V International Scientific and Technical Conference Actual Issues of Power Supply Systems

Mechanisms of Power Quality Degradation Caused by Nonlinear Loads at the Point of Common Coupling

AIPCP25-CF-ICAIPSS2025-00530 | Article

Mechanisms of Power Quality Degradation Caused by Nonlinear Loads at the Point of Common Coupling

Sultonkhoja Mahmutkhonov [1,4, a)], Makhfuza Radjabova [1], Shoxrux Rubidinov [2], Timur Sodiqov [3]

[1] *Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan*
[2] *Fergana state technical university, Fergana, Uzbekistan*
[3] *Namangan State Technical University, Namangan, Uzbekistan*
[4] *Termez State University of Engineering and Agrotechnology, Termez, Uzbekistan*

[a)] *Corresponding author: mahmutkhonov.sultonkhoja.93@gmail.com*

Abstract. Power quality degradation has become a critical issue in modern power systems due to the widespread integration of nonlinear loads such as electric arc furnaces, power electronic converters, and variable-speed drives. These loads generate non-sinusoidal currents that interact with network impedance, leading to voltage distortion at the point of common coupling (PCC) and adversely affecting connected consumers[1-3]. This paper investigates the fundamental mechanisms of power quality degradation caused by nonlinear loads, with a primary focus on conductive impact at the PCC. A simplified analytical model is developed to describe the formation of non-sinusoidal voltage resulting from harmonic current injection and network impedance characteristics. The relationship between current distortion, short-circuit power at the PCC, and voltage quality deterioration is analytically demonstrated. In addition, key electrical and non-electrical factors influencing power quality are classified and analyzed, including network topology, load characteristics, operating conditions, and time-dependent effects. The proposed approach provides a systematic framework for understanding voltage distortion mechanisms in distribution networks with nonlinear consumers. The obtained results contribute to improved assessment of power quality issues and support the development of effective mitigation and compensation strategies in industrial power systems[1-6].

INTRODUCTION

The rapid development of industrial technologies and the extensive application of power electronic equipment have significantly increased the share of nonlinear loads in modern power systems. Industrial consumers such as electric arc furnaces, rolling mills, rectifiers, variable-speed drives, and uninterruptible power supply systems draw highly distorted currents from the grid, thereby causing substantial deviations in voltage and current waveforms. As a result, power quality degradation has emerged as one of the most critical challenges in distribution and industrial power networks.

Power quality disturbances primarily originate at the point of common coupling (PCC), where multiple consumers are connected to the supply network. Even the connection of a single nonlinear load to the PCC can lead to harmonic current injection, which interacts with the equivalent network impedance and produces non-sinusoidal voltage drops. These voltage distortions propagate through the network and adversely affect other connected consumers, including linear loads, sensitive equipment, and control systems. This phenomenon is commonly referred to as conductive impact and represents a fundamental mechanism of power quality degradation in power systems with nonlinear consumers [6-7].

The severity of voltage distortion at the PCC depends on both the characteristics of the nonlinear load and the electrical parameters of the supply network. In particular, the magnitude and spectral composition of harmonic currents, the equivalent impedance of the network, and the short-circuit power at the PCC play a decisive role in determining voltage quality. Therefore, power quality should be considered as an integrated indicator combining current quality, voltage waveform integrity, and system impedance properties.

In addition to electrical parameters, power quality is influenced by a wide range of non-electrical factors, including operating regimes, load variability, environmental conditions, and time-dependent effects. Short-term, medium-term, and long-term variations in load behavior can significantly affect the manifestation of harmonics, flicker, and voltage fluctuations. Consequently, a comprehensive analysis of power quality degradation mechanisms requires systematic consideration of both electrical and non-electrical influencing factors [5].

This paper aims to analyze the fundamental mechanisms of power quality degradation caused by nonlinear loads at the PCC by combining analytical modeling with a structured classification of influencing factors. The proposed approach provides a clear physical interpretation of voltage distortion formation and establishes a methodological basis for further assessment and mitigation of power quality problems in industrial power systems.

