its whole length is appropriately taken into account using the

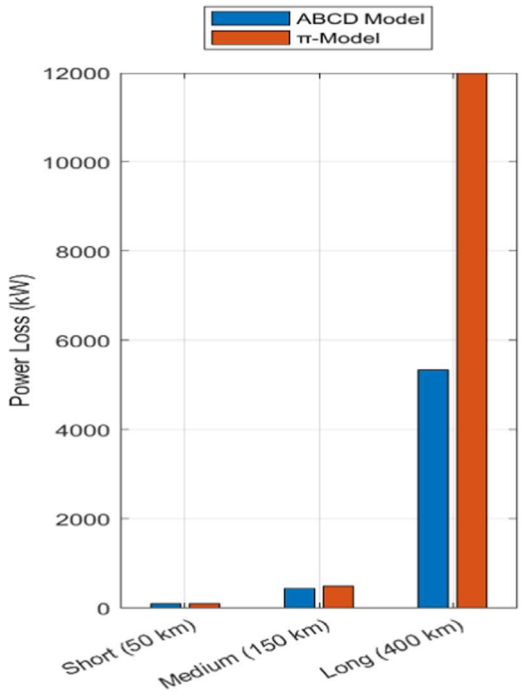


Figure 7. Comparison of power loss.

Table 4. Comparison of results obtained by ABCD parameters and the equivalent π-model for a long line, 400km.

	Derived ABCD	equivalent π-model
I_S	163.12 ∠-3.9 A	313 A
V_S	108694.18 ∠22.00 V	76528.12∠-0.266 V
Line Efficiency	88.8%	2%
Voltage regulation	64.99%	20%

ABCD parameters technique. Because of this, it offers a more thorough and precise depiction of the performance of the line, particularly for long transmission lines. However, in long transmission line modeling, the analogous π-model reduces the transmission line to lumped parameters, which may not adequately describe the dispersed effects of the line.

Figure 7 illustrates the comparison of power losses in transmission lines of varying lengths using the ABCD model and the equivalent π-model. The results indicate that while both models predict similar losses for short transmission lines, noticeable discrepancies emerge for medium-length lines, with the π-model estimating slightly higher losses. However, for long transmission lines (400 km), the π-model predict nearly twice the loss compared to the ABCD model. This inaccuracy is attributed to the π-model's inability to accurately represent distributed transmission line parameters, particularly at long distances. These findings demonstrate the superiority of the ABCD model in providing realistic loss estimations, ensuring more reliable power system planning and efficiency optimization. The results further emphasize the necessity of adopting distributed parameter models for accurate long-distance transmission analysis.

3.4. Transmission line analysis using simulink simulation

To evaluate the performance of transmission lines under various operational conditions, a Simulink model was developed to simulate short, medium, and long transmission lines as can be seen in figure 8. The simulation made use of several key blocks, as seen in figure 8, each of which plays a specific role in analyzing transmission line behavior.

Below is a detailed description of the key blocks used in the model:

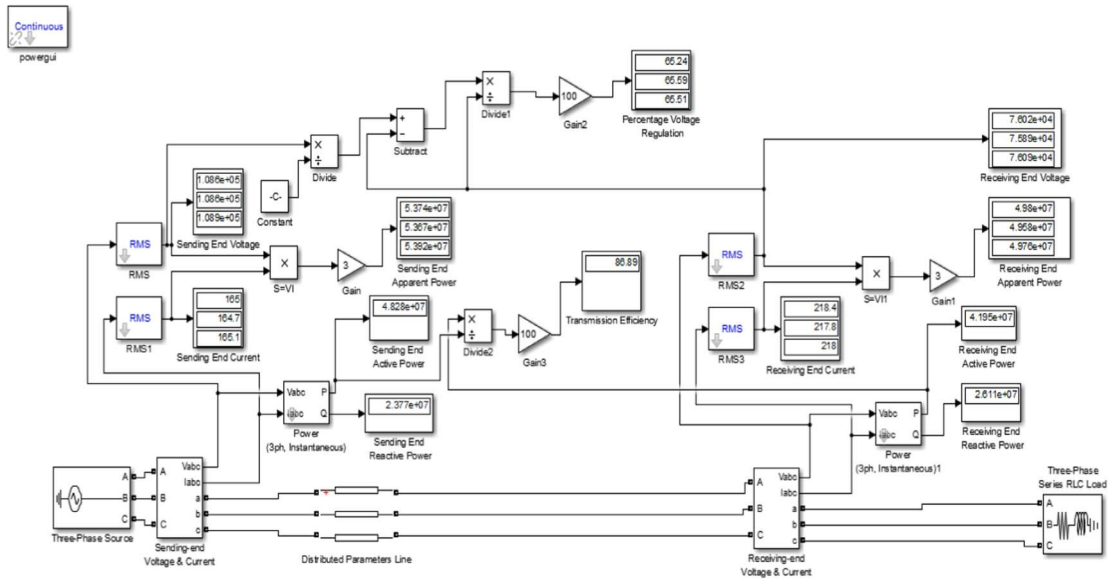


Figure 8. Simulink model for transmission line performance analysis.

