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CONTENT

1. Chapter **5**
Super-Twisting Sliding Mode Liquid Level Control Implementation for Raspberry Pi
Erdem ILTEN

2. Chapter **19**
Artificial Magnetic Conductor in Antenna Application
Mohamed Abdiaziz MOHAMED, Ediz ERDEM

3. Chapter **34**
Enerji Depolama Sistemleri
Nurullah AKGÜN, Serdal DAMARSEÇKİN

4. Chapter **51**
Comparative Analysis of Transmission Line Models Across Varying Lengths: A Comprehensive Study on Relative Comparison in Terms of Current, Voltage, Power, Loss, Regulation and Efficiency
Cemil ALTIN

5. Chapter **65**
Büyük Yolcu Uçaklarındaki Kokpit Kapısı Kilit Sisteminin İncelenmesi
Fuat ŞAYLAN, Fatih Alpaslan KAZAN

6. Chapter **75**
Harmonic Compensation Using Fuzzy Logic Controlled Active Filters
Mouhammedi MOUFID, Bahi TAHAR

7. Chapter **88**
Study of the Effect of Partial Shading on Photovoltaic Conversion Systems
Layate ZAKARIA, Bahi TAHAR, Lekhchine SALIMA

8. Chapter **100**
Atık Suyla Elektrik Üretimi: Mikrobiyal Yakıt Hücreleriyle Yenilenebilir Enerji
Serkan UZAN, Serdal DAMARSEÇKİN, Edip TAŞKESEN, Hakan DUMRUL, Hüseyin GÜRBÜZ

Comparative Analysis of Transmission Line Models Across Varying Lengths: A Comprehensive Study on Relative Comparison in Terms of Current, Voltage, Power, Loss, Regulation and Efficiency

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ABSTRACT

In this study, the absolute differences between long, medium and short transmission line models in terms of sending end voltage, current, power factor, apparent power, active power, reactive power, voltage regulation, voltage drop, active power loss, line efficiency, charging current and voltage rise as the total length of the transmission line is varied are investigated. According to the results obtained, it was seen that the long transmission line models performed excellent calculations for medium and long transmission lines, while they were able to accurately calculate many parameters of short transmission lines. It has been observed that the parameters of the short transmission line that cannot be calculated correctly are due to the neglected admittance. As a result, it has been shown that the values of transmission lines of all lengths can be calculated accurately with the long transmission line model. It has also been observed that approximate and exact models give very close values to each other in transmission lines up to 500 km. It has been proven that using the approximate model for all lines between 80-500 km will not cause any problems, as the approximate model, which is easier to apply than the exact model, gives the same results as the nominal pi model on lines up to 250 km.

Keywords – Transmission Line, ABCD parameters, Nominal pi, Line models, Approximate model

INTRODUCTION

Precise modeling and analysis of transmission lines are essential in the field of electrical power transmission to guarantee effective and dependable energy delivery over long distances. Power distribution networks' main support structure, transmission lines, are available in a variety of lengths, each with its own set of characteristics. Within the field of transmission line analysis, a great deal of work has gone into creating models that faithfully capture the behavior of these systems at different lengths. Long transmission line models seek to capture the nuances of line behavior over long distances, whereas short length transmission line models are frequently used due to their ease of use and computational efficiency. Optimizing the design, operation, and maintenance of transmission lines requires a thorough understanding of their behavior over a range of lengths. This paper offers a thorough analysis

of transmission line models with lengths ranging from 10 to 1000 kilometers, divided into short, medium, and long categories. For power system analysis and planning to be as accurate as possible, it is essential to comprehend the variations and constraints of these models. Comparing and analyzing these transmission line models' behaviors, as well as assessing important variables like sending voltage, current, power factor, apparent power, active power, reactive power, voltage regulation, voltage drop, active power loss, line efficiency, charge current, and voltage increase is the main goal. The objective of this work is to examine the absolute errors between models of long, medium and short transmission line models, with a focus on how these errors change as the transmission line's overall length varies. The suitability and accuracy of each model under various operating conditions can be better understood by methodically examining the differences between these models over a range of transmission line lengths. This study is significant because it can shed light on how transmission line models behave in different operating scenarios. This research attempts to provide useful information for engineers, planners, and operators involved in the design and management of power transmission systems by utilizing various models and taking a wide range of line lengths into consideration. The goal of this study is to improve understanding of power transmission engineering and support the development of better transmission system designs and operations that meet the changing needs of contemporary electrical grids. This study aims to improve transmission line modeling techniques and ultimately increase the efficiency and reliability of power system analysis and operation by quantifying the absolute errors between these models and analyzing how they change with increasing line length.

