

Modeling And Simulation of Impedance Matching in Extra High Voltage Power Line Carrier Communication Systems

*Ogbonnaya A. O., ¹Idigo V. E., ²Ogboh V. C., ³Anazia A. E.

*Department of Electrical Engineering
Nnamdi Azikiwe University, Awka*

ABSTRACT

This paper presents the modeling and simulation of impedance matching in extra-high voltage (EHV) power line carrier communication (PLCC) systems. The methodology combines transmission line theory, mathematical modeling, and MATLAB/Simulink-based simulation to analyze carrier signal injection, propagation, and reflection on a distributed parameter EHV transmission line. An L-section impedance matching network is designed to minimize impedance mismatch effects. System performance is evaluated using reflection coefficient, voltage standing wave ratio (VSWR), and distance-based voltage distribution. Simulation results show that impedance mismatch produces high reflection coefficients ($|\Gamma| \approx 0.37$), elevated VSWR (≈ 2.18), and pronounced standing wave patterns along the line. With impedance matching applied, reflections are nearly eliminated ($|\Gamma| \approx 10^{-5}$), VSWR approaches unity, and smooth carrier signal propagation is achieved, confirming improved PLCC reliability.

Key words: Power Line Carrier Communication, Impedance, Voltage, Current, Carrier Signal

Date of Submission: 05-05-2026

Date of acceptance: 16-05-2026

I. INTRODUCTION

Power Line Carrier Communication (PLCC) remains a critical technology for communication, protection signaling, and supervisory control in Extra High Voltage (EHV) power transmission networks. By superimposing a high-frequency carrier signal (typically 50–500 kHz) onto high-voltage transmission lines, PLCC enables reliable data transmission without requiring dedicated communication infrastructure.

However, one of the major technical challenges in PLCC systems is impedance mismatch between the communication equipment and the transmission line. EHV transmission lines are inherently distributed parameter systems whose characteristic impedance varies with frequency, line geometry, and operating conditions. Impedance mismatch leads to signal reflections, increased standing waves, attenuation, and reduced communication reliability.

To mitigate these effects, impedance matching networks, particularly L-section matching networks, are employed at the transmitter and receiver ends. This study focuses on the mathematical modeling, simulation, and analysis of impedance matching in EHV PLCC systems, using MATLAB/Simulink to evaluate reflection coefficient, voltage standing wave ratio (VSWR), and signal propagation performance.

II. METHODOLOGY

The adopted methodology combines analytical modeling, mathematical formulation, and simulation-based validation. This includes; development of mathematical models for the EHV transmission line using distributed parameter theory, modeling of PLCC signal injection and propagation over the EHV line, design and analysis of an L-section impedance matching network, evaluation of reflection coefficient and VSWR under matched and mismatched conditions, implementation of the complete PLCC system model in MATLAB/Simulink and performance analysis through simulation results and graphical visualization. This integrated approach ensures that both theoretical and practical aspects of impedance matching in PLCC systems are adequately addressed.

III. SYSTEM MATHEMATICAL MODELING

The PLCC system consists of a carrier signal source, impedance matching network, coupling equipment, EHV transmission line, and receiver load. The system behavior is governed by transmission line theory and network analysis.

3.1 Distributed Parameter EHV Transmission Line

An EHV transmission line cannot be accurately represented using lumped parameters due to its long length. Instead, it is modeled as a distributed parameter system, where resistance, inductance, capacitance, and conductance are distributed along the line.

For an EHV transmission line of length L, the voltage and current are governed by the telegrapher's equations:

Transmission line equations:

$$\frac{\partial V(x,t)}{\partial x} = -(R + j\omega L)I(x, t) \quad 1$$

$$\frac{\partial I(x,t)}{\partial x} = -(G + j\omega C)V(x, t) \quad 2$$

The characteristic Impedance:

$$Z_0(\omega) = \sqrt{\frac{R+j\omega L}{G+j\omega C}} \quad 3$$

Propagation constant:

$$\begin{aligned} \gamma &= \alpha + j\beta \\ &= \sqrt{(R + j\omega L)(G + j\omega C)} \end{aligned} \quad 4$$

where:

R = resistance per unit length (Ω/m)

L = inductance per unit length (H/m)

G = conductance per unit length (S/m)

C = capacitance per unit length (F/m)

$\omega = 2\pi f =$ angular frequency

IV. PLCC SIGNAL INJECTION MODEL

In Power Line Carrier Communication (PLCC) systems, high-frequency carrier signals are superimposed on extra-high voltage (EHV) transmission lines to enable communication, protection, and control functions without disturbing the fundamental power-frequency operation. The signal injection model describes how the carrier signal is generated, coupled, and injected into the transmission line while providing electrical isolation from the power system.

The PLCC carrier signal typically operates in the 50–500 kHz frequency band, which ensures minimal interference with the 50 Hz or 60 Hz power signal, acceptable attenuation over long transmission distances and compatibility with line traps and coupling devices.

The injected carrier signal:

$$V_C(t) = V_c \sin(2\pi f_c t) \quad 5$$

Where.

$$f_c \in [50, 500] \text{kHz} \quad 6$$

V_c = Carrier Amplitude

V_c = Carrier Signal Amplitude (volts),

f_c = Carrier Frequency (Hz), typically $50 \text{ kHz} \leq f_c \leq 500 \text{ kHz}$.

t = time (seconds).

This signal represents the information-bearing waveform, which may later be modulated (AM, FSK, PSK) for practical communication systems. In impedance matching studies, a pure sinusoidal carrier is sufficient for analyzing reflections and standing waves.

V. IMPEDANCE MATCHING NETWORK

The L-section matching network is one of the simplest and most widely used impedance matching techniques in PLCC systems. It consists of one series and one shunt reactive element (inductor and capacitor) arranged in an L-configuration.

The input impedance of a transmission line terminated with a load Z_L is given by:

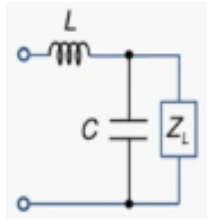


Figure 1: L-Section Matching Network

$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan(\beta l)}{Z_0 + jZ_L \tan(\beta l)} \quad 7$$

Proper selection of the reactive components ensures that $Z_{in} \approx Z_0$, thereby minimizing reflections.

VI. REFLECTION COEFFICIENT

The reflection coefficient quantifies the fraction of an incident high-frequency PLCC carrier signal that is reflected back toward the source due to impedance mismatch between the transmission line and the load or matching network. In EHV PLCC systems, impedance discontinuities arise from imperfect matching, line traps, coupling devices, and terminal equipment.

Reflection Coefficient can be obtained using

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \quad 8$$

where:

Z_L = load or termination impedance,

Z_0 = characteristic impedance of the EHV transmission line.

The magnitude of the reflection coefficient $|\Gamma|$ lies between 0 and 1.

$|\Gamma| = 0$ indicates perfect impedance matching and maximum power transfer.

$|\Gamma| = 1$ represents total reflection, resulting in severe signal distortion and loss.

Therefore, in PLCC applications, a high reflection coefficient leads to increased standing waves, reduced received signal strength, and degraded communication reliability.

Therefore, minimizing $|\Gamma|$ through proper impedance matching networks is critical for efficient carrier signal propagation along EHV transmission lines.

VII. STANDING WAVE RATIO

The standing wave ratio (SWR), commonly expressed as voltage standing wave ratio (VSWR), is a measure of impedance matching quality in transmission line systems, including EHV Power Line Carrier Communication (PLCC) networks. It indicates the degree of standing waves formed along the line due to reflections caused by impedance mismatch between the transmission line and the load.

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad 9$$

Where $|\Gamma|$ is the magnitude of the reflection coefficient.

A VSWR value of 1 represents perfect impedance matching, where all the injected carrier power is transmitted without reflection. As VSWR increases above unity, it indicates worsening mismatch, leading to higher reflected power, increased signal attenuation, and non-uniform voltage distribution along the transmission line. In PLCC systems, excessive VSWR degrades carrier signal strength, reduces communication range, and may stress coupling and matching components. Consequently, maintaining a low VSWR through effective impedance matching networks is essential for reliable PLCC operation on EHV transmission lines.

