Faculty of Engineering

HARMONIC MITIGATION USING SHUNT ACTIVE POWER FILTER BASED ON SYNCHRONOUS REFERENCE FRAME THEORY

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Bachelor of Engineering

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Final Year Project Report ☑

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HARMONIC MITIGATION USING SHUNT ACTIVE POWER FILTER BASED ON SYNCHRONOUS REFERENCE FRAME THEORY

IRDINA IZZATI BINTI ABDUL HARUN

A dissertation submitted in partial fulfilment
of the requirement for the degree of
Bachelor of Engineering
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ABSRACT

Harmonic distortion, arising from nonlinear loads in modern power systems, poses a significant power quality issue, deteriorating overall power quality and affecting sensitive equipment. Extensive research has been conducted to develop effective mitigation techniques, including filters, harmonic compensators, low harmonic drives, oversizing of neutral conductors, and power factor correction devices. However, tailored solutions are necessary due to the diversity of power sources, harmonics, and equipment. This project focuses on the design aspects of a three-phase Shunt Active Power Filter (SAPF) as an efficient harmonic mitigation device. The SAPF utilizes the synchronous reference frame theory and a hysteresis Proportional-Integral (PI) control algorithm to extract harmonic components and provide compensating currents. Extensive simulation analysis using MATLAB Simulink evaluates the SAPF's performance under different operating conditions, demonstrating its ability to restore distorted current waveforms and surpass the harmonic limits specified by the IEE-519 standards. The SAPF achieves a remarkable reduction in Total Harmonic Distortion (THD) through Frequency Fourier Transform (FFT) analysis. The successful implementation of the proposed filter and its superior harmonic mitigation capabilities represent significant advancements in power quality improvement, surpassing existing methods. The used of synchronous reference frame theory (SRF) for harmonic signal extraction holds promise for future developments in harmonic mitigation techniques.

ABSTRAK

Harmonic distortion, yang timbul daripada beban tak linear dalam sistem kuasa moden, menimbulkan isu kualiti kuasa yang ketara, kualiti kuasa keseluruhan merosot dan menjejaskan peralatan yang sensitif. Penyelidikan meluas telah dijalankan untuk membangunkan teknik mitigasi yang berkesan, termasuk penapis, pemampas harmonik, pemacu harmonik rendah, saiz konduktor neutral yang besar dan peranti pembetulan faktor kuasa. Walau bagaimanapun, penyelesaian yang sesuai diperlukan kerana kepelbagaian sumber kuasa, harmonik dan peralatan. Projek ini fokus pada aspek reka bentuk "Shunt Active Power Filter" (SAPF) tiga fasa sebagai peranti tebatan harmonik yang cekap. SAPF menggunakan teori "synchronous reference frame theory" dan algoritma kawalan PI histeresis untuk mengekstrak komponen harmonik dan memberikan arus pampasan. Analisis simulasi yang meluas menggunakan MATLAB Simulink menilai prestasi SAPF di bawah keadaan operasi yang berbeza, menunjukkan keupayaannya untuk memulihkan bentuk gelombang semasa yang herot dan melepasi had harmonik yang ditentukan oleh piawaian IEE-519. SAPF mencapai pengurangan yang luar biasa dalam "Total Harmonic Distortion" (THD) melalui analisis Frekuensi Fourier Transform (FFT). Kejayaan pelaksanaan penapis yang dicadangkan dan keupayaan pengurangan harmoniknya yang unggul mewakili kemajuan ketara dalam peningkatan kualiti kuasa, mengatasi kaedah sedia ada. Penggunaan teori rangka rujukan segerak untuk pengekstrakan isyarat harmonik menjanjikan perkembangan masa depan dalam teknik mitigasi harmonik

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LIST OF ABBREVIATIONS

PQ	Power quality
AVR	Automated voltage regulators
STATCOM	Static compensators
UPS	Uninterrupted power supply
MFDG	Multipurpose distributed generators
APF	Active power filter
VSI	Voltage source inverter
SRF	Synchronous reference frame
THD	Total distorted harmonic
SAPF	Shunt active power filter
LED	Light emitting diode
IHD	Individual harmonic distortion
SEHAF	Series hybrid active filter
PV	Photovoltaic
RECKF	Robust extended complex Kalman filter
SSG	Simplified synchronous generator
UPQC	Unified power quality conditioner
DVR	Dynamic voltage restorer
IEEE	The Institute of Electrical and Electronics Engineers-Standards Association