MATERIALS AND METHOD

The primary components of transmission line models are inductive and capacitive elements, which are calculable based on the length and geometric

configuration of the line. Based on their length, they can be divided into three groups (Khoshkalam & Ali, 2024).

• Short-Line (L<80 km)

• Medium-Line (80 km<L<250 km)

• Long-Line (L>250 km)

A two-port network illustrates the relationship between the per phase voltages and currents at the two ends of the transmission line. The parameters A, B, C, and D are referred to as transmission line parameters. Two-port network can be seen in Figure 1.



Figure 1: Two port-network representation of a transmission line(Al-Roomi & El-Hawary, 2020)

Matrix form of the two port-network is given by Equation 1.

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \quad (1)$$

Short Transmission Line Model

Any transmission line that is 80 km or shorter can be reduced to a short line model in which the conductance (G) and per-phase capacitance (C) are not taken into account. All that is included are the reactance and series resistance. One line diagram of the short line model can be seen in Figure 2.

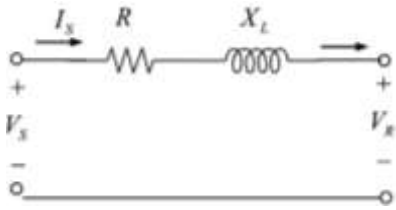


Figure 2: Short transmission line one line diagram

In short line model V_s is sending end voltage, I_s is sending end current, V_R is receiving end voltage and I_R is receiving end current. The relationship between sending and receiving end is given by equation 2 and 3.

$$V_S = V_R + ZI_R \tag{2}$$

$$I_S = I_R \tag{3}$$

All current and voltage equations are rewritten in matrix format in equation 4.

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \tag{4}$$

So the A, B, C and D parameter of the short line model is A=D=1, B=Z and C=0. Z is the series impedance and acquired by equation 5.

$$Z = (R + j\omega L)l \tag{5}$$

Here R is unit resistance of the conductor, L is unit inductance and l is the length of the transmission line.

Medium Transmission Line Model (Nominal π circuit)

When it comes to medium-length transmission lines, a nominal pi circuit that is longer than 80 km overall but not more than 250 km could be used, taking into account the shunt capacitance. One line diagram of the nominal π circuit can be seen in Figure 3.

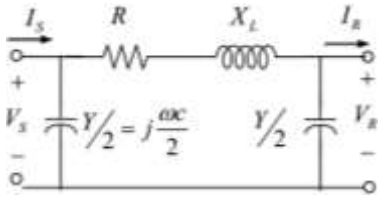


Figure 3: Nominal π circuit

The sending end and receiving and relations (ABCD parameters) of the Nominal π circuit is given by equation 6.

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} 1 + \frac{YZ}{2} & Z \\ Y\left(1 + \frac{YZ}{4}\right) & 1 + \frac{YZ}{2} \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \tag{6}$$

Long Transmission Line Exact Model

Long transmission line exact model used when the transmission line length is longer than 250 km. Long transmission line model circuit can be seen in Figure 4.

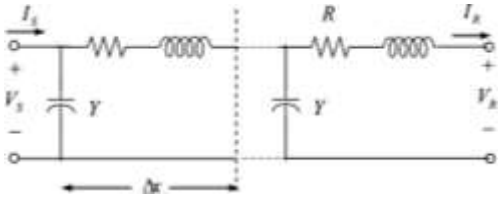


Figure 4: Long transmission line equivalent circuit

The sending end - receiving end relations (ABCD parameters) of the Long transmission line exact model circuit is given by equation 7.