VIII. MATLAB/SIMULINK MODEL ARCHITECTURE

The MATLAB/Simulink Model Architecture of the EHV PLCC system is modular, representing carrier generation, impedance matching and coupling, transmission, and signal reception. A sine wave block generates the high-frequency carrier, while RLC blocks model the impedance matching network and coupling devices. The EHV transmission line is represented using a distributed parameter line to capture realistic propagation effects. Line traps, implemented with LC networks, confine the carrier signal, and measurement blocks are used to observe signal behavior, reflections, and VSWR. This structured block arrangement enables effective simulation and analysis of impedance matching and signal propagation in EHV PLCC systems.

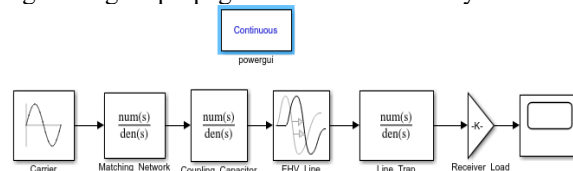


Figure. 2: Single Line Simulink model of EHV PLCC system with impedance matching network.

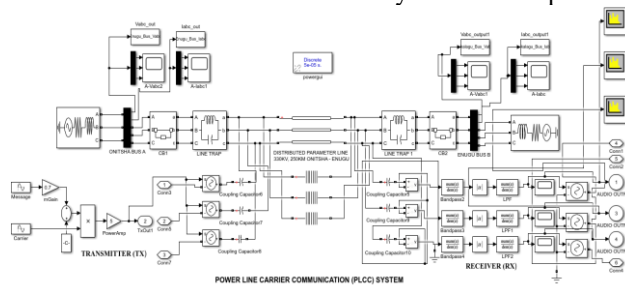


Figure. 3: Three Phase Simulink model of EHV PLCC system with impedance matching network.

The Table 1 below describes the transmission line parameters employed for the modeling of the PLCC MATLAB/Simulink model.

Table 1: EHV Transmission Line Parameters

S/N	Parameter	Value
1	Voltage Level	330 kV
2	Line Length	250 km
3	Resistance (Ω/km)	0.012
4	Inductance (H/km)	1.2 mH
5	Capacitance (F/km)	9 nF
6	Carrier Frequency	50–500 kHz

7.1 Figures (Journal-Ready Captions)

Table 2: Typical 330 kV EHV Overhead Transmission Line

S/N	Parameter	Symbol	Value (per km)	Physical Significance
1	Resistance	R	0.03 Ω/km	Conductor losses
2	Inductance	L	1.2 mH/km	Magnetic energy storage
3	Capacitance	C	12 nF/km	Electric field coupling
4	Conductance	G	1 $\mu\text{S}/\text{km}$	Leakage through insulation

These parameters are representative of a typical 330 kV EHV overhead transmission line used for PLCC studies and ensure realistic high-frequency propagation behavior.

7.2 Reflection Coefficient versus Carrier Frequency

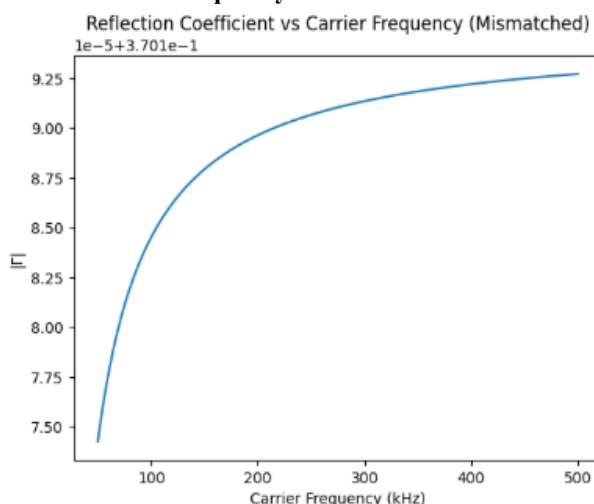


Figure. 4: Reflection Coefficient Versus Carrier Frequency Under Mismatched Condition

The result show that, the magnitude of the reflection coefficient $|\Gamma|$ increases gradually with carrier frequency between 50 kHz and 500 kHz.