- Three-Phase Source Block. This block provided the three-phase voltage input to the system. It represents the sending-end voltage of the transmission line and is the primary power source for the simulation. The three phases (A, B, C) are connected to the transmission line to simulate real-world power delivery conditions.
- Three-Phase Voltage and Current Measurement Block. This block measures the three-phase voltages and currents at both the sending and receiving ends of the transmission line. The outputs are essential for calculating power, efficiency, and voltage regulation. The measurements were sent to other blocks for further analysis.
- Distributed Parameters Line Block. This block models the transmission line itself, incorporating the distributed parameters of resistance (R), inductance (L), and capacitance (C) along the length of the line. It simulates the real behavior of a transmission line over a distance, making it crucial for assessing the line's performance under various loads.
- Three-Phase Series RLC Load Block. This block simulates the load at the receiving end of the transmission line. The load is modeled using resistance (R), inductance (L), and capacitance (C) to reflect the real-world behavior of electrical loads. The block is key for analyzing how the transmission line performs under different loading conditions.
- RMS Blocks (Sending-End and Receiving-End Measurements). The RMS blocks measure the root-mean-square (RMS) values of the sending-end and receiving-end voltages and currents. These RMS values are necessary for calculating the active, reactive, and apparent power of the transmission line. These blocks provide stable and meaningful voltage and current readings for further analysis.
- Apparent Power Calculation Blocks. The Gain blocks are used to calculate the apparent power at both the sending and receiving ends using the formula

$$S = VI$$

where V is the voltage and I is the current. This gives an understanding of the total power being transmitted by the line, including both real and reactive components.

- Active and Reactive Power Calculation (Three-Phase Instantaneous Power Block). This block calculates the real (active) power and reactive power at the sending and receiving ends of the transmission line. The real power represents the actual power consumed by the load, while reactive power is associated with the energy stored in the system. These are critical metrics for evaluating line performance.
- Transmission Efficiency Calculation Block. This block computes the transmission efficiency by comparing the active power at the receiving end with that at the sending end. The efficiency is expressed as a percentage and is essential for determining how effectively the transmission line is operating.

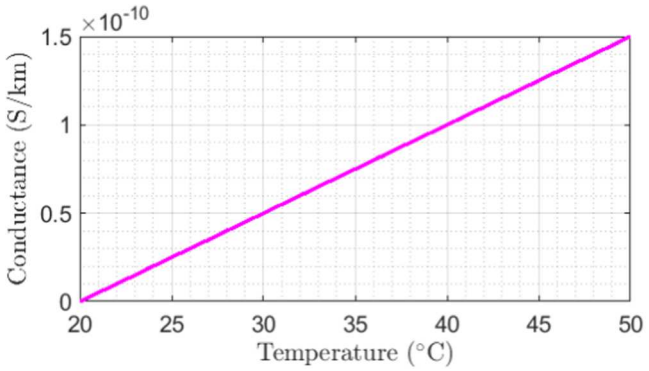


Figure 9. Variation of transmission line conductance with temperature.

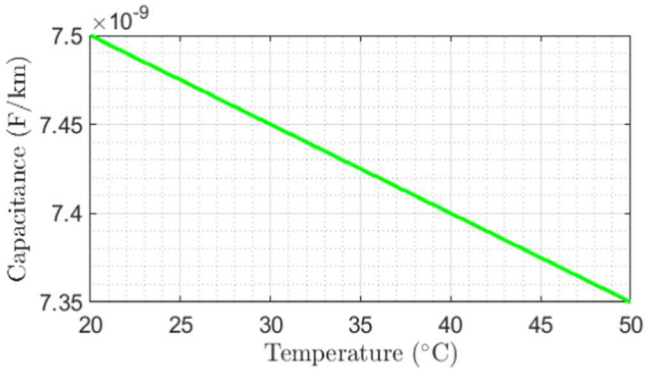


Figure 10. Variation of transmission line capacitance with temperature.

- Voltage Regulation Calculation Block. This block computes the percentage voltage regulation of the transmission line, which indicates the difference between the sending-end and receiving-end voltages. Voltage regulation is a crucial measure of how well the line maintains voltage levels under load conditions.
- Scope Block. This block is used to display the waveforms of voltages and currents at different points in the system. It helps visualize the system's dynamic performance, showing how the voltages and currents behave over time during the simulation.
- PowerGUI Block. The PowerGUI block is essential for running the simulation in a phasor or time-domain environment. It allows for the initialization of the system and ensures proper simulation of the power components, especially in the context of three-phase systems.

