A Detailed Framework for Modeling Three-Phase Power System Components in Phase Coordinates at Harmonic Frequencies

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ABSTRACT

This paper presents a comprehensive framework for modeling three-phase power system components in phase coordinates under harmonic frequency conditions. The increasing presence of nonlinear loads and harmonic components in power systems necessitates accurate modeling of system elements. Within this framework, transformers, transmission lines, series-parallel components, as well as passive loads, are modeled in detail with respect to harmonic frequencies. Transformer models incorporate considerations such as connection groups, phase shifts, and leakage reactance's, while nonlinear effects like core saturation are not included. Transmission lines are represented by harmonic impedance and shunt admittance matrices, accommodating both symmetrical and asymmetrical configurations. Additionally, series and parallel elements and passive loads are modeled using frequency-dependent matrix formulations. The proposed modeling approach provides a robust foundation for harmonic load flow analysis and power quality simulations, contributing both theoretical rigor and practical applicability.

Keywords: Three-phase system modeling, phase coordinates, harmonic frequency, transformer modeling, transmission line modeling, passive loads, series-parallel elements

INTRODUCTION

In contemporary power systems, the increasing presence of nonlinear loads has significantly amplified the impact of harmonic distortions on power quality. Nonlinear loads cause the emergence of undesirable frequency components in electrical systems, which can lead to overheating in devices, reduced efficiency, and malfunctions in protection systems. Therefore, accurate modeling and analysis of harmonics is a critical requirement for effective system design and operation (Htita, 2024; Tweve, 2025; Peerzada 2024). Today's electric power systems are becoming increasingly complex due to growing demand, the integration of renewable energy sources, and evolving technologies (Rustemli, 2023). As a result of this complexity, power quality issues have gained substantial attention. Harmonics have emerged as a key factor directly affecting the reliability and efficiency of power systems (Michalec, 2021). Harmonics refer to multiple frequency components that differ from the fundamental frequency and are typically generated by nonlinear loads. These components increase energy losses, cause overheating, vibrations, and mechanical stress in transmission lines and equipment, and may lead to false operations in protection systems (Karakaya, 2023; Wakileh, 2001).

Three-phase long transmission lines play a fundamental role in delivering energy across vast geographical areas. However, the asymmetry of phase structures, the physical arrangement of conductors, and their geometric

configurations relative to one another cause harmonic propagation to occur in a complex manner (Becker, 2024). Moreover, various reactive components used in transmission lines (such as shunt capacitors, reactors, and series-connected capacitors), along with passive loads, significantly influence system behavior at harmonic frequencies (Satish, 2021). To ensure accurate harmonic analysis, it is essential to represent line impedances, admittances, and parallel-series elements using harmonic-sensitive models. In this context, calculations based on phase coordinates were employed to construct impedance and admittance matrices, considering parameters such as the geometric mean radius of conductors, inter-conductor distances, and soil resistivity (Sezgin, 2015). Referring to the works of researchers such as Anderson, Makram, and Girgis, the impedance and admittance matrices were detailed as a function of harmonic order. Additionally, matrix size reduction was achieved using the Kron reduction method, facilitating analytical solutions for the system.

Shunt/parallel elements are widely used in power systems for reactive power compensation. Accurate modeling of their behavior at harmonic frequencies is critical for the development of harmonic load flow analyses and reactive power control strategies (Akdogan, 2020). The admittance matrices of shunt reactors and capacitors were defined based on harmonic components, and their effects on the system were examined in detail. Similarly, the modeling of series-connected capacitors is important for evaluating their impact on transmission lines (Ahmed, 2016). Passive loads play a substantial role in power systems, facilitating a more precise analysis of system behavior in harmonic load flow studies when modeled with precision (Xiao, 2016). Of the several passive load models accepted in the literature, Model B is particularly favored due to its broad scope and practical applicability with respect to harmonic frequency dependencies. Model B allows one to determine harmonic impedances based on active and reactive power values measured at the fundamental frequency.