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} \cosh(\gamma l) & Z_c \sinh(\gamma l) \\ \frac{1}{Z_c}\sinh(\gamma l) & \cosh(\gamma l) \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \tag{7}$$

Here γ is propagation constant and acquired by equation 8.

$$\gamma = \sqrt{zy}\ km^{-1} \tag{8}$$

And Z_c is characteristic impedance and acquired by equation 9.

$$Z_c = \sqrt{\frac{z}{y}} \tag{9}$$

Long Transmission Line Approximate Model

This transmission line model is also used for long transmission lines. The sending end - receiving end relations (ABCD parameters) of the Long transmission line approximate model circuit is given by equation 10.

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} 1 + \frac{YZ}{2} & Z\left(1 + \frac{1}{6}YZ\right) \\ Y\left(1 + \frac{1}{6}YZ\right) & 1 + \frac{YZ}{2} \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \tag{10}$$

Comparison Parameters

As stated in introduction section the comparisons are made in terms of important variables like sending voltage, current, sending end power factor, apparent power, active power, reactive power, voltage regulation, voltage drop, active power loss, line efficiency, charge current, and voltage increase.

Sending voltage and and currents are acquired from the line model matrices. Sending end power factor is calculated by eqution 11.

$$\cos(\theta_S) = \cos\left(\theta_{V_S} - \theta_{I_S}\right) \tag{11}$$

Appareant power is calculated by equation 12.

$$S_S = \sqrt{3} V_S I_S \tag{12}$$

Active power is calculated by equation 13.

$$P_S = \sqrt{3} V_S I_S \cos(\theta_S) \tag{13}$$

Reactive power is calculated by equation 14.

$$Q_S = \sqrt{3} V_S I_S \sin(\theta_S) \quad (14)$$

Percent voltage regulation is calculated by equation 15.

$$\%V_{reg} = \left| \frac{\left(\frac{V_S}{A}\right) - V_R}{V_R} \right| x100 \quad (15)$$

Percent voltage drop is calculated by equation 16.

$$\%e = (V_S - V_R)/V_R \quad (16)$$

Active power loss is calculated by equation 17.

$$P_{loss} = P_S - P_R \quad (17)$$

Line efficiency is calculated by equation 18.

$$\eta = \frac{P_R}{P_S} x100 \quad (18)$$

Charging current at sending end at no load is calculated by equation 19.

$$I_C = 0.5 * Y * V_S \quad (19)$$

Voltage increase at the receiving end of the line under no load is calculated by equation 20.

$$V_{R+} = V_S - Z * I_C \quad (20)$$

Load Characteristics

This study was carried out to demonstrate the relative differences of different transmission line models for variable line lengths to feed a fixed load. The values for the fixed load are presented in Table 1.

Table 1: Load charecteristics

Frequency(Hz)	60	Receiving end voltage(kV)	138
Unit resistance(Ω/km)	0.1858	Apparent power(MVA)	50
Unit inductance(H/km)	2.6x10^{-3}	Power factor	0.85
Unit capacitance(S/km)	0.012$x10^{-6}$		

RESULTS AND DISCUSSION

In this study transmission line models were compared by varying total length of the transmission line. Line length is varied from 10 to 1000 km. The absolute comparisons of the sending end variables are plotted in Figures 5, 6, 7 and 8. Absolute comparisons between the transmission line models calculated by varying total transmission line length in terms of sending voltage (V_S,), sending current (I_S), sending power factor, and sending apparent power are can be seen in Figure 5.