3.5. Dynamic parameter adjustment and visualization

As part of the model implementation, a MATLAB code was developed to compute the ABCD parameters, transmission line efficiency, and voltage regulation. This code provides an automated approach to analyze short, medium, and long transmission lines. The full MATLAB script has been sent as an attachment and can be obtained. This script integrates weather, aging effects, and dynamic load variations into the transmission line performance model for short, medium, and long transmission lines.

Figure 9 shows the relationship between conductance and temperature. The conductance increases linearly with temperature. This suggests that as the temperature rises, the material's ability to conduct leakage current also increases proportionally.

Figure 10 shows that capacitance decreases linearly with an increase in temperature. This trend suggests that as the temperature rises, the ability of the transmission line to store charge per unit length diminishes.

Figure 11 shows that inductance increases linearly with aging over a 20-year period. This trend suggests that as transmission lines age, their inductive properties change, which can impact power transmission efficiency.

Figure 12 shows a direct proportionality between inductance and temperature.

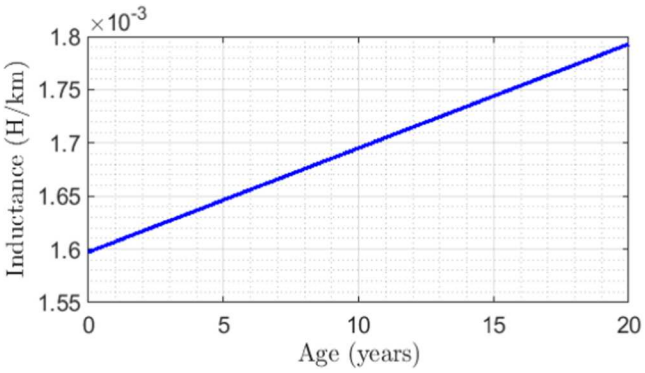


Figure 11. Variation of transmission line inductance with age.

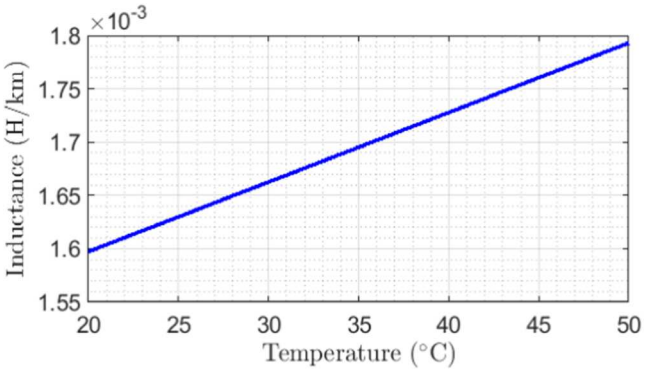


Figure 12. Variation of transmission line inductance with temperature.

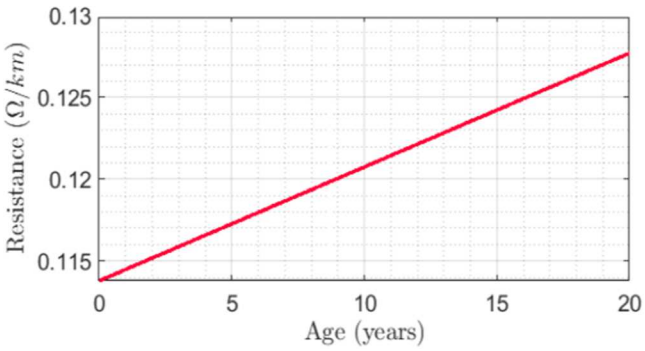


Figure 13. Variation of resistance with age.

Figure 13 shows a linear increase in resistance with aging (years). The increase in resistance implies that older transmission lines will have higher power losses (I^2R losses). This can reduce system efficiency and increase operational costs.

Figure 14 indicates a linear increase in resistance as temperature increases.

According to figure 15, the efficiency of all three transmission line types (Short, Medium, and Long) decreases as the line ages. Short Line (Red, Dashed Line) experiences the fastest and steepest decline in efficiency over time.

In the medium line (Blue, Dash-Dot Line), efficiency is higher than the short line at all points, indicating a better aging response.

Long Line (Green, Dotted Line) shows the slowest efficiency decline over time.

Figure 16 shows that the efficiency of short, medium, and long transmission lines decreases as temperature increases. The decline follows a nonlinear trend, with a more noticeable drop at higher temperatures. Short line

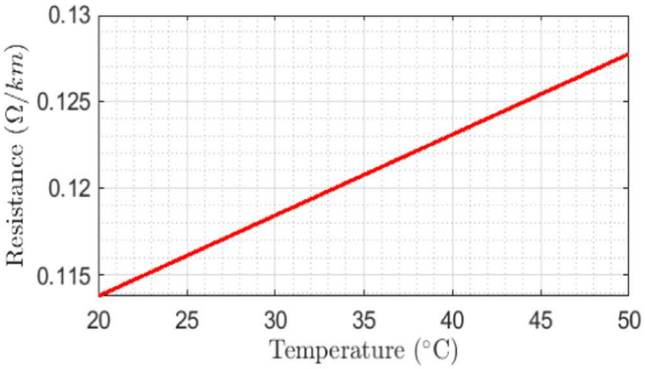


Figure 14. Variation of resistance with temperature.