This study presents a comprehensive modeling approach for the harmonic analysis of both asymmetric and symmetric three-phase long transmission lines. The methodology systematically examines the calculation of impedance and admittance matrices in phase coordinates, the modeling of shunt and series reactive elements at harmonic frequencies, and the determination of passive load impedance dependencies on harmonics. This comprehensive modeling approach aims to enable accurate analysis of the effects of harmonics in power systems, thereby enhancing system reliability and power quality. In modern electric power systems, the increasing integration of renewable energy sources, the widespread use of power electronics devices, and the proliferation of nonlinear loads have significantly heightened the importance of harmonic issues. Harmonic components adversely affect system reliability and power quality, leading to energy losses, equipment damage, and malfunctions in protection systems. Therefore, for accurate and effective harmonic analysis in three-phase power systems, it is crucial to represent system components with detailed and frequency-dependent models at harmonic frequencies. In the current literature, harmonic modeling primarily focuses on the fundamental frequency or selected harmonics, while the complex behavior of transmission lines, reactive elements, and passive loads at harmonic frequencies remains inadequately explored. Additionally, the necessity of addressing both asymmetric and symmetric systems in phase coordinates with respect to harmonic effects is often overlooked. These limitations restrict the accuracy and scope of harmonic analyses. This study aims to present a theoretical and comprehensive modeling framework of grid components for more accurate harmonic analysis. The developed models will serve as a solid foundation for future studies involving harmonic power flow calculations, power quality assessments, and resonance analyses. Also, this study proposes a theoretically robust modeling framework that lays the groundwork for practical applications in the harmonic modeling of power systems. Future work will build upon this framework to perform experimental validation and detailed harmonic analyses.

The main contributions of the study are as follows:

- Development of detailed impedance and admittance matrices for synchronous generator, transformer, and transmission lines at harmonic frequencies in phase coordinates for three-phase power systems,
- Frequency-dependent modeling of reactive elements connected in series or parallel according to harmonic frequencies,
- Realistic representation of passive loads' harmonic impedances using different load models,

- Enhancement of computational efficiency in harmonic modeling through the application of matrix reduction techniques such as the Kron method,
- Establishment of a robust theoretical modeling framework to support future applied analyses and simulations.

HARMONIC MODELLING IN THREE-PHASE POWER SYSTEMS

Today, the complexity of electrical power systems, the increasing integration of renewable energy sources and the widespread use of power electronic devices have made it necessary to analyze harmonic components. Harmonics are non-sinusoidal currents and voltages occurring at frequencies that are exact multiples of the fundamental frequency. The effects of these components in the system lead to overheating of equipment, increased energy losses, false detection of protection systems and deterioration of power quality (Akbari, 2019). Therefore, accurate modeling of harmonic components on a component-by-component basis is critical for improving system safety and performance (Htita, 2024). In this part, the modeling of harmonics in phase coordinates in three-phase power systems, the behavior of transmission lines, parallel and series connected elements at harmonic frequencies and the harmonic frequency dependent characteristics of passive loads will be discussed in detail.

Synchronous Generator Modeling

A detailed synchronous generator model developed for load flow analysis in three-phase unbalanced systems is introduced. Unlike conventional models, the generator internal and end busbars are defined separately, and the generator impedance is expressed in phase coordinates. The model allows the calculation of impedance and admittance matrices for both fundamental and harmonic components in phase coordinates as given Equation 1. Thus, unbalanced loading and harmonic effects can be analyzed more accurately. Phase-coordinate modeling of a synchronous generator for the h-th harmonic component is illustrated in Figure 1.

$$\left.\begin{aligned} Z_{g0}^{(h)} &= {R_{g0}}^{(h)} + jhX_{g0}^{(1)} \\ Z_{g1}^{(h)} &= {R_{g1}}^{(h)} + jhX_{g1}^{(1)} \\ Z_{g2}^{(h)} &= {R_{g2}}^{(h)} + jhX_{g2}^{(1)} \end{aligned}\right\} \Longrightarrow [Z_g]_{abc}^{(h)} = \begin{bmatrix} Z_{g_{aa}}^{(h)} & Z_{g_{ab}}^{(h)} & Z_{g_{ac}}^{(h)} \\ Z_{g_{ba}}^{(h)} & Z_{g_{bb}}^{(h)} & Z_{g_{bc}}^{(h)} \\ Z_{g_{ca}}^{(h)} & Z_{g_{cb}}^{(h)} & Z_{g_{cc}}^{(h)} \end{bmatrix} \tag{1}$$