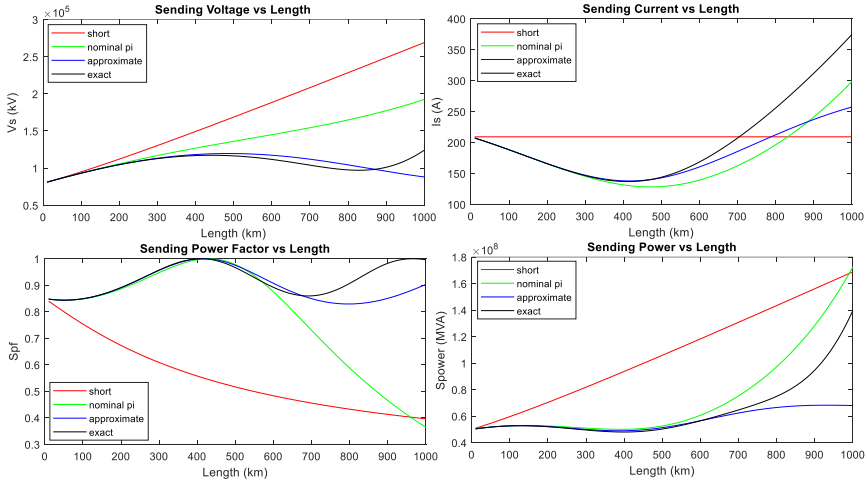


Figure 5: Absolute comparisons between the transmission line models calculated by varying total transmission line length in terms of V_S, I_S, pf, S

When Figure 5 is analyzed, it is seen that all models give the same results for transmission lines up to 100 km in length of the Sending end voltage. For medium lines between 100 km and 250 km, it is seen that medium and long

line models give similar results. For lines longer than 250 km, it is seen that the long transmission line models give similar results. In short, it is observed that long transmission line models can produce accurate results for all line lengths in sending end voltage calculation. In the calculation of sending end current, sending power factor and sending apparent power, it is seen that short transmission model can be used for short lines and long transmission line models can be used for medium and long lines. Absolute comparisons between the transmission line models calculated by varying total transmission line length in terms of sending active power (P_S), sending reactive power (Q_S), percent voltage regulation, and percent voltage drop are can be seen in Figure 6.

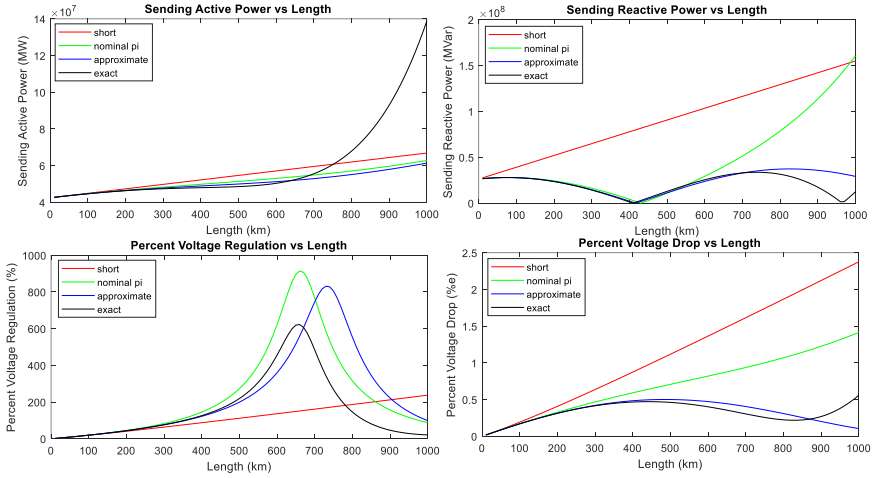


Figure 6: Absolute comparisons between the transmission line models calculated by varying total transmission line length in terms of P_S, Q_S, %r, and %e

When Figure 6 is analyzed, it is seen that even for short (0-80 km) and medium length lines (80-250 km), long transmission line models show very successful results in the calculation of Sending active power, percent voltage regulation and percent voltage drop. However, in Sending reactive power calculation, short transmission line model should be preferred for short transmission lines. It is seen that the short transmission line model can obtain accurate results only for short transmission lines. Absolute comparisons

between the transmission line models calculated by varying total transmission line length in terms of delta, active power loss, line efficiency, and charge current are can be seen in Figure 7.