METHODOLOGY

The proposed methodology is based on analytical modeling of power quality degradation mechanisms caused by nonlinear loads connected at the point of common coupling (PCC). The analysis focuses on the conductive impact mechanism, which represents the primary physical process through which nonlinear consumers distort voltage and current waveforms in distribution and industrial power systems. To describe this mechanism, a simplified equivalent circuit of the supply network at the PCC is considered. The upstream power system is modeled as an ideal voltage source U_0 connected in series with an equivalent network impedance $Z_n(\omega)$, which characterizes the electrical strength of the grid and is directly related to the short-circuit power at the PCC. Nonlinear loads are represented by frequency-dependent admittances, while other connected consumers with linear voltage–current characteristics are modeled as constant admittances [5-9].

When a nonlinear load is supplied by a sinusoidal voltage, it draws a non-sinusoidal current containing harmonic components. These harmonic currents flow through the equivalent network impedance and generate voltage drops at corresponding frequencies, resulting in distortion of the PCC voltage waveform. This relationship can be expressed in the frequency domain as

$$U_{PCC}(\omega) = U_0(\omega) - I(\omega)\, Z_n(\omega) \qquad (1)$$

where U_{PCC} is the voltage at the PCC, $I(\omega)$ is the current spectrum of the nonlinear load, and $Z_n(\omega)$is the frequency-dependent network impedance. This expression demonstrates that voltage distortion at the PCC is jointly determined by the magnitude and harmonic content of the injected current and by the impedance characteristics of the supply network. Consequently, power quality degradation becomes more pronounced in electrically weak networks, where higher impedance values amplify the impact of harmonic currents.

The overall interaction of multiple connected consumers at the PCC is described by the total admittance, which is obtained as the sum of individual load admittances in the frequency domain. For nonlinear loads, this admittance varies with frequency due to switching behavior, arc instability, or nonlinear voltage–current characteristics, leading to selective amplification of specific harmonic orders. This representation provides a convenient analytical basis for evaluating the contribution of individual loads to voltage distortion and for assessing the effectiveness of network reinforcement or harmonic mitigation measures[10].

In addition to electrical parameters, the methodology incorporates a systematic consideration of non-electrical factors influencing power quality, such as operating conditions, load variability, environmental effects, and temporal characteristics of power consumption. To capture the time-dependent nature of power quality disturbances, the analysis distinguishes between short-term, medium-term, and long-term observation intervals, allowing transient effects, seasonal variations, and long-term structural changes in the network to be evaluated consistently. By combining analytical modeling with factor classification and time-scale analysis, the proposed methodology provides a comprehensive framework for understanding and assessing power quality degradation mechanisms caused by nonlinear loads at the point of common coupling.

RESEARCH RESULTS

The obtained results clearly demonstrate that power quality degradation at the point of common coupling is a complex phenomenon resulting from the combined influence of nonlinear load behavior, network characteristics, and external operating conditions. Time-domain analysis of the PCC voltage waveform confirms significant deviations from an ideal sinusoidal shape under nonlinear load operation. Typical waveform distortions include peak flattening, asymmetry, and irregular oscillations, which are directly associated with harmonic current injection and dynamic load behavior. These effects are especially pronounced in industrial power systems supplying nonlinear consumers such as electric arc furnaces and high-power power-electronic equipment.

Quantitative evaluation of voltage quality indices shows that total harmonic distortion of voltage (THDU_UU) strongly depends on the short-circuit power of the network at the PCC. In electrically strong networks, characterized by high short-circuit capacity, the impact of injected harmonic currents on voltage quality remains relatively limited. However, as the network impedance increases and the short-circuit power decreases, voltage distortion grows rapidly. This trend is clearly illustrated by the results summarized in Table 1, which indicate a pronounced increase in THDU_UU under heavy nonlinear loading and weak network conditions.