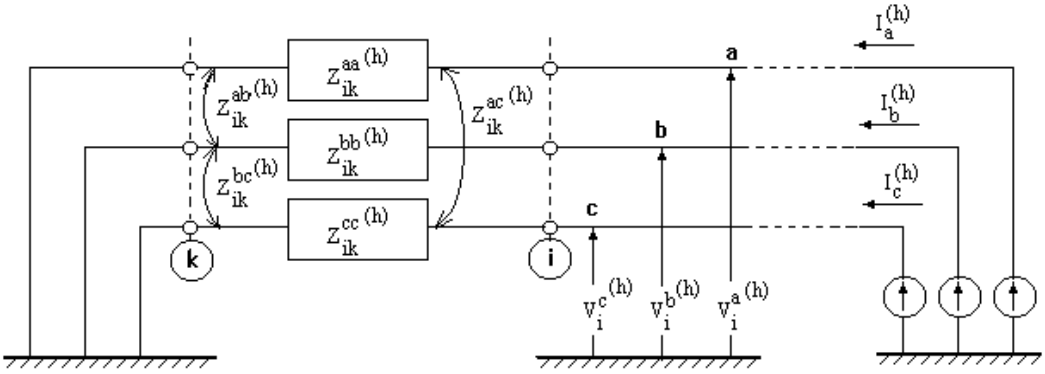


Figure 1. Phase-coordinate modeling of a synchronous generator for the h-th harmonic component

Transmission line modeling

Transmission lines are critical components in power systems, enabling the delivery of energy from generation sources to load points. At harmonic frequencies, the impedance of transmission lines deviates from that at the fundamental frequency. Due to their electrical properties and geometrical configurations, each phase of a transmission line exhibits its own self-impedance (Z_{ii}) and mutual impedance between phases (Z_{ij}), both of which vary with frequency. This frequency dependence governs the propagation of harmonics and inter-phase interactions. The impedance matrix at harmonic frequency can be expressed in Equation 2.

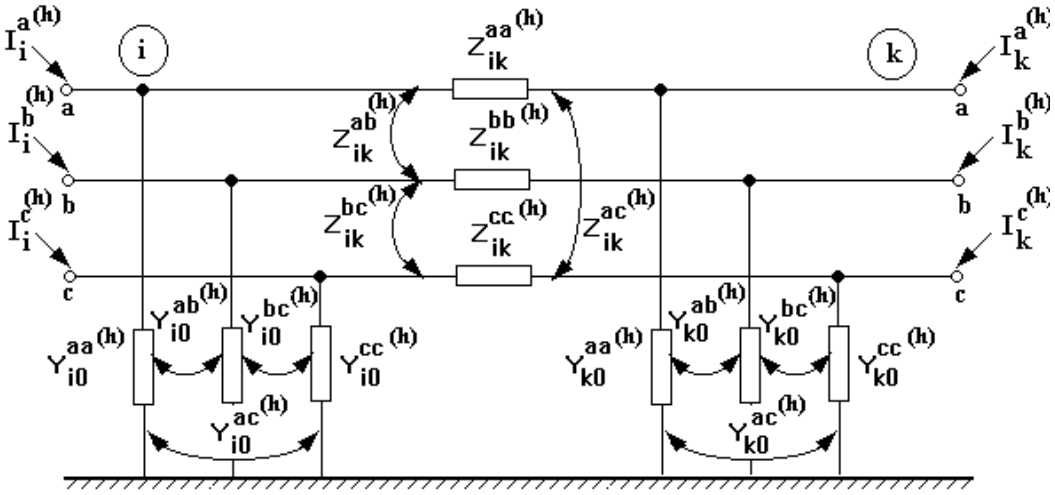


Figure 2. Lumped parameter π-equivalent model of a three-phase transmission line at the h-th harmonic

$$Z_{abc}(h) = R_{abc} + j\omega h L_{abc} \tag{2}$$

where R_{abc} denotes the resistance of the conductors, L_{abc} represents the inductance, and $\omega_h = 2\pi h f_1$ is the angular frequency of the hth harmonic. At higher harmonic frequencies, phenomena such as skin effect leads to increased resistance, while inductance becomes frequency dependent. Additionally, the physical arrangement and phase spacing of transmission lines significantly influence the magnitude of mutual impedances. These coupling impedances affect how harmonic components interact across phases and can contribute to the emergence of resonance conditions. The lump parameter-equivalent model of a three-phase transmission line at the h-th harmonic is depicted in Figure 2.