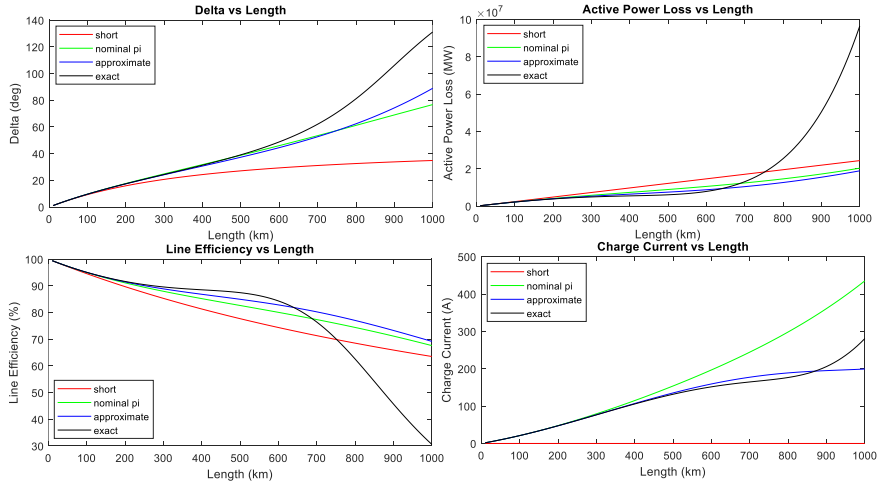


Figure 7: Absolute comparisons between the transmission line models calculated by varying total transmission line length in terms of δ, P_{loss}, η, and I_c

When Figure 7 is analyzed, it is seen that the long transmission line models perform well in the calculation of delta, active power loss and line efficiency for short, medium and long lines. However, since the admittance is neglected in short transmission lines in charge current calculation, other line models cannot provide successful results. It is seen that the short transmission line model does not show successful performance except for short lines. Figure 8 shows absolute comparisons between the transmission line models calculated by varying total transmission line length in terms of voltage increase at receiving end in case of no load.

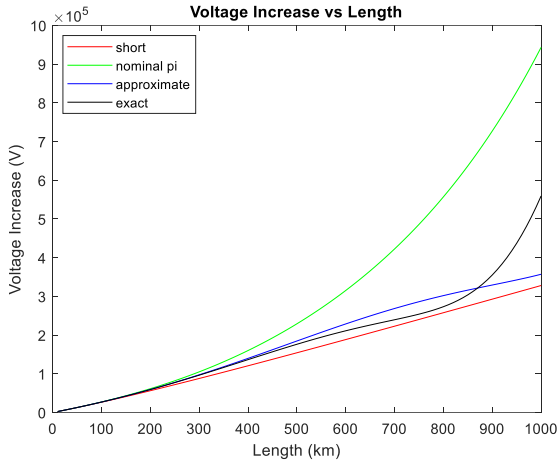


Figure 8: Absolute comparisons between the transmission line models calculated by varying total transmission line length in terms of voltage increase at receiving end in case of no load

When Figure 8 is analyzed, it is seen that the long transmission line models for voltage increase at receiving end in case of no load give accurate results for all line types.

Overall, the results show that the long transmission line models perform very well for medium length lines (80-250 km). At the same time, the long transmission line models also showed excellent performance in the calculation of many parameters of short transmission lines.

Over a variety of transmission line lengths, from 10 to 1000 kilometers, the study examines the absolute differences between these models. According to the results, long transmission line models perform exceptionally well when determining parameters for medium and long lines, but because admittance is overlooked, they have difficulty with certain elements of short lines. Notably, values for transmission lines of all lengths may be computed precisely when utilizing the long model. The results indicate that approximate models produce comparable results for lines up to 500 km, while long transmission line models provide precise estimations for a wide range of line lengths. This calls into

question the viability of striking a balance between computing economy and accuracy by utilizing simpler models for shorter lines.

CONCLUSION

To sum up, the research offers significant understanding into the precision of transmission line models at varying distances. The research advances attempts to construct more dependable and efficient electrical grids and advances power transmission engineering by methodically analyzing the variations between these models and their performance under different scenarios. For power systems to become more reliable and efficient in the future, transmission line modeling techniques will need to be further researched. Through the quantification of absolute errors among distinct models and an analysis of their behavior at varied line lengths, engineers can improve system performance and modify modeling methodologies.n this section, the conclusion of the research should be evaluated.

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