TABLE 1. Voltage harmnic distortion indices at the point of common coupling under nonlinear load conditions

Operating condition	Short-circuit power at PCC (MVA)	THDU_UU (%)	Dominant harmonics
Light nonlinear load	500	1.8	5th, 7th
Moderate nonlinear load	250	3.6	5th, 7th, 11th
Heavy nonlinear load	120	6.9	5th, 7th, 11th, 13th
Weak network condition	80	8.4	5th, 7th, 11th

Harmonic spectrum analysis further reveals that lower-order harmonics dominate the voltage distortion process at the PCC. The 5th and 7th harmonic components exhibit the highest amplitudes and represent the main contributors to the total harmonic distortion, while higher-order harmonics, although smaller in magnitude, contribute cumulatively to waveform degradation. This distribution is typical for nonlinear industrial loads and explains why voltage distortion remains significant even when individual higher-order harmonics appear relatively weak.

The time-domain voltage waveform analysis supports these findings by visually confirming the presence of non-sinusoidal voltage behavior at the PCC. The observed waveform deformation is consistent with the analytical model proposed in this study and validates the conductive impact mechanism as the dominant source of power quality degradation. These results emphasize that voltage distortion cannot be fully understood without considering both the spectral composition of the current and the impedance characteristics of the supply network.

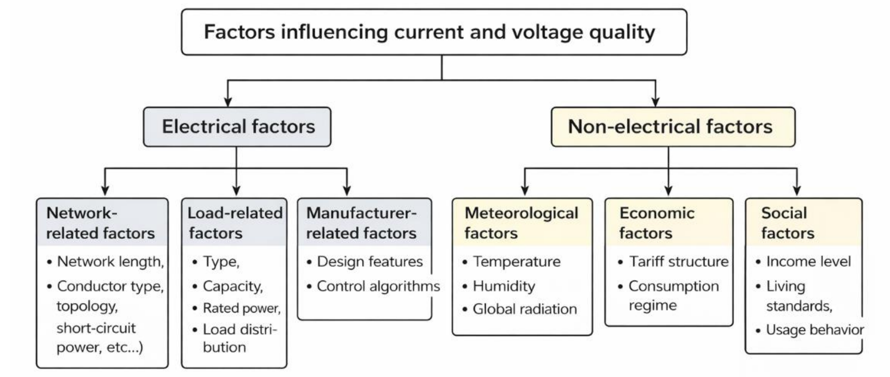

FIGURE 1. Classification of electrical and non-electrical factors influencing current and voltage quality at the point of common coupling

In addition to electrical phenomena, the results confirm that power quality degradation is significantly influenced by non-electrical factors. The systematic classification of influencing factors presented in Figure 4 highlights the combined role of electrical and non-electrical parameters in shaping current and voltage quality at the PCC. Electrical factors include network-related characteristics such as topology, conductor type, and short-circuit power, as well as load-related and manufacturer-specific features. At the same time, non-electrical factors—such as meteorological conditions, economic influences, and social usage patterns—indirectly affect load behavior and operating regimes, thereby modifying harmonic generation and voltage distortion levels.

Temporal analysis further demonstrates that power quality disturbances exhibit different characteristics depending on the observation interval. Short-term operating conditions primarily influence transient distortion and flicker phenomena, whereas medium-term and long-term regimes affect average harmonic content and voltage stability. This confirms that power quality assessment requires a time-dependent and multi-factor approach rather than reliance on instantaneous electrical measurements alone.

Overall, the combined analysis of voltage waveforms, harmonic spectra, THD indices, and influencing factor classification validates the proposed analytical framework and provides a comprehensive interpretation of power quality degradation mechanisms at the point of common coupling. The results clearly indicate that effective mitigation strategies must simultaneously address nonlinear load characteristics, network impedance properties, and external influencing factors in order to ensure acceptable power quality levels in modern industrial and distribution power systems.