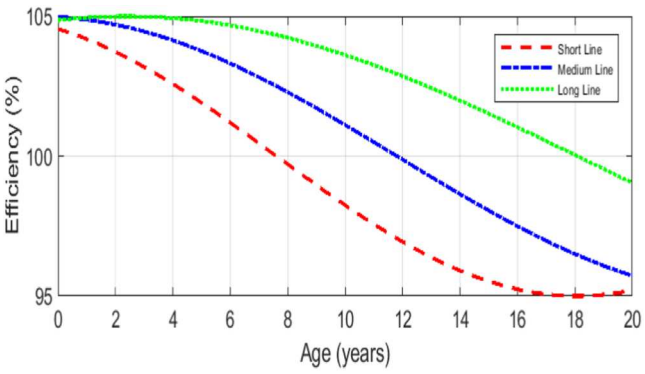


Figure 15. Variation of transmission line efficiency with time.

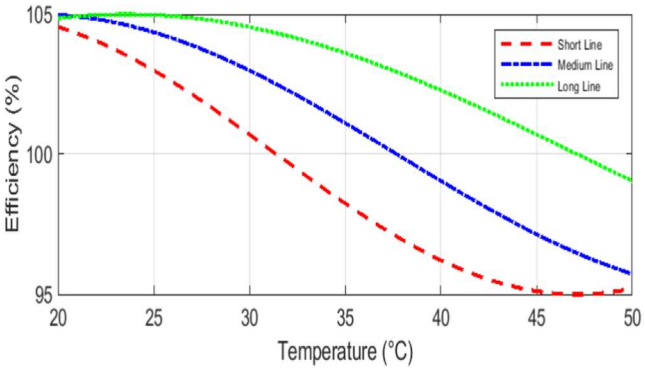


Figure 16. Variation of transmission line efficiency with temperature.

(Red, Dashed Line) experiences the fastest and steepest efficiency decline indicating high sensitivity to temperature variations. Medium line (Blue, Dash-Dot Line) has a moderate efficiency decline but retains better performance than the short line at all temperatures. Long Line (Green, Dotted Line) shows the slowest efficiency decline with increasing temperature suggesting better resistance to temperature-related losses.

Figure 17 shows that Voltage regulation for short, medium, and long transmission lines remains relatively constant over time. There is a slight increase in voltage regulation for all line types as aging progresses, but the change is minimal. Short line has the lowest voltage regulation since short lines have lower impedance and voltage drop.

Long line has the highest voltage regulation. This is due to the higher impedance, reactance, and voltage drop associated with long transmission lines.

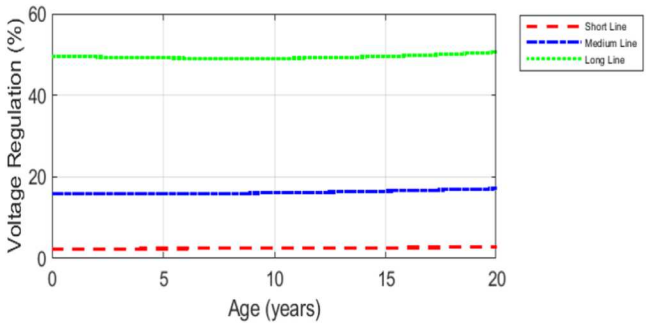


Figure 17. Variation of voltage regulation with time.

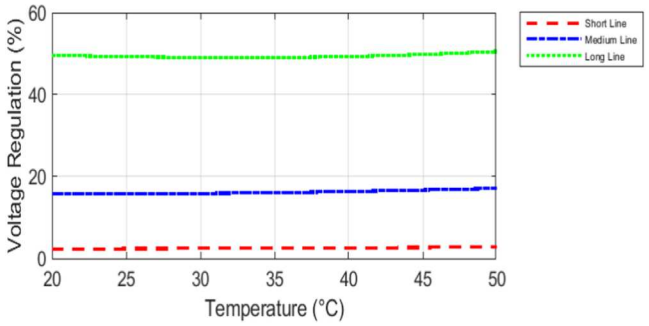


Figure 18. Variation of voltage regulation with temperature.