Modeling ground return currents and ground impedances is also critical for harmonic analysis. Zero-sequence components behave differently depending on soil conductivity and grounding system characteristics. Therefore, decomposing the impedance matrices into zero, positive, and negative sequence components (using the symmetrical component method given in Equation 3) allows for more accurate harmonic analysis (Cen, 2018). To make these complex impedance matrices more computationally tractable, mathematical techniques such as the Kron reduction method are applied. This facilitates harmonic analysis in large-scale systems and enables the identification of potential resonance conditions in advance (Akbari, 2019). This approach not only enhances the understanding of harmonic propagation but also contributes to the optimization of filter design and the prevention of overcurrent and voltage fluctuations within the system (Yumurtacı, 2000).

$$\left.\begin{aligned} Z_{h0}^{(1)} &= R_{h0}^{(1)} + jX_{h0}^{(1)} \\ Z_{h1}^{(1)} &= R_{h1}^{(1)} + jX_{h1}^{(1)} \\ Z_{h2}^{(1)} &= R_{h2}^{(1)} + jX_{h2}^{(1)} \end{aligned}\right\} \Rightarrow \begin{aligned} Z_{h0}^{(h)} &= R_{ho}^{(h)} + jhX_{h0}^{(1)} \\ Z_{h1}^{(h)} &= R_{h1}^{(h)} + jhX_{h1}^{(1)} \\ Z_{h2}^{(h)} &= R_{h2}^{(h)} + jhX_{h2}^{(1)} \end{aligned} \tag{3}$$

The zero sequence impedance, positive sequence impedance and negative sequence impedance for the fundamental frequency, the real and imaginary components $R_{h0}^{(h)}, R_{h1}^{(h)}$ ve $R_{h2}^{(h)}$ are the symmetrical component resistances of the line, where the skin effect at the hth harmonic frequency is considered.

The impedance matrix of the three-phase line consisting of phase conductors (a, b, c) and the protection conductor at earth potential (g) at the hth harmonic frequency is the impedance matrix of the line given in Equation 4 obtained when the fourth node is removed using the Kron method

$$[Z]_{abcg}^{(h)} = \begin{bmatrix} Z_{aa}^{(h)} & Z_{ab}^{(h)} & Z_{ac}^{(h)} & Z_{ag}^{(h)} \\ Z_{ba}^{(h)} & Z_{bb}^{(h)} & Z_{bc}^{(h)} & Z_{bg}^{(h)} \\ Z_{ca}^{(h)} & Z_{cb}^{(h)} & Z_{cc}^{(h)} & Z_{cg}^{(h)} \\ Z_{ga}^{(h)} & Z_{gb}^{(h)} & Z_{gc}^{(h)} & Z_{gg}^{(h)} \end{bmatrix} \Rightarrow [Z]_{abc}^{(h)} = \begin{bmatrix} Z_{aa}^{(h)} & Z_{ab}^{(h)} & Z_{ac}^{(h)} \\ Z_{ba}^{(h)} & Z_{bb}^{(h)} & Z_{bc}^{(h)} \\ Z_{ca}^{(h)} & Z_{cb}^{(h)} & Z_{cc}^{(h)} \end{bmatrix} \quad (4)$$

The capacitive effects of transmission lines become particularly significant at high frequencies and appear as shunt elements in the system's overall admittance matrix. Line capacitances depend on the positions of the conductors relative to each other and to the grounding system. As frequency increases, the capacitive admittance increases linearly, directly influencing the propagation of harmonic components along the transmission line. The shunt admittance matrix is expressed in Equation 5.

$$Y_{\text{shunt}}(h) = j\omega_h C_{abc} \quad (5)$$

where C_{abc} represents the capacitance matrix between conductors, and $\omega_h = 2\pi h f_1$ denotes the angular frequency of the hh-th harmonic component. The effect of ground capacitances becomes particularly important in zero-sequence harmonic components, as it can either hinder or facilitate their propagation. Therefore, accurate modeling of capacitances is essential for identifying resonance points and preventing undesirable harmonics in the system. Calculating shunt admittances at harmonic frequencies provides valuable insights for filter design, resonance prediction, and maintaining power quality. Neglecting capacitive effects can adversely affect system stability at higher harmonics (Akbari, 2019).