CONCLUSIONS

This paper presented a comprehensive analysis of power quality degradation mechanisms caused by nonlinear loads at the point of common coupling. The results confirmed that voltage distortion at the PCC is primarily driven by the interaction between harmonic currents injected by nonlinear consumers and the equivalent impedance of the supply network. Analytical modeling demonstrated that the magnitude of voltage distortion is jointly determined by the harmonic content of load currents and the short-circuit power of the network, with electrically weak networks exhibiting significantly higher sensitivity to nonlinear load effects.

The time-domain and frequency-domain analyses showed that lower-order harmonics, particularly the 5th and 7th components, dominate the voltage distortion process and constitute the main contribution to total harmonic distortion. At the same time, higher-order harmonics, although smaller in amplitude, contribute cumulatively to waveform deformation and cannot be neglected in comprehensive power quality assessment. The obtained THD values clearly increase under heavy nonlinear loading and reduced short-circuit power conditions, confirming the validity of the proposed analytical framework.

The systematic classification of electrical and non-electrical influencing factors highlighted the multi-dimensional nature of power quality degradation at the PCC. In addition to network topology and load characteristics, external factors such as operating regimes, environmental conditions, and socio-economic influences indirectly affect current and voltage quality by modifying load behavior over different time scales. This confirms the necessity of a time-dependent and factor-oriented approach to power quality analysis.

Overall, the findings of this study provide a clear physical interpretation of power quality degradation mechanisms and establish a methodological basis for improved assessment and mitigation of voltage distortion in industrial and distribution power systems. The proposed approach can support the development of coordinated mitigation strategies, including network reinforcement, harmonic filtering, and adaptive compensation techniques, aimed at ensuring acceptable power quality levels in modern power networks.

REFERENCES

1. Bollen M.H.J. Understanding Power Quality Problems: Voltage Sags and Interruptions. — New York: IEEE Press, 2000.
2. Arrillaga J., Watson N.R. Power System Harmonics. — 2nd ed. Chichester: John Wiley & Sons, 2003.
3. IEEE Power and Energy Society. IEEE Std 519-2014: IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems. — New York: IEEE, 2014.
4. Emanuel A.E. Harmonics in power systems. // IEEE Power Engineering Review. Vol. 21(1), 2001. pp. 8–12. https://doi.org/10.1109/39.893970
5. Meyer J. Power quality in electrical power systems. — Dresden: Technische Universität Dresden, 2010.
6. Bobojanov M.K., Mahmutkhonov S.K. Harmonic analysis of an electric Arc Furnace through time-based dynamic modeling of the Electric Arc // International Journal of Advanced Research in Science, Engineering and Technology. India, 2024. – Vol. 11, Issue 9, September 2024. ISSN: 2350-0328. PP. 22311-22314.
7. Mahmutkhonov S., Baizhonova L., Mustayev R., Tashmatova S. Dynamic analysis of voltage-ampere characteristics and harmonic distortions in electric arc furnaces. // *AIP Conference Proceedings*. 3331(1), 2025. pp. 070023, 1–5. https://doi.org/10.1063/5.0305745.
8. Bobojanov M., Mahmutkhonov S. Influence of the consumer to power quality at the point of connection // E3S Web of Conferences 384. 2023. PP, 01041, 1-5. https://doi.org/10.1051/e3sconf/202338401041.

9. Bobojanov M.K., Karimov R.Ch., Popkova O.S., Tuychiev F.N., Makhmutkhanov S.K. Analysis of the results of experimental studies of the arc furnace DSP-30. // *Power Engineering Research & Technology*. 27(2), 2025. pp. 126–137. https://doi.org/10.30724/1998-9903-2025-27-2-126-137
10. Alimov A.A., Ruzinazarov M.R., Mahmutkhonov S.K., Uzakov B. Methods of phase, chain analysis and calculation of electric consumption of complex objects with interproduction relations // International Journal of Advanced Science and Technology. Vol. 29, No. 11s, (2020), pp. 1386-1393.