CHAPTER 1

INTRODUCTION

1.1 Research Background

In the modern power system, power quality is a crucial topic that may have an impact on utilities and consumers. Nonlinear loads such as light emitting diodes (LEDs), computers, and chargers contribute to various power quality (PQ) issues, including harmonic distortion, voltage imbalance, and voltage sags. PQ monitoring is important to enhance the efficiency of power system components and end-user loads due to the increased integration of nonlinear components. Modern electrical engineering is advancing in areas like concise distribution system calibration and analysis, in addition to use new methodologies and approaches to enhance the state of the supply system. The primary problem in PQ is harmonic pollution, which is caused by the nonlinearity of the electrical components [1]. A sinusoidal voltage or current that has a harmonic component is one that has an integer multiple of the fundamental frequency [2]. Figure 1.1 show the typical harmonic distorted wave.

Figure 1.1 Variation of Voltage During a Harmonic Distortion [3]

Low-voltage distribution systems with harmonic distortion experience power dissipation, insulation issues, communications network interference, electric device overheating, and in the worst circumstances, a failure of the electrical system [4]. As an outcome, both the utility and the customer now view the necessity for the elimination of harmonics to be a serious issue. IEEE has issued the harmonics limits standard to prevent the uncontrolled introduction of harmonic currents into power networks (IEEE Std 519-2014) [5]. According to this standard, the maximum allowed total harmonic distortion (THD) is 5%. As a result, to stay inside the 5% limit, researchers and engineers has come up with new technologies to mitigate harmonics.

According to [6], power quality mitigation can be classified into three phases as shown in Figure 1.2. The first generation involved installing filters that were either passive, active, or hybrid. The major goal of this generation was to mitigate harmonics to prevent grid voltage quality degradation. More sophisticated gadgets like automatic static compensators (STATCOMs) and uninterrupted power supplies evolved in the generation after that (UPSs). These mitigations able to compensate harmonic and deal with voltage swell and sag for a brief period. The third generation would be electric springs which work by supplying electricity to vital loads during disruptions and multipurpose distributed generators (MFDGs). MFDGs try to lessen harmonics and other power quality related issues like sag or swells by using the appropriate control methods.

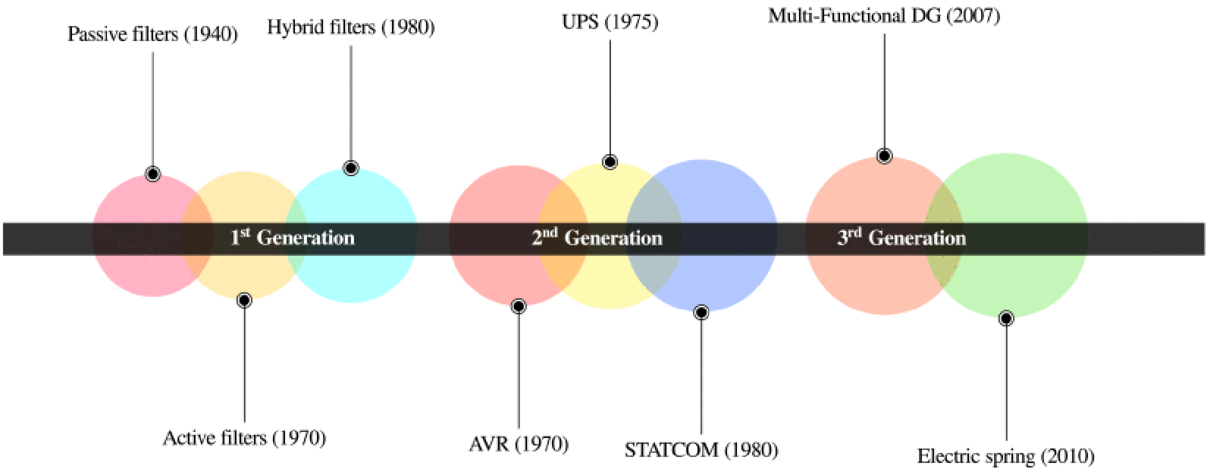

Figure 1.2 Evolution of several power quality mitigation generations [6]

In recent years, significant advancements have been made in power quality mitigation technologies and practices. One notable advancement is the development of active power filters (APFs). APFs are electronic devices specifically designed to compensate for power quality issues, including harmonics. They operate by continuously monitoring the power supply and injecting corrective currents to mitigate disturbances. APFs are capable of handling both balanced and unbalanced loads, effectively suppressing harmonics and improving power factor. These intelligent harmonic control devices play a crucial role in enhancing power quality.