Modeling Parallel and Series Elements

The behavior of parallel and series connected reactors and capacitors used for reactive power control and compensation in power systems at harmonic frequencies determines the overall harmonic response of the system. Modeling the impedance or admittance of these elements with respect to harmonic frequencies plays a critical role in preventing the occurrence of harmonic resonances and voltage fluctuations (Giudice, 2022). The admittance of parallel-connected capacitors depends linearly on frequency as expressed in Equation 6.

$$Y_C(h) = j\omega_h C = j2\pi h f_1 C \quad (6)$$

where C is the capacitance value, and h is the harmonic order. As the frequency increases, the shunt admittance of the capacitors increases, and this causes the higher harmonics to dominate over the capacitors. This can lead to resonance at some harmonic frequencies. The admittance of parallel connected reactors is inversely proportional to frequency as seen in Equation 7. Therefore, the effect of parallel reactors decreases as the frequency increases. As shown in Figure 3, the parallel element is represented using an appropriate modeling approach.

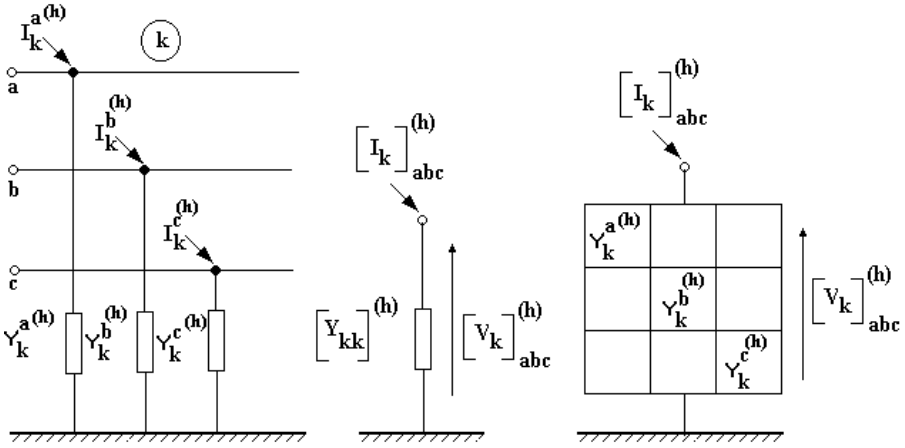


Figure 3. Modeling of a parallel element

$$Y_L(h) = \frac{1}{j\omega_h L} = \frac{1}{j2\pi h f_1 L} \tag{7}$$

This change directly affects the selection and design of reactors in harmonic filters. Series connected capacitors are used in reactive power control of power transmission lines and their admittance matrix has a diagonal structure since they are connected phase-wise. The admittance matrices for the h-th harmonic of the parallel reactors and capacitors can be calculated using Equations 8 and 9, respectively.

$$[Y_{sh}]_{abc}^{(h)} = -j\frac{1}{h}\begin{bmatrix} 1/X_k^{a(1)} & 0 & 0 \\ 0 & 1/X_k^{b(1)} & 0 \\ 0 & 0 & 1/X_k^{c(1)} \end{bmatrix} \tag{8}$$

$$[Y_{sh}]_{abc}^{(h)} = jh\begin{bmatrix} 1/X_k^{a(1)} & 0 & 0 \\ 0 & 1/X_k^{b(1)} & 0 \\ 0 & 0 & 1/X_k^{c(1)} \end{bmatrix} \tag{9}$$

The impedance changes of series capacitors at harmonics affect the total impedance of the transmission line and can especially displace resonant frequencies. Failure to correctly model these elements with respect to harmonic frequencies can lead to the unexpected appearance of resonances and excessive voltage fluctuations in the system. This can lead to equipment damage and system instability (Akbari, 2019). The phase-coordinate representation of a three-phase series element at the h-th harmonic is illustrated in Figure 4.

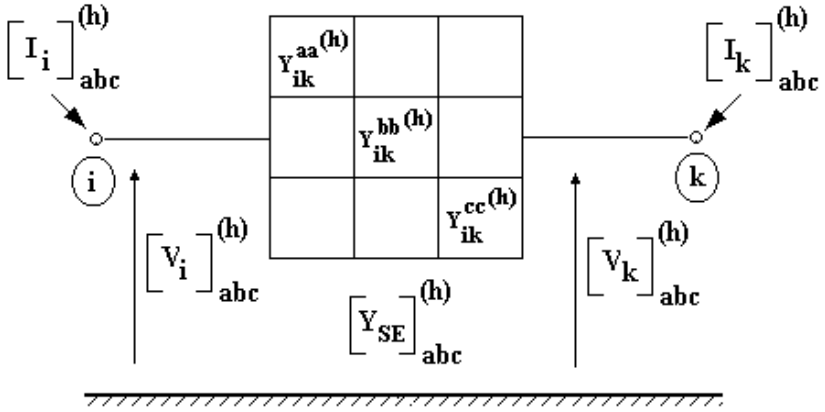


Figure 4. Phase-coordinate model of a three-phase series element for the h-th harmonic component