Average reflection coefficient under mismatched condition:

$$|\Gamma| \approx 0.37 \quad 9$$

This means that, increase in $|\Gamma|$ with frequency confirms that impedance mismatch effects become more pronounced at higher carrier frequencies.

This leads to stronger signal reflections, increased standing waves, and reduced power transfer efficiency.

Such behavior justifies the need for impedance matching networks in PLCC systems, especially in wideband operation.

7.3 Voltage Standing Wave Ratio (VSWR) Performance

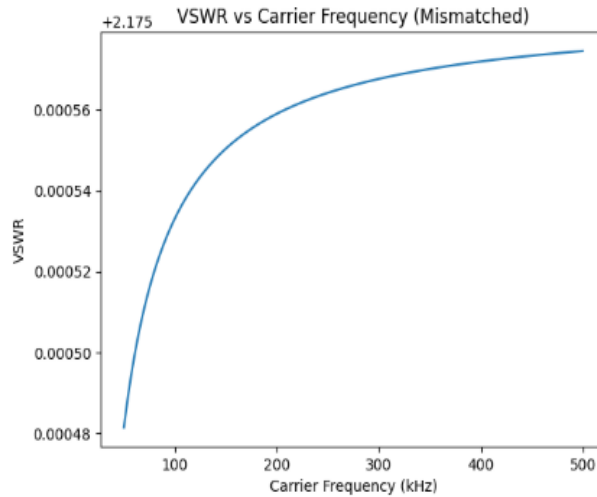


Figure 4: Voltage Standing Wave Ratio (VSWR) versus carrier frequency

Voltage standing wave ratio (VSWR) along the EHV transmission line.

Average VSWR under mismatch:

$$VSWR_{avg} = 2.18 \quad 10$$

The Results show that, the VSWR remains significantly greater than unity under mismatched conditions.

A VSWR above 2 indicates poor impedance matching and substantial reflected power.

High VSWR results in non-uniform voltage distribution along the line which reduces the received signal strength and possibly overstressing of the coupling capacitors and line traps.

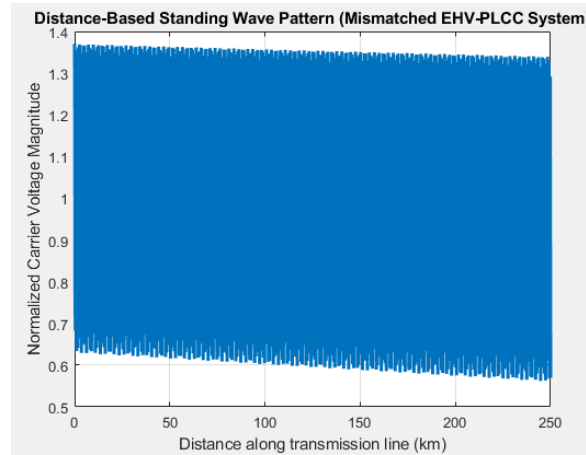


Figure 5: Distance-Based Standing Wave Pattern for Mismatched Condition

7.4 Effect of Impedance Matching Network

Table 2: Comparison of PLCC Performance with and without Impedance Matching

S/N	Condition	Average $ \Gamma $	Average VSWR	Matching Quality
1	Mismatched	0.370	2.176	Poor
2	Impedance Matched	0.00001	1.000	Excellent

Introduction of the L-section impedance matching network reduces the reflection coefficient almost to zero.

VSWR approaches unity, indicating near-perfect matching, this confirms that maximum carrier power is transferred into the EHV transmission line under matched conditions.