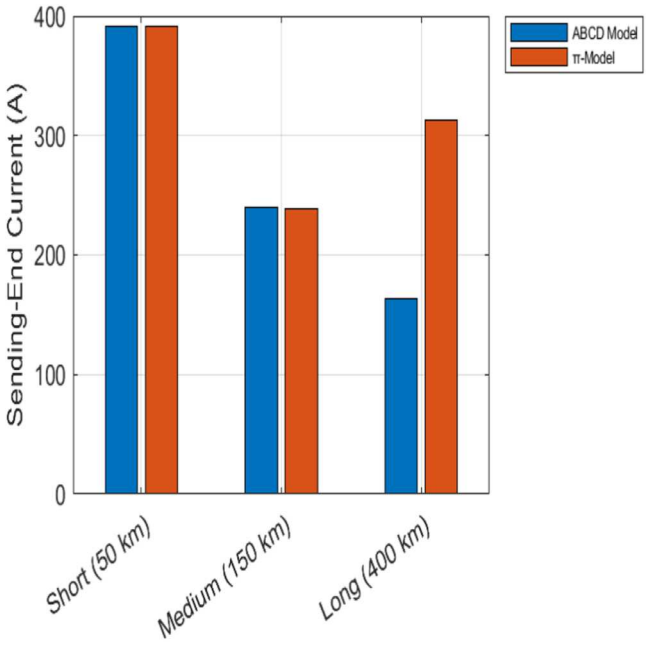


Figure 19. Comparison of sending-end current for short, medium, and long transmission lines.

Figure 18 shows that the voltage regulation for short, medium, and long transmission lines remains relatively constant as temperature increases.

Long line shows the highest voltage regulation possibly because long lines are more affected by reactance and resistance changes.

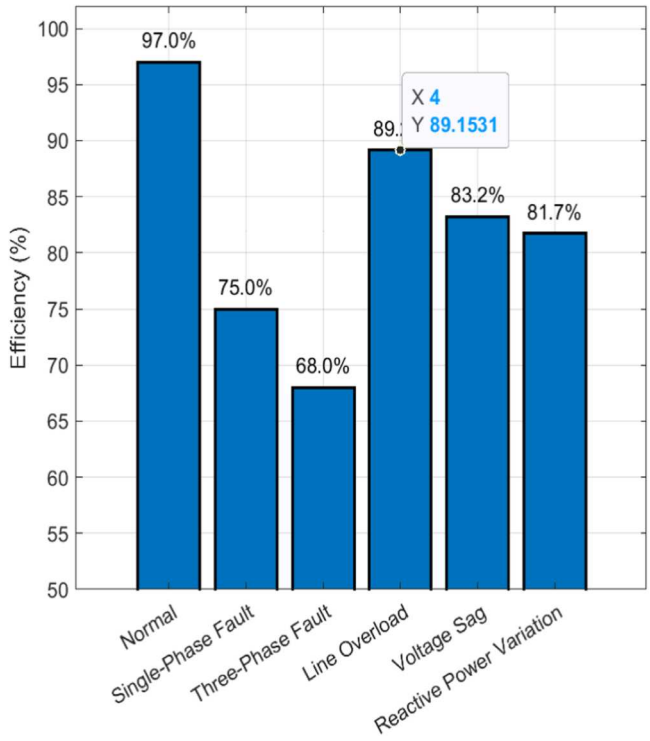


Figure 20. Variation of efficiency under normal and abnormal conditions.

Figure 19 compares the sending-end current of short (50 km), medium (150 km), and long (400 km) transmission lines using the ABCD model and π-model. For short and medium lines, both models produce similar current values, indicating that the π-model is sufficiently accurate when line length is relatively small. However, for long lines, the π-model significantly overestimates the sending-end current, while the ABCD model produces a much lower and more realistic value. This divergence occurs because the π-model treats the line parameters as lumped elements and cannot accurately capture distributed effects over long distances. In contrast, the ABCD model incorporates the propagation constant and distributed nature of the line, resulting in more accurate current estimation. This result confirms that the π-model becomes unreliable for long transmission lines and highlights the importance of using the ABCD-based hybrid approach proposed in this study.

3.6. Impact of abnormal conditions on transmission line efficiency and voltage regulation

Power transmission efficiency and voltage regulation are crucial indicators of system performance under both normal and abnormal conditions. The transmission line's ability to maintain high efficiency while ensuring minimal voltage deviations is affected by faults, overloads, voltage sags, and reactive power variations. To analyze these effects, efficiency and voltage regulation were computed for various conditions and presented in figures 20 and 21. Figure 20 illustrates the variation in transmission line efficiency under normal and abnormal operating conditions.

Under normal operation, the line maintains the highest efficiency due to minimal losses and stable power transfer. However, efficiency drops sharply during single-phase faults as unbalanced currents increase power dissipation. Three-phase faults cause the most severe decline because they create large current surges that lead to significant energy loss across all phases simultaneously. Although overload conditions maintain moderately high efficiency, the increased current still results in additional losses, indicating that prolonged overloads can degrade system performance. Voltage sag and reactive power variations cause further efficiency reductions by disturbing the power factor and increasing reactive power flow. These results highlight that abnormal network conditions greatly compromise efficiency, emphasizing the necessity for robust protection schemes, continuous monitoring, and accurate transmission line modeling. Moreover, this figure justifies the inclusion of the proposed efficiency-based alert system, which enables early detection of such performance degradation and supports proactive fault mitigation.