The basic circuit structure of a single-phase active power filter comprises several components, including a grid voltage source, a grid current sensor, a filter output compensation current, an AC inductor, an equivalent resistor, and a DC capacitor [7]. APFs employ various methods of current tracking control, such as hysteresis current control, triangular wave modulation control, and space vector modulation control. These control strategies ensure accurate compensation and effective harmonic elimination.

Based on extensive research, power filters have emerged as effective and widely used technologies for minimizing harmonic distortion. To improve power quality, passive power filters are typically connected in series and shunt configurations to the distribution network [8]. However, designing an efficient passive power filter that effectively reduces harmonic current distortion can be challenging when dealing with nonlinear loads in industrial settings connected to the power grid. This is where active power filters (APFs) present an excellent solution to address power quality issues, offering several key features such as high filtering precision, immediate dynamic response, and flexibility [9].

Numerous methods have been proposed by researchers for extracting fundamental and harmonic components. For example, in [10], the authors introduced a fuzzy logic controller combined with synchronous reference frame (SRF) and proportional-integral (PI) control to achieve superior harmonics compensation. Another approach, presented in [11] involved the utilization of a current-controlled ĈUK (capacitor-inductor-capacitor) AC to DC converter, which demonstrated satisfactory results in terms of input power factor and input current total harmonic distortion (THD). In [12], a three-level boost rectifier-based method was developed to address imbalanced currents and asymmetric voltages. Additionally, in [13] a unified power quality conditioner was proposed to mitigate harmonics, abrupt load changes, voltage fluctuations, and enhance power quality in distribution networks.

These are just a few examples of the various mitigation techniques that have been proposed by researchers to minimize harmonic distortions. Thus, this project aims to propose an enhancement to the existing technique, specifically focusing on a shunt active power filter (SAPF). The following sections will delve into the concept of SAPF operation, the methods employed, and the type of harmonic signal extraction technique utilized in this proposed system. Furthermore, this study will present simulation results obtained using MATLAB Simulink, providing valuable insights and analysis to assess the performance and effectiveness of the proposed SAPF enhancement.

1.2 Problem Statement

Power quality problems, such as sags, swells, transients, harmonics, and power factor issues, have been a topic of significant concern in the field of electrical power systems. These problems arise due to various factors, including an increase in energy demand and the extensive utilization of non-linear loads. According to data from the energy commission, the total electricity consumption reached 2,471 ktoe in 2015, and this figure rose to 2,715 ktoe in 2019, indicating a steady growth in energy consumption.

Among the power quality issues, harmonic distortions have become increasingly concerning. Harmonics are variations in voltage and current caused by frequency changes in electrical distribution networks [14]. With the proliferation of non-linear loads such as computers, televisions, light emitting diode (LED), and chargers, distorted waveforms with harmonics are commonly observed. These harmonics give rise to a range of problems and can have adverse effects on electrical systems.

One of the main problems associated with harmonics is the degradation of conductors, which leads to an increase in Joule effect losses. The presence of harmonics causes losses in the copper windings and core of transformers to escalate, resulting in elevated temperatures and a reduced lifespan for these crucial components [15]. Furthermore, harmonics can introduce complications in electrical motors, reducing torque and overall performance. In addition, certain harmonics can activate protective devices, such as fuses and circuit breakers, impacting the reliability of the system. Moreover, depending on the sensitivity of components, harmonics can cause noise or interference in communication circuits, disrupting signal integrity.

The consequences of harmonics can extend beyond individual systems. In severe cases, harmonics can lead to blackouts and failures that propagate through interconnected electrical subgrids, posing risks to the overall power system stability and reliability. Therefore, addressing harmonic distortions and mitigating their effects is crucial in maintaining a high-quality power supply.

To evaluate the extent of harmonic distortions, the concept of total harmonic distortion (THD) is commonly used. THD quantifies the sum of harmonics in a system [16], providing a measurement of the actual harmonic voltage (THDv) or current (THDi) [17]. Various standards, such as those established by the Institute of Electrical and Electronics Engineers (IEEE) in its IEEE-519 guideline, set limits on voltage and current distortions to ensure acceptable power quality levels. By taking into consideration the issue, the aim of this study was to improve an existing shunt active power filter (SAPF) for harmonic mitigation and analyse it by using MATLAB Simulink.