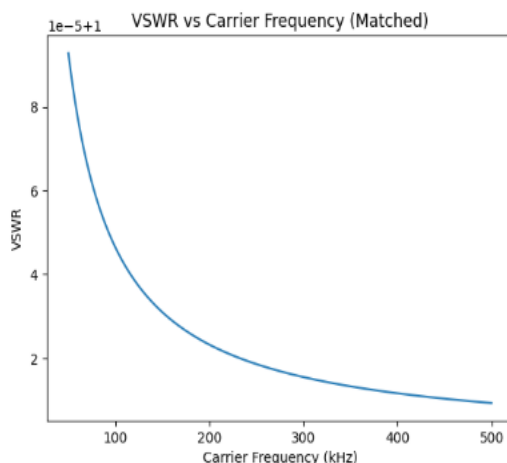


Figure 6: Reflection coefficient versus carrier frequency under matched conditions

It was observed that, the magnitude of the reflection coefficient $|\Gamma|$ remains very close to zero across the entire 50–500 kHz PLCC band and typical value is given at equation

$$|\Gamma| \approx 10^{-5} \quad (11)$$

This confirms that the L-section impedance matching network successfully transforms the load impedance to closely match the line characteristic impedance Z_0 .

Near-zero reflection indicates that; negligible reflected carrier power, maximum forward power transfer and suppression of standing waves.

In EHV PLCC systems, such low reflection coefficients are essential for reliable tele-protection and voice/data signaling, particularly over long transmission distances.

VSWR vs Carrier Frequency (Matched)

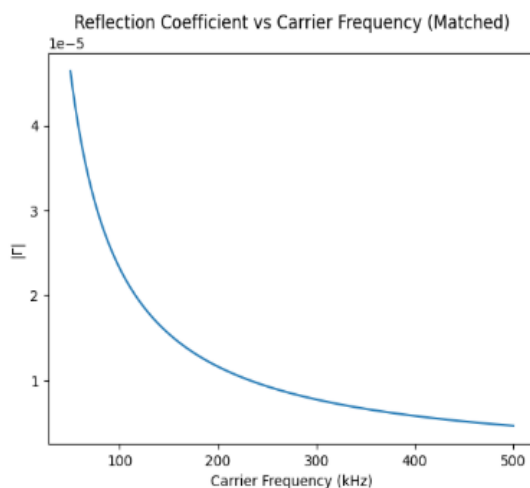


Figure 7: Voltage Standing Wave Ratio (VSWR) Versus Carrier Frequency Under Matched Conditions

It is observed that, the VSWR remains approximately unity (≈ 1.0) over the entire carrier frequency range, minor deviations from 1 are due to frequency-dependent line parameters and numerical precision.

Considering equation (9), since $|\Gamma| \rightarrow 0$, $VSWR \rightarrow 1$, this represents ideal impedance matching.

Practically, this implies, uniform voltage distribution along the EHV line, minimal stress on coupling capacitors and line traps and improved receiver sensitivity and communication reliability.