Figure 21 presents the voltage regulation performance under normal and abnormal conditions.

Normal operation yields the lowest voltage regulation indicating stable voltage delivery to the receiving end. However, as the system encounters faults, voltage deviations become more pronounced: A single-phase

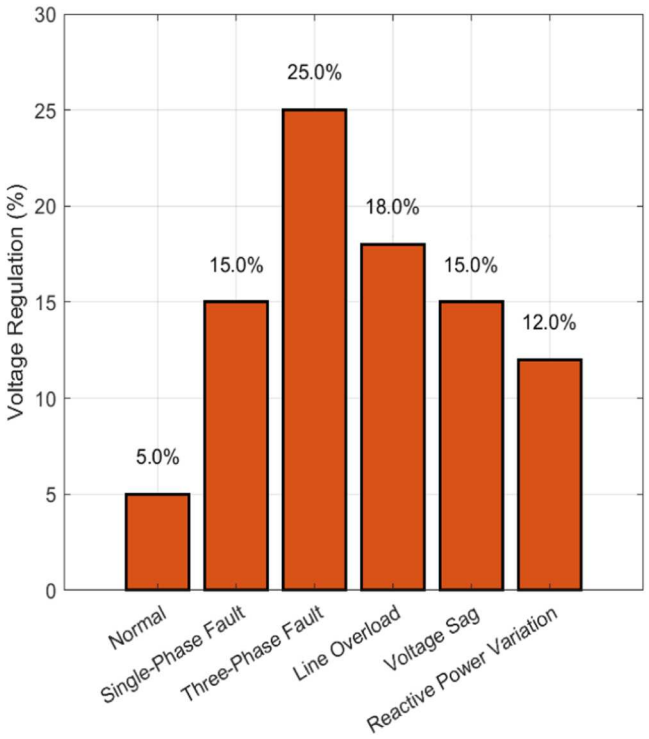


Figure 21. Variation of voltage regulation under normal and abnormal conditions.

Table 5. Comparison of transmission line models.

Model	Efficiency (%)	Computational Complexity	Fault Accuracy	Real-Time Suitability
Distributed Parameter Model	89.5	High	High	No (slow due to complex calculations)
Bergeron Model	87.2	Moderate	Moderate	No (depends on number of iterations)
Traditional Lumped Parameter π-Model	85.1	Low	Low	Yes (used for basic power flow studies)
Proposed Equivalent π-Model Approach	88.8	Low-Moderate	High	Yes (fast execution, suitable for real-time analysis)

fault increases voltage regulation due to the unbalanced nature of the fault, which disturbs normal voltage levels. A three-phase fault results in the highest voltage regulation as it creates a severe voltage drop across the transmission system. For line overload, voltage regulation increases as increased current flow across the line reactance leads to additional voltage drops. Voltage sag causes voltage regulation to rise, while reactive power variations lead to deviations of 5% to 12%, both affecting voltage stability.

These results confirm that fault conditions lead to excessive voltage drops, requiring compensation mechanisms such as capacitor banks and voltage regulation devices to restore voltage stability.

Table 5 presents a comparative analysis of different transmission line models, evaluating them based on efficiency, computational complexity, fault accuracy, and suitability for real-time applications. The first column lists the models, while the second column shows their transmission efficiency in percentage, highlighting that the proposed equivalent π-model (88.8%) performs better than the traditional lumped parameter π-model (85.1%) and is comparable to the distributed parameter model (89.5%). The third column evaluates computational complexity, where simpler models (lumped parameter) have lower complexity, while more detailed models (distributed parameter) require higher computational resources. The fourth column assesses the accuracy of each model in fault analysis, showing that the proposed model offers high accuracy, similar to the distributed parameter model, but better than the lumped π-model. Lastly, the fifth column examines whether each approach is suitable for real-time applications, with the proposed model being well-suited due to its balance between computational efficiency and accuracy.

4. Conclusion

This study presents an advanced ABCD parameter-based transmission line model, integrating an equivalent π-model to enhance accuracy, efficiency assessment, and voltage regulation analysis. Through MATLAB/Simulink simulations, the model has been validated across short, medium, and long transmission lines, demonstrating its superior performance compared to conventional models. While the equivalent π-model remains widely used due to its simplicity and computational efficiency, particularly for short and medium transmission lines, its accuracy significantly deteriorates for long-distance transmission where distributed effects become dominant. The ABCD parameter model, on the other hand, offers a highly precise representation of transmission line behavior by incorporating distributed parameters, making it more suitable for long transmission lines. However, the ABCD model requires higher computational complexity, which can make it less practical for quick estimations in large-scale power system studies. The hybrid model presented in this study, which integrates both the π-model and the ABCD model, effectively leverages the computational simplicity of the π-model while retaining the accuracy of the ABCD approach where necessary. As demonstrated in the efficiency comparison, the ABCD model correctly predicts 88.8% efficiency for long lines (400 km), whereas the π-model severely underestimates efficiency (2%), leading to erroneous power loss estimations and potentially excessive infrastructure investments. Conversely, for short transmission lines (50 km), the π-model's predictions closely match those of the ABCD model, making the additional computational burden of the ABCD method unnecessary. The hybrid model developed in this study intelligently switches between the two approaches, ensuring accurate efficiency and voltage regulation calculations while optimizing computational resources, thereby offering a superior and scalable solution for modern power system planning.