Considering these power quality challenges; the objective of the study is to enhance an existing SAPF for harmonic mitigation and evaluate its performance using MATLAB Simulink. By focusing on improving the capabilities of the active power filter, it aims to contribute to the development of more effective and efficient solutions for managing power quality issues caused by harmonics.

1.3 Objectives

I. To investigate the existing harmonic mitigation for nonlinear load.
II. To design a shunt active power filter (SAPF) for harmonic mitigation using MATLAB Simulink.
III. To analyse the performance of proposed shunt active power filter circuit.

1.4 Project Significance

The primary objective of this project is to demonstrate the effectiveness of an active power filter as a suitable solution for mitigating harmonics caused by nonlinear loads, including personal computers, chargers, telecom systems, and various other devices. To achieve this goal, the shunt active power filter will be thoroughly investigated using a reference circuit, with the aim of improving its current performance.

To enhance the system's performance, different signal extraction techniques will be explored and evaluated. The proposed circuit will utilize the Synchronous Reference Frame Theory (SRF) as the chosen method for harmonic signal extraction. SRF is a widely recognized and utilized technique that allows for accurate extraction of harmonic components from the system, enabling precise compensation and mitigation of harmonics.

Through rigorous experimentation and analysis, the project aims to demonstrate the superiority of the active power filter and the efficacy of the SRF-based harmonic signal extraction technique. By showcasing the improved performance and effectiveness of the proposed system, the project seeks to contribute to the advancement of harmonic mitigation methods for nonlinear loads, paving the way for enhanced power quality in various applications and industries.

1.5 Project Scope

The objective of this project is to design a shunt active power filter (SAPF) for harmonic mitigation using MATLAB Simulink. To achieve better performance and results, a reference circuit is employed as a basis for the design. The effectiveness of the system with the proposed improvements will be evaluated in terms of total harmonic distortion (THD).

Among the various mitigation techniques considered, SAPF has been selected as the optimal choice after comparing it with ten different techniques. The detailed comparison is presented in Section 2 of the project report. The main goal of the proposed design filter is to improve the power factor performance while mitigating harmonic currents and minimizing the negative effects caused by harmonics.

The control of the shunt active power filter involves four fundamental algorithms: harmonic extraction, current control, synchronizer algorithms, and DC-link capacitor voltage regulation. These algorithms work together to enable effective harmonic mitigation and regulation within the system.

By implementing and evaluating the SAPF design using MATLAB Simulink, this project aims to contribute to the advancement of harmonic mitigation techniques and enhance the overall power quality. The performance assessment will focus on THD reduction, ensuring a cleaner and more stable power supply while minimizing the adverse effects of harmonics in various electrical systems.

1.6 Project Outline

In this research paper, there will be consist of five chapters. The first chapter is the Introduction of the project, followed by Literature Review, then Methodology, Result, Discussion and lastly Conclusion of this project. Chapter 1 consists of research background, problem statement, objectives, project significance and project scope. In Chapter 2 includes literature review of harmonic phenomenon, problems caused by harmonics, harmonic distortion, harmonic detection and categorization, harmonic analysis, comparison of existing harmonic mitigation techniques, SAPF, synchronous reference frame (SRF) theory and a research gap. Chapter 3 will be based on the methodology of the project. The project material, project workflow, general workflow of SAPF, parameters, proposed methodology, SAPF topology and operation, proposed circuit, performance evaluation and a summary. The project outcome will be discussed in detail in Chapter 4 and lastly, Chapter 5 cover the project conclusion, advantages and limitations and future improvements of the project.

Chapter 2

LITERATURE REVIEW

2.1 Overview

The purpose of this chapter is to provide extensive overview of previous research on harmonic mitigation. This review aims to serve as a basis for the project by analysing the key findings of prior research and critically assessing the approaches and restrictions of these studies. The primary findings of earlier research, essential terms and concepts connected to harmonic mitigation, and any overall problems in the existing literature will all be covered in this review. The project will be constructed with sufficient context according to this review, and its contributions to the body of current knowledge will become clearer.