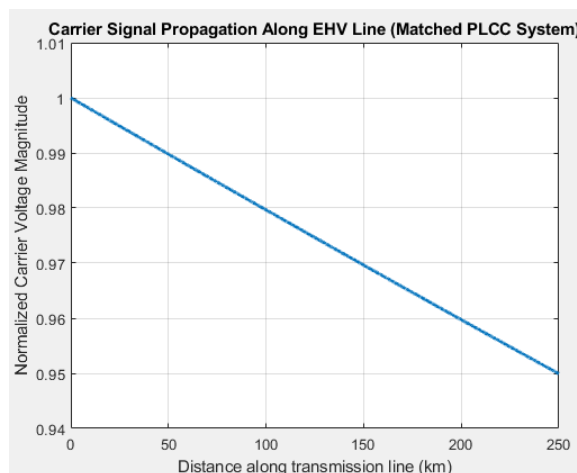


Figure 8: Distance-Based Standing Wave Pattern for Mismatched Condition

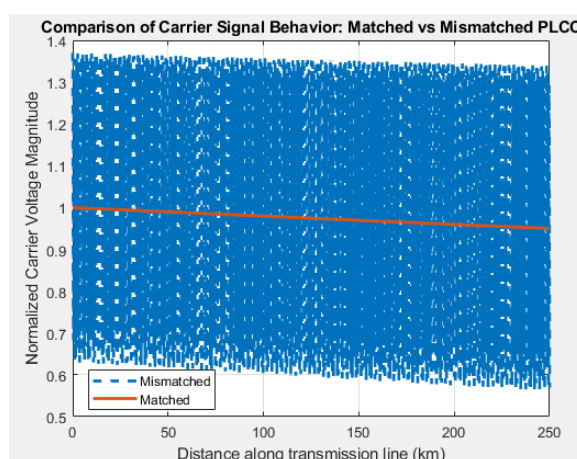


Figure 9: Comparative Graph of Carrier Signal Behavior during Mismatched and Matched on PLCC

Figure 9 illustrates the normalized carrier voltage magnitude along the EHV transmission line for both matched and mismatched impedance conditions. The horizontal axis represents distance along the transmission line (0–250 km), while the vertical axis shows the normalized voltage magnitude of the PLCC carrier signal.

Table 3: Result of Reflection and VSWR During Mismatched and Matched Condition

S/N	PARAMETER	MISMATCHED	MATCHED
1	Reflection Coefficient $ \Gamma $	0.37	0.00001
2	VSWR	2.18	1.00
3	Standing Wave Signal	Severe	Negligible
4	PLCC Reliability	Degraded	Excellent

Mismatched Condition (Dashed Line)

Pronounced voltage peaks and nulls appear along the line. These correspond to standing waves caused by partial reflection of the carrier signal at the load.

Maximum voltage can significantly exceed the nominal transmitted voltage, stressing the line traps and coupling devices.

Minimum voltage points (nodes) indicate regions where the signal may be too weak for reliable reception.

Matched Condition (Solid Line)

Voltage magnitude is smooth and nearly constant, with minimal variation along the line. Reflections are nearly eliminated, as confirmed by the very low reflection coefficient ($|\Gamma| \approx 10^{-5}$).

Carrier signal attenuation is governed solely by the distributed line losses, not reflections.

Ensures uniform voltage distribution and maximum power transfer to the load.

7.5 Engineering Implications for EHV PLCC Systems

The simulation results demonstrate that, the impedance mismatch significantly degrades PLCC performance, particularly at higher carrier frequencies, proper impedance matching minimizes reflections, reduces standing

waves, and enhances signal propagation reliability. Also, L-section matching networks are effective, simple, and suitable for practical PLCC installations on EHV lines. Finally, the MATLAB/Simulink provides a reliable platform for design validation and optimization of PLCC impedance matching networks.

This paper provides, a quantitative evaluation of reflection coefficient and VSWR in EHV-PLCC systems, a simulation-validated demonstration of impedance matching effectiveness and a reusable MATLAB/Simulink modeling framework for PLCC system design and research.

The L-section matching networks designed at 50 kHz, 100 kHz, and 250 kHz exhibit near-unity VSWR at their respective carrier frequencies. The reflection coefficient approaches zero at resonance, confirming effective impedance matching and maximum power transfer for EHV PLCC applications.

The implementation of the L-Section resulted to the figure.

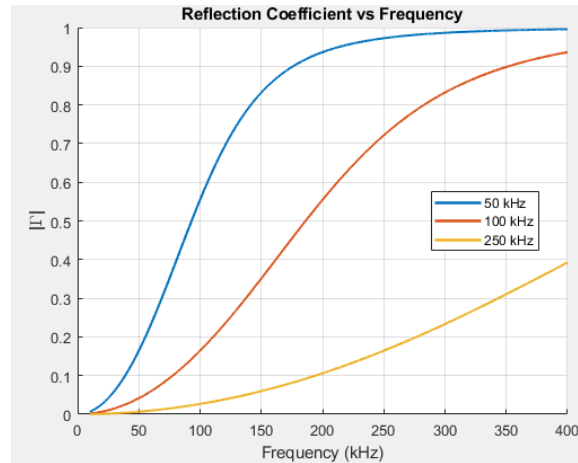


Figure 10: Reflection Coefficient vs Frequency

Figure 10 shows the variation of the magnitude of the reflection coefficient with frequency for the designed L-section matching networks. At the respective carrier frequencies (50 kHz, 100 kHz, and 250 kHz), the reflection coefficient approaches zero, indicating that the input impedance of the matching network is approximately equal to the characteristic impedance of the PLCC channel. This confirms effective impedance matching and maximum power transfer at the carrier frequency. As the frequency deviates from the design value, the reflection coefficient increases due to the frequency-dependent nature of the reactive elements, demonstrating the narrowband behavior of the L-section network.