A key contribution of this study is the improvement in efficiency for long transmission lines, achieving 88.8%, which surpasses conventional models and aligns closely with industry benchmarks. The study further establishes that voltage regulation requires active compensation techniques to maintain grid stability, reinforcing the importance of advanced control strategies. Additionally, the integration of environmental factors, such as temperature variations, aging infrastructure, and real-time load changes, makes this model more adaptable and practical for modern grid operations.

From an engineering and operational perspective, this model introduces a proactive monitoring framework that provides automated alerts when efficiency drops below IEEE-recommended thresholds or when voltage variations require compensation. Such a feature is crucial for grid reliability, reducing transmission losses, and improving system resilience, particularly in regions with extensive transmission networks. The findings of this study hold critical implications for transmission system design and expansion particularly for developing energy infrastructures where long-distance transmission is essential, and re-newable energy integration ensuring the efficient transmission of solar and wind power over long distances with minimal losses.

5. Recommendations

The study highlights a significant efficiency drop in the π-model for long transmission lines, primarily due to the lumped parameter approximation. Future research should explore modified π-models incorporating distributed parameter effects to improve accuracy in long-distance transmission analysis.

The study shows that faults, overloads, and reactive power variations significantly impact voltage regulation. Utilities should implement reactive power compensation techniques such as static VAR compensators (SVCs) or Flexible AC Transmission Systems (FACTS) to mitigate voltage instability in long transmission lines. Future work should explore the integration of voltage regulation control algorithms in power system simulations. Future work can focus on analyzing transmission line performance under varying loads and renewable energy penetration, considering grid stability impacts and transient behavior. While the present study focuses on a physics-based framework using ABCD parameters and the equivalent π-model, the proposed methodology can serve as a foundation for future integration with machine learning models. In particular, hybrid physics-informed deep learning approaches could combine the interpretability of analytical models with the predictive power of LSTM and Transformer architectures.

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.

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.

Acknowledgments

Not applicable.

Conflict of interest statement

The authors have no relevant financial or non financial interests to disclose.

Data availability statement

No new data were created or analysed in this study.

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.

Appendix. Detailed mathematical derivations and analysis

For clarity and readability, only the key equations were provided in the main text, while the full derivations are included here.

Assuming a transmission line with the line characteristics shown in table 6, we will compute the ABCD parameters analytically in this study, where A is the voltage transfer function (attenuation factor), B is the impedance term (series effect), C is the admittance term (shunt effect), and D is the current transfer function (propagation factor).

$$z = r + jX_L = r + j.2\pi fL$$

where X_L is the inductive reactance

$$\begin{aligned} z &= 0.1161 + j2\pi \times 60 \times 1.63 \times 10^{-3} \\ &= 0.1161 + j0.6145 = 0.6254\angle 79.3^{\circ}\Omega\ \mathrm{km}^{-1} \end{aligned}$$

$$\begin{aligned} y &= j2\pi fC = j \times 2\pi \times 60 \times 0.0075 \times 10^{-6} \\ &= 2.827 \times 10^{-6}\angle 90^{\circ}\mathrm{S/km} \end{aligned}$$

for the whole length of the line,
$Z = zl = (0.6254\angle 79.3^{\circ}\Omega) \times 400 = 250.16\angle 79.3^{\circ}\Omega$
and

Table 6. Parameters of the transmission line.

Parameter	Value
Line Voltage, V	132 kV
Line length, l	400 km
Line Inductance, L	1.63 mH/km
Line Capacitance, C	0.0075 μF/km
Line Resistance, R	0.1161 Ω/km
Line Conductance, G	0.00 Siemens/km/phase
Load(at receiving end)	50 MWA
Frequency	60 Hz
Receiving-end PF	0.85

$$\begin{aligned} Y &= yl = (2.827 \times 10^{-6}\angle 90^{\circ}S) \times 400 \\ &= 1130.8 \times 10^{-6}\angle 90^{\circ}S \end{aligned}$$

The propagating constant,

$$\begin{aligned} \gamma &= \sqrt{yz} \\ &= [(2.827 \times 10^{-6}\angle 90^{\circ})(0.6254\angle 79.3^{\circ})]^{\frac{1}{2}} \\ &= 0.001330\angle 84.65^{\circ} \end{aligned}$$