2.2 Harmonic Phenomenon

To develop a comprehensive understanding of harmonics, it is important to search into the complex properties of voltage or current waveforms in relation to their fundamental frequency. Harmonics arise when waveforms deviate from the ideal sinusoidal shape, presenting deviations that can be observed in various electrical systems such as power grids and electronic circuits due to the presence of non-sinusoidal waveforms. Many factors including transformers, nonlinear loads, switching electronics, and generators contribute to the generation of harmonics, give them a pervasive phenomenon in power systems. While harmonic orders theoretically extend beyond 100, it is the notable magnitudes of the first 25 orders that garner primary attention in harmonic studies [17].

In the world of power systems, loads can be broadly classified into two categories: linear loads and nonlinear loads, each capable of exerting distinct impacts on power quality. Linear loads, encompassing devices such as transformers, motors, and capacitors, exhibit the characteristic of drawing sinusoidal currents that adhere to the ideal waveform shape (as depicted in Figure 2.1). These loads, commonly found in household appliances and conventional electrical devices, do not introduce waveform distortions, and maintain power quality within acceptable limits. On the other hand, nonlinear loads, represented by a broad range of electronic devices and systems, manifest current waveforms that deviate from the ideal sinusoidal shape (as illustrated in Figure 2.2). Consequently, the presence of nonlinear loads gives rise to abnormalities in the voltage waveform, potentially engendering power quality disturbances [16].

It is essential to recognize that the presence of harmonics in nonlinear loads can engender various issues, leading to a degradation of power quality within electrical systems. Nonlinear loads draw non-sinusoidal currents, thereby distorting the voltage waveform and imposing undesirable effects on system performance. These effects can range from increased losses, reduced efficiency, and overheating in power distribution systems to malfunctioning of sensitive equipment and communication disruptions. To mitigate the adverse impact of harmonics on electrical systems, a nuanced understanding of the distinction between linear and nonlinear loads is of paramount importance. This knowledge serves as a foundation for accurately assessing the effects of harmonics and implementing appropriate mitigation measures to ensure the optimal functioning of power systems.

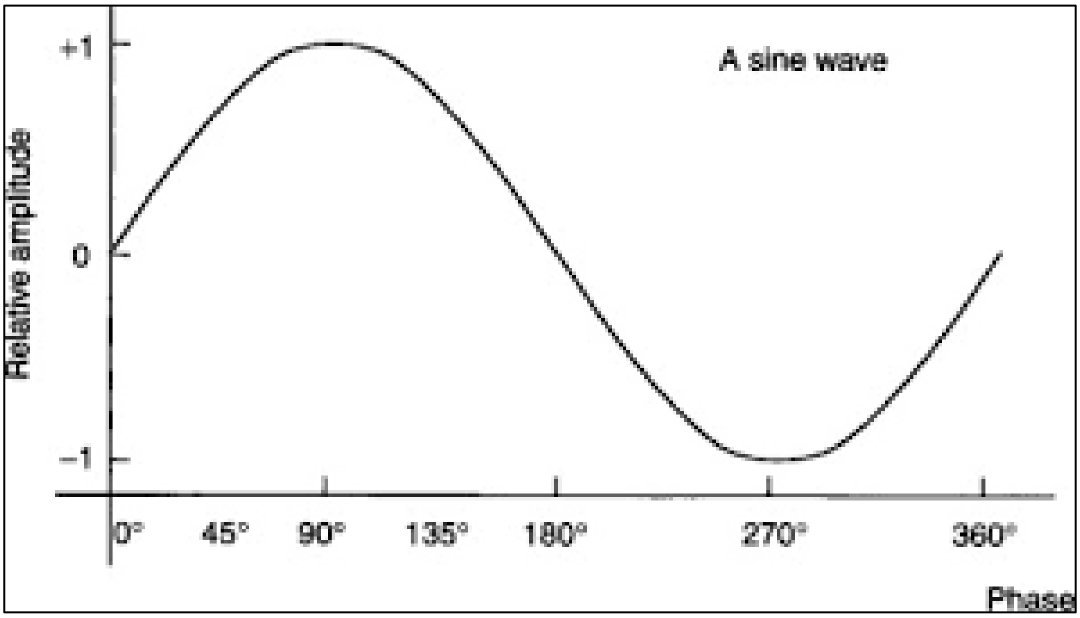

Figure 2.1 Sine Wave