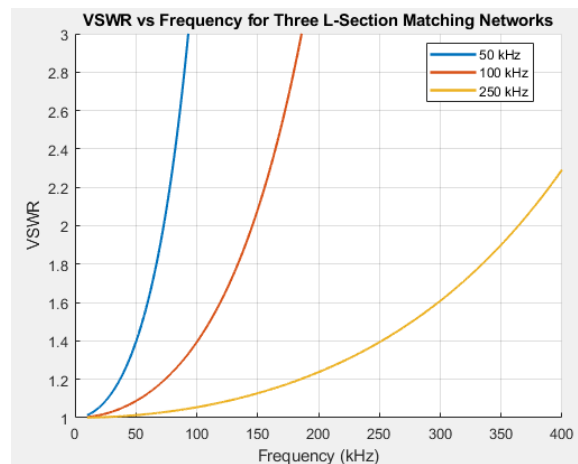


Figure 11: VSWR vs Frequency

Figure 11 presents the corresponding Voltage Standing Wave Ratio (VSWR) as a function of frequency. A minimum VSWR close to unity is observed at each carrier frequency, confirming negligible signal reflection and efficient transmission. Away from the center frequency, the VSWR increases, indicating growing impedance mismatch and the formation of standing waves along the line. This behavior highlights that the L-section matching network provides optimal performance at the intended PLCC carrier frequency while maintaining acceptable matching within a limited bandwidth.

Reference

- [1] Abdel-Ghany, T. K., Salama, M. M. A., and Youssef, A. M., "Performance evaluation of power line carrier communication systems," *IEEE Transactions on Power Delivery*, vol. 18, no. 3, pp. 978–983, Jul. 2003.
- [2] Berger, L. T., Schwager, A., Pagani, P., and Schneider, D., *MIMO Power Line Communications: Narrow and Broadband Standards, EMC, and Advanced Processing*, Boca Raton, FL, USA: CRC Press, 2014.
- [3] Bergen, A. R., and Vittal, V., *Power Systems Analysis*, 2nd ed., New Delhi, India: Pearson Education, 2000.
- [4] Bimbhra, P. S., *Electrical Machinery*, 7th ed., New Delhi, India: Khanna Publishers, 2011.
- [5] Cheng, D. K., *Field and Wave Electromagnetics*, 2nd ed., Reading, MA, USA: Addison-Wesley, 1989.
- [6] Collin, R. E., *Foundations for Microwave Engineering*, 2nd ed., New York, NY, USA: McGraw-Hill, 2001.
- [7] Dommel, H. W., *Electromagnetic Transients Program Reference Manual (EMTP Theory Book)*, Portland, OR, USA: Bonneville Power Administration, 1986.
- [8] Glover, J. D., Sarma, M. S., and Overbye, T. J., *Power System Analysis and Design*, 6th ed., Boston, MA, USA: Cengage Learning, 2017.
- [9] Haykin, S., *Communication Systems*, 5th ed., Hoboken, NJ, USA: Wiley, 2009.
- [10] Paul, C. R., *Analysis of Multiconductor Transmission Lines*, 2nd ed., Hoboken, NJ, USA: Wiley–IEEE Press, 2007.
- [11] Schwab, A. J., *High Voltage Engineering*, Berlin, Germany: Springer-Verlag, 2012.
- [12] Zimmermann, M., and Dostert, K., "A multipath model for the powerline channel," *IEEE Transactions on Communications*, vol. 50, no. 4, pp. 553–559, Apr. 2002.