The admittance matrices for the h-th harmonic of the series capacitors can be calculated using Equation 10.

$$[Y_{SE}]_{abc}^{(h)} = jh.\begin{bmatrix} 1/X_{C_{ik}}^{aa(1)} & 0 & 0 \\ 0 & 1/X_{C_{ik}}^{bb(1)} & 0 \\ 0 & 0 & 1/X_{C_{ik}}^{cc(1)} \end{bmatrix} \tag{10}$$

Passive load models

The parameters required for modeling passive linear loads depend on their power draw. For harmonic load flow, passive loads must be modeled according to their respective harmonic frequencies. General representations of single-phase and three-phase passive balanced linear loads can be modelled with equivalent impedances for the nth harmonic component as given Figure 5. Table 1 shows the variations of resistance and inductive reactance of three different passive load models depending on the harmonic order. Figure 6 presents passive load models.

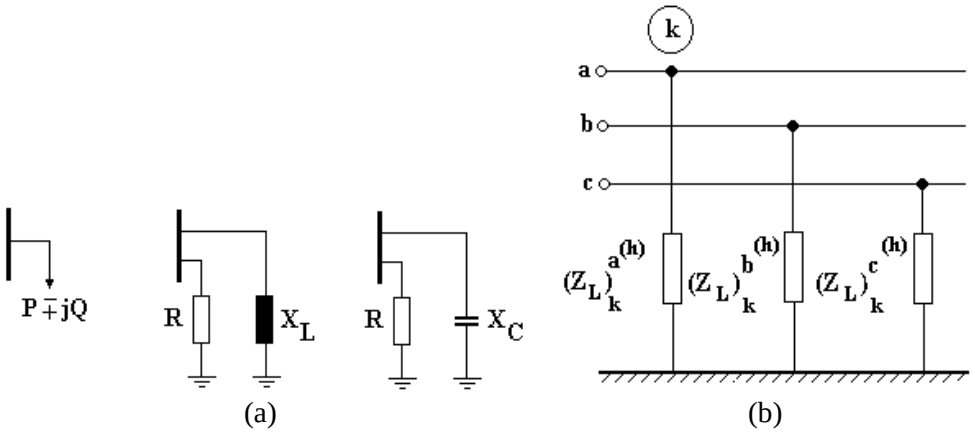


Figure 5. Modeling of Single-phase (a) and Three-phase (b) Balanced Linear Loads

The parameters P_{50} and Q_{50} indicate the active and reactive power values at the fundamental frequency (e.g., 50 Hz), V represents the voltage, and $^{(h)}$ stands for the harmonic order. These models are used to calculate the impedance behavior at harmonic frequencies based on the power values at the fundamental frequency (Yumurtacı, 2000).

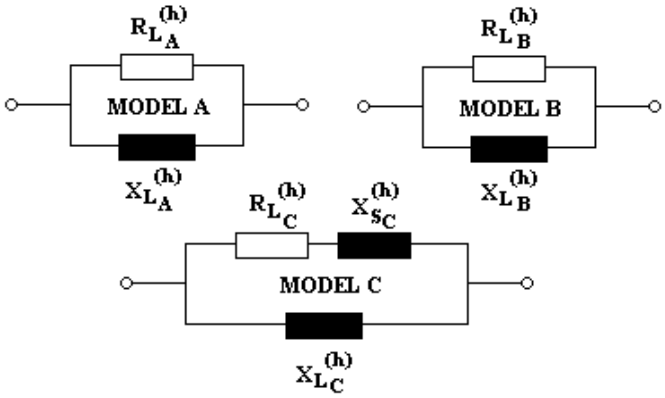


Figure 6. Passive load models

$R_{LA}^{(h)}, R_{LB}^{(h)}$, and $R_{LC}^{(h)}$ represent the resistance components at the harmonic frequency for Models A, B, and C, respectively, while $X_{LA}^{(h)}$, $X_{LB}^{(h)}$, $X_{LC}^{(h)}$, and $X_{SC}^{(h)}$ denote the inductive reactance components at harmonic frequencies for the corresponding models.

