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A review on the harmonic analysis in the power system

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ABSTRACT:

Harmonic distortion in power systems has become a growing concern with the increasing integration of nonlinear loads and power electronic devices. These distortions degrade power quality, cause equipment malfunctions, increase losses, and reduce system efficiency. This review paper presents a comprehensive overview of harmonic generation mechanisms, their impact on power system components, and the regulatory standards governing harmonic limits. It also explores various methods for harmonic analysis, including time-domain and frequency-domain approaches, along with simulation tools such as ETAP and MATLAB. Additionally, the paper reviews different mitigation techniques, such as passive and active filters, and highlights recent advancements in harmonic control strategies. Through this study, a detailed understanding of harmonic issues in modern power systems is provided, aiming to support future research and guide engineers in designing more robust and power-quality-compliant systems.

Keywords: Harmonic Distortion, Power Quality, Nonlinear Loads

INTRODUCTION

Power electronic converter-fed devices and equipment such as computers, Adjustable Speed Drives (ASDs), and Light Emitting Diodes (LEDs) for lighting are frequently used in industrial applications and distribution networks. Therefore, due to a massive employment of such devices and their nonlinear behavior in power systems, power quality has emerged as a major concern for energy companies and network operators **[1, 2].** The efficiency of electrical equipment is affected by a range of power quality issues, including voltage and current harmonics, interharmonics, voltage instability (sag and swell), flicker, voltage notch, transient instability, and grid imbalance **[3].** Among them, harmonic distortion is the most significant factor which manifests as voltage and current emissions. Harmonics will heat up motors, cables, and transformers, reduce efficiency, nuisance in operating circuit breakers, and create notch voltages, lightning strikes, grid instability and network equipment misoperation. It is worth noting that nonlinear loads alter the sinusoidal nature of the AC supply current, causing harmonic currents to flow through the AC power system and potentially disrupting communication circuits and other types of devices. Additionally, these harmonic currents increase heating and losses in a variety of electromagnetic equipment (motors, transformers, etc.) **[4].** Resonant circumstances that can lead to large levels of harmonic voltage and current distortion can arise when reactive power compensation, in the form of power factor improvement capacitors, is utilized. This is especially true when the resonance condition occurs at a harmonic due to nonlinear loads **[5].** The main contributors of harmonics in power systems are power electronic switching devices and converters acting as non-linear loads, ASDs, Electric Vehicle (EV) chargers, LED fluorescent lights, and computer power supplies.

In various industrial applications, circuit configurations like motor drive systems—featuring a diode-rectifier at the front-end and an inverter at the rear-end—are being increasingly adopted. These systems play a vital role in controlling motor operations efficiently. Notably, motor drive systems are estimated to consume approximately 46% of the total global electricity, underscoring their significant impact on energy demand. This has led manufacturers and power system operators to focus on enhancing power quality, energy efficiency, and overall network performance **[6].**

A typical Adjustable Speed Drive (ASD) setup, as illustrated in Fig. 1, shows a unit or product-level system connected to the distribution network through a three-phase diode rectifier and a DC-choke filter. In this configuration, Zg denotes the grid impedance. The DC-choke impedance is constituted by the inductance Ldc and resistance Rdc , while the DC-link capacitor impedance is represented by the capacitance Cdc and resistance Rc.

It is important to highlight that both single-phase and three-phase power electronic equipment act as significant sources of current harmonics. These harmonics, when combined with the nonlinear characteristics of such devices, can severely affect power system stability and quality by injecting distorted currents into the network.

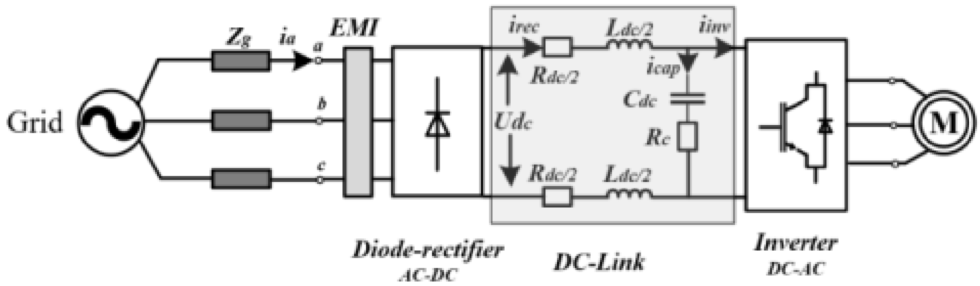

Figure 1 ASD with three-phase diode-rectifier

Techniques to reduce harmonics

To reduce the adverse effects of harmonics in power systems, a broad spectrum of mitigation techniques has been developed and employed. The effectiveness of these harmonic mitigation strategies is influenced by several factors, including the grid inductance, transformer characteristics, system architecture, load profiles, and the specific topology used in the electrical network **[8, 9].**

Several devices and technologies have been widely implemented to address harmonic distortion. These include Unified Power Quality Conditioners (UPQCs) **[10],** passive damping filters **[11],** and Active Power Filters (APFs) **[12].** Other effective mitigation solutions involve Electronic Inductors (EIs) **[13],** Distribution Static Compensators (D-STATCOMs) **[14],** and selective harmonic compensation techniques **[15].** Furthermore, digital signal processing approaches like Finite Impulse Response (FIR) and Infinite Impulse Response (IIR) filters **[16]** are also commonly utilized to suppress harmonic emissions in distribution systems.