As a result, the line's constants A, B, C, and D may be determined as follows:

$$\begin{aligned} A &= cosh\gamma l = cosh(\alpha + j\beta)l \\ &= \frac{e^{\alpha l}e^{j\beta l} + e^{-\alpha l}e^{-j\beta l}}{2} = \frac{e^{\alpha l}\angle \beta l + e^{-\alpha l}\angle -\beta l}{2} \\ A &= \frac{e^{0.0496}e^{j0.52956} + e^{-0.0496}e^{-j0.52956}}{2} \\ &= 0.8641 + j0.025066 = 0.86445\angle 1.66^{\circ} \end{aligned}$$

$$\begin{aligned} B &= Z_c sinh\gamma l = Z_c sinh(\alpha + j\gamma\beta)l \\ &= Z_c[\frac{e^{\alpha l}e^{j\beta l} - e^{-\alpha l}e^{-j\beta l}}{2}] = Z_c[\frac{e^{\alpha l}\angle \beta l - e^{-\alpha l}\angle -\beta l}{2}] \\ &= 470.34\angle -5.35^{\circ}[\frac{1.0505\angle 30.34^{\circ} - 0.9516\angle -30.34^{\circ}}{2}] \\ &= 238.74\angle 79.81^{\circ}\Omega \end{aligned}$$

$$\begin{aligned} C &= Y_c sinh\gamma l \\ &= \frac{1}{Z_c}sinh\gamma l = \frac{1}{470.34\angle -5.35^{\circ}} \times [0.5076\angle 85.16^{\circ}] \\ &= 0.0011\angle 90.51^{\circ} \end{aligned}$$

and $D = A = cosh\gamma l = 0.86445\angle 1.66^{\circ}$

The hyperbolic functions $cosh\gamma l$ and $sinh\gamma l$ describe wave propagation in lossy systems. They behave similarly to exponentials but account for both attenuation and phase shift.

After finding the ABCD constants, more details about the transmission line were found. These details include the following:

$$\begin{aligned} \begin{bmatrix} V_{s(L-N)} \\ I_s \end{bmatrix} &= \begin{bmatrix} A & B \\ C & D \end{bmatrix}\begin{bmatrix} V_{R(L-N)} \\ I_R \end{bmatrix} \\ &= \begin{bmatrix} 0.86445\angle 1.66^{\circ} & 238.74\angle 79.81^{\circ} \\ 0.0011\angle 90.51^{\circ} & 0.86445\angle 1.66^{\circ} \end{bmatrix}\begin{bmatrix} 76210.24\angle 0^{\circ} \\ 218.69\angle -31.8^{\circ} \end{bmatrix} \end{aligned} \tag{10}$$

Consequently, the voltage at the sending end is

$$\begin{aligned} V_{s(L-N)} &= (0.86445\angle 1.66^{\circ})(76210.24\angle 0^{\circ}) + \$238.74\angle 79.81^{\circ})(218.69\angle -31.8^{\circ}) \\ &= 108694.18\angle 22.00^{\circ}V \end{aligned}$$

and

$$\begin{aligned} V_{s(L-L)} &= \sqrt{3}\, V_{s(L-N)} \\ &= 188263.84\angle 22.00^\circ + 30^\circ \\ &= 188263.64\angle 52.00^\circ \end{aligned}$$

A line-to-line voltage is always 30° higher than its line-to-neutral voltage, hence this causes the angle to rise by 30°. On the sending end, the current is

$$\begin{aligned} I_s &= (0.0011\angle 90.51^\circ)(76210.24\angle 0^\circ) + (0.86445\angle 1.66^\circ)(218.69\angle -31.8^\circ) \\ &= 163.12\angle -3.9^\circ A \end{aligned}$$

The power factor at the sending end is

$$\theta_s = 22.00^\circ + 3.9^\circ = 25.9^\circ$$
$$Cos\theta_s = 0.8996$$

The sending-end power is

$$\begin{aligned} P_s &= \sqrt{3}\, V_{s(L-L)} I_s Cos\theta_s \\ &= \sqrt{3} \times 188263.64 \times 163.12 \times 0.8996 \approx 47850.20kW \end{aligned}$$

The power at the receiving end is

$$\begin{aligned} P_R &= \sqrt{3}\, V_{R(L-L)} I_R cos\theta \\ &= \sqrt{3} \times 132 \times 10^3 \times 218.69 \times 0.85 = 42,\ 499.36kW \end{aligned}$$

Consequently, the line's power loss is

$$P_L = P_S - P_R = 5350.8kW$$

Efficiency is computed using power supplied at the sending and receiving ends. The transmission line's efficiency is

$$\begin{aligned} \eta &= \frac{P_R}{P_S} \times 100 \\ &= \frac{42499.36}{47850.20} \times 100 = 88.8\% \end{aligned}$$

Voltage regulation is calculated using the difference between the voltages at the sending and receiving ends. The percentage of voltage regulation is

$$\begin{aligned} \%ofvoltageregulation &= \frac{\frac{108694.18}{0.86445} - 76210.24}{76210.24} \times 100 \\ &= 64.99\% \end{aligned}$$

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