Table 1. Resistance and reactance relations in passive load models (Yumurtacı, 2000).

MODEL	Resistance (Ω)	Reactance (Ω)
A	$R_{LA}^{(h)} = \frac{V^2}{(0.1h + 0.9).P_{50}}$	$X_{LA}^{(h)} = \frac{V^2}{(0.1h + 0.9).Q_{50}}$
B	$R_{LB}^{(h)} = \frac{V^2}{P_{50}}$	$X_{LB}^{(h)} = h\frac{V^2}{Q_{50}}$
C	$R_{LC}^{(h)} = \frac{V^2}{P_{50}}$	$X_{LC}^{(h)} = h\frac{R_{LC}^{(h)}}{6.7\left(\frac{Q_{50}}{P_{50}}\right) - 0.74}$ $X_{SC}^{(h)} = 0.073hR_{LC}^{(h)}$

In Model A, both resistance and inductive reactance show a mild frequency dependence expressed by the term $(0.1\mathrm{h} + 0.9)(0.1\mathrm{h} + 0.9)$ related to the harmonic order; this implies a gradual decrease in impedance with increasing harmonic order. Model B assumes that the resistance component remains constant at the fundamental frequency, while the inductive reactance increases linearly with the harmonic order hh; this behavior is especially valid for loads where skin effect and frequency-dependent magnetic losses dominate. Model C presents a more complex and parametric dependence for resistance and inductive reactance. While resistance remains constant at the fundamental frequency, the inductive reactance $X_{LC}^{(h)}$ varies according to the harmonic order and power ratios, and $X_{SC}^{(h)}$ acts as an additional reactance component contributing to the load impedance. This model more realistically represents high-frequency losses and magnetic effects. These models provide a basis for accurate impedance estimation in harmonic analysis and help prevent harmonic resonance and power quality issues in power systems.

DISCUSSION

In this study, comprehensive theoretical models have been developed to enable a more realistic and detailed examination of behaviors at harmonic frequencies in three-phase power systems. Specifically, the construction of frequency-dependent impedance and admittance matrices in phase coordinates for transmission lines, the dynamic modeling of parallel and series connected reactive elements according to harmonic frequencies, and the realistic representation of passive loads using different load models aim to address significant deficiencies found in existing models in the literature. In most harmonic analysis studies in literature, frequency dependence is either neglected or only simplified models of certain components are used. As a result, accurately capturing harmonic behaviors, especially at high frequencies, becomes challenging, which negatively impacts the accuracy and reliability of the analyses. The comprehensive and frequency-dependent modeling approach proposed in this study overcomes these shortcomings, enabling more consistent and robust results in power system harmonic analyses. However, the scope of this study is limited to theoretical modeling only. The practical application of the proposed models, experimental validations, and testing model performance in real systems will be important topics for future research. In this context, factors such as parameter uncertainties, measurement errors, and changes in system dynamics encountered in practical applications need to be evaluated. Future studies are planned to include the implementation of this theoretical framework in simulation environments and real systems. Furthermore, research will focus on improving computational efficiency by employing matrix reduction techniques such as the Kron method, adapting the model to large-scale power systems, and enhancing modeling according to different load types and operating conditions. In conclusion, this study provides a strong theoretical foundation for harmonic analyses in power systems and offers a solid reference point for future applied and experimental work. This comprehensive approach, developed by considering the gaps in the existing harmonic modeling literature, will contribute to more effective and accurate analysis of harmonic problems in power systems.

CONCLUSION

In this paper, a comprehensive theoretical framework for modeling three-phase power system components in phase coordinates at harmonic frequencies has been presented. The proposed models account for the frequency-dependent behavior of transmission lines, series and parallel reactive elements, and passive loads, addressing important gaps in existing literature. By incorporating detailed impedance and admittance matrices and applying matrix reduction techniques such as Kron's method, the framework enhances the accuracy and computational efficiency of harmonic analysis in complex power systems. Although this study focuses on theoretical model development without experimental validation or simulation results, it lays a solid foundation for future practical applications. The proposed models can be effectively utilized in harmonic load flow studies, power quality assessments, and resonance analyses. Future work will include experimental verification and integration of these models into comprehensive simulation tools to evaluate their performance under real-world conditions. Overall,

this framework contributes to improving the reliability and quality of power systems by enabling more precise harmonic analysis and facilitating the design of better harmonic mitigation strategies.

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