While deploying these mitigation devices and strategies is critical, it is even more essential to first accurately estimate the harmonic content in the system. Harmonic estimation involves determining key properties of the distorted signal, including the amplitude and phase angle of each harmonic component **[17, 18].** This estimation is a prerequisite for implementing targeted and efficient harmonic mitigation measures, ensuring that power quality standards are consistently met. Various techniques are used to perform harmonic estimation in distribution networks. These include traditional approaches like the Fast Fourier Transform (FFT) **[20]** and Harmonic State Estimation (HSE) **[21],** as well as more advanced methods such as Bayesian inference techniques **[19]** and metaheuristic optimization algorithms like Particle Swarm Optimization (PSO) **[22].** It is worth noting that with the increasing use of power electronic converters in modern electrical systems, the combined harmonic contribution of multiple converters often exhibits complex interactions—far beyond simple linear addition. As a result, the challenge of harmonic suppression has become more intricate, requiring smart, adaptive, and high-precision estimation and mitigation techniques.

Previous works

In research paper **[22],** it is mentioned that With the growing demand for electrical energy, there is an increasing need for more reliable and higher quality power. This necessity has led to the emergence of the concept of **"power quality"** within the field of electrical engineering. In modern industrial applications, the widespread use of power electronic components, transformers, arc furnaces, converters, and other harmonic-generating equipment has contributed significantly to the degradation of power quality. Consequently, it has become essential to explore effective methods for mitigating harmonics. Ensuring the delivery of high-quality electrical energy requires adherence to several key criteria, including energy continuity, voltage and frequency stability, a power factor close to unity, phase voltage balance, and acceptable harmonic levels in the voltage supply.

In this study, the power quality of various units within the Giresun University Güre Campus was assessed using the CA 8333 energy analyzer. The collected data was transferred to a computer for graphical analysis and interpretation. To further investigate the presence and impact of harmonics and interharmonics in the power system, a series active power filter was modeled and simulated in the MATLAB/Simulink environment under different nonlinear load conditions. The effectiveness of the harmonic mitigation was evaluated using Fast Fourier Transform (FFT) analysis to observe the extent of harmonic elimination and the filter's response.

A comparative analysis of the power system's harmonic behavior—both before and after filtering—was conducted. Based on the results, several recommendations are provided regarding possible measures to enhance power quality and reduce the impact of harmonics in electrical systems.

In research paper **[23],** it is mentioned that fundamental concepts of harmonics through MATLAB-based simulations. It analyzes harmonic waveforms and explores the phenomenon of spectral leakage observed in Fast Fourier Transform (FFT) analysis. To address spectral leakage, two key solutions are introduced: extending the window length and selecting an appropriate window function. Both approaches are examined individually. Through simulation, the performance of several commonly used window functions is evaluated, highlighting their respective characteristics and effectiveness in suppressing spectral leakage.

In research paper **[24],** it is mentioned that when nonlinear loads are present in a ship's power system, they generate significant harmonic currents, which degrade the system's power quality and interfere with the normal operation of onboard electrical and electronic equipment. To address this, CCS regulations specify limits for harmonic distortion in marine power systems. This study focuses on an icebreaking research vessel and uses ETAP simulation software to model its power system and perform harmonic analysis. The simulation results demonstrate that the AFE (Active Front End) frequency converter effectively suppresses harmonic distortion. The total harmonic distortion (THD) of the 690V and 400V busbars under various typical operating conditions remains within acceptable limits. These findings offer valuable insights and references for managing harmonics in similar marine vessels.

In research paper **[25],** it is mentioned that their study explores the feasibility of using standard periodic non-harmonic signals as an alternative to the conventional set of harmonic signals for calibrating power quality analyzers based on total harmonic distortion (THD). It proposes the use of square, triangular, and sawtooth waveforms, as well as truncated sine waves—each characterized by specific harmonic components in their Fourier series representations. By selecting a particular standard periodic signal, a corresponding reference value for THD can be established. The paper presents the results of calibrating a Fluke 435 power quality analyzer using a Metrix CX1651 calibrator, providing experimental evidence on the effectiveness of using non-harmonic periodic signals for THD-based calibration.

Conclusion

Harmonic analysis is a critical aspect of modern power system design and operation, especially with the growing use of nonlinear loads and power electronic devices. This review highlights the sources and effects of harmonics, their impact on power quality, and the importance of adhering to regulatory standards. Various analysis techniques and simulation tools have been explored, offering insights into how harmonics can be accurately identified and evaluated. Additionally, mitigation strategies, including both passive and active filtering methods, have been discussed to address harmonic issues effectively. As power systems continue to evolve with renewable integration and advanced electronics, ongoing research and the development of adaptive harmonic control methods will be essential to ensure system reliability, efficiency, and compliance with power quality standards.

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