# *Harmonic Analysis in Power Systems Using Circuit Models: Methods and Applications*

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**Abstract**

*Harmonics in power systems, generated by nonlinear loads and switching devices, can lead to equipment overheating, increased losses, voltage distortion, and resonance phenomena. Accurate modeling and analysis of harmonics are essential for system design, operation, and mitigation strategies. This paper explores the use of circuit models for harmonic analysis in electrical power systems, including modeling techniques, frequency-domain analysis, and mitigation approaches. The paper discusses the application of linearized network models, frequency-sweep simulations, and power quality indices. Tables and two-dimensional figures illustrate harmonic spectra, voltage distortion, and system impedance characteristics. The insights provided are intended for researchers, engineers, and students focused on power system analysis and design.*

**Keywords:** *Harmonics, power systems, circuit models, nonlinear loads, voltage distortion, harmonic mitigation*

 

## INTRODUCTION

The increasing use of nonlinear devices such as power electronic converters, variable speed drives, and UPS systems has introduced significant harmonic content into electrical power networks. Harmonics affect power quality, leading to additional losses, malfunctioning of sensitive equipment, and increased stress on system components. Circuit-based modeling provides a systematic approach to study harmonic propagation, interaction with system impedance, and resonance phenomena.

This paper presents techniques for harmonic analysis using equivalent circuit models, emphasizes frequency-domain methods, and explores mitigation strategies to maintain power system integrity.

## 2. Sources of Harmonics in Power Systems

Major sources of harmonics include:

- Nonlinear loads (rectifiers, variable frequency drives)
- Power electronic devices (inverters, converters)
- Saturable magnetic components (transformers, reactors)
- Arc furnaces and other industrial loads

## 3. Circuit Modeling for Harmonic Analysis

### 3.1 Linearized Network Models

A linearized circuit model represents each system component with its fundamental and harmonic impedance. This method simplifies the analysis of harmonic currents and voltages across the network.

### 3.2 Frequency-Domain Analysis

Circuit elements are represented by their frequency-dependent impedances:

$$Z(f) = R + j2\pi f L + \frac{1}{j2\pi f C}$$

where (f) represents harmonic frequencies.

## 4. Harmonic Impedance Modeling

### 4.1 Transmission Line and Transformer Modeling

Transformers and transmission lines are modeled with series RLC components for each harmonic order. This allows evaluation of voltage drops and resonant conditions.

***Table 1: Example Transformer Impedance at Fundamental and Harmonics***

| Harmonic Order | R (Ω) | L (mH) | C (μF) |
|---|---|---|---|
| 1 (Fundamental) | 0.5 | 1.2 | 0 |
| 3 | 0.6 | 1.0 | 0 |
| 5 | 0.7 | 0.8 | 0.01 |
| 7 | 0.9 | 0.7 | 0.01 |

## 5. Harmonic Spectrum Analysis

### 5.1 Voltage and Current Harmonics

Harmonics are quantified using Total Harmonic Distortion (THD):

$$\text{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \times 100\%$$

where ($V_n$) is the RMS voltage of the ($n$)th harmonic.

```
            Amplitude
                |
         |    | |      |
         | |  | |  |   |
   |__|___|__|__|___|____| Harmonic Order
          1   3  5   7
```

***Figure 1: Sample Voltage Harmonic Spectrum***

The figure represents voltage amplitude across fundamental and selected harmonic orders.

 

## 6. Simulation Techniques

### 6.1 Frequency-Sweep Analysis

By sweeping the frequency across expected harmonic orders, resonance conditions and voltage amplification can be detected.

### 6.2 Harmonic Load Flow

Harmonic load flow analysis incorporates nonlinear load models into standard power flow techniques to predict harmonic propagation.

## 7. Harmonic Mitigation Methods

- Passive filters (LC, LCL) tuned to dominant harmonics
- Active filters using PWM converters
- Phase-shifting transformers to cancel specific harmonic orders
- Proper system design to avoid resonance conditions

*Table 2: Typical Harmonic Mitigation Approaches*

| Technique | Target Harmonics | Advantages | Limitations |
|---|---|---|---|
| Passive LC Filter | 5th, 7th | Simple, reliable | Fixed frequency, size |
| Active Filter | All orders | Adaptive, precise | Expensive, complex |
| Phase-Shifting Transformer | 3rd, 9th | Reduces specific harmonics | Limited scope |

## 8. Two-Dimensional Illustrations

Without Filter: ~~~/\~~~/\~~~/\~~~
With Filter: ~~/\~~/\/\~~/\

**Figure 2: Voltage Distortion Before and After Filtering**

The figure demonstrates reduction in voltage waveform distortion using filtering.

Nonlinear Load → Transformer → Bus → Filter → Grid
Illustrates current flow and harmonic filtering path.
***Figure 3: Harmonic Current Flow in Network***

## 9. Challenges in Harmonic Analysis

- Modeling highly nonlinear and time-varying loads
- Interaction between multiple harmonic sources
- Resonance amplification
- Computational complexity for large-scale systems

## 10. Applications

Harmonic analysis using circuit models is essential for:

- Industrial power distribution networks
- Renewable energy integration (inverters and PV systems)
- Power quality compliance with standards (IEEE 519, IEC 61000)
- Design of harmonic mitigation devices

## CONCLUSION

Circuit-based harmonic analysis provides an effective approach for understanding and mitigating harmonics in electrical power systems. By combining linearized models, frequency-domain analysis, and load flow simulations, engineers can predict harmonic behavior, assess system vulnerabilities, and design appropriate mitigation strategies. As power systems integrate more nonlinear and renewable energy sources, accurate harmonic analysis remains essential for reliability, efficiency, and power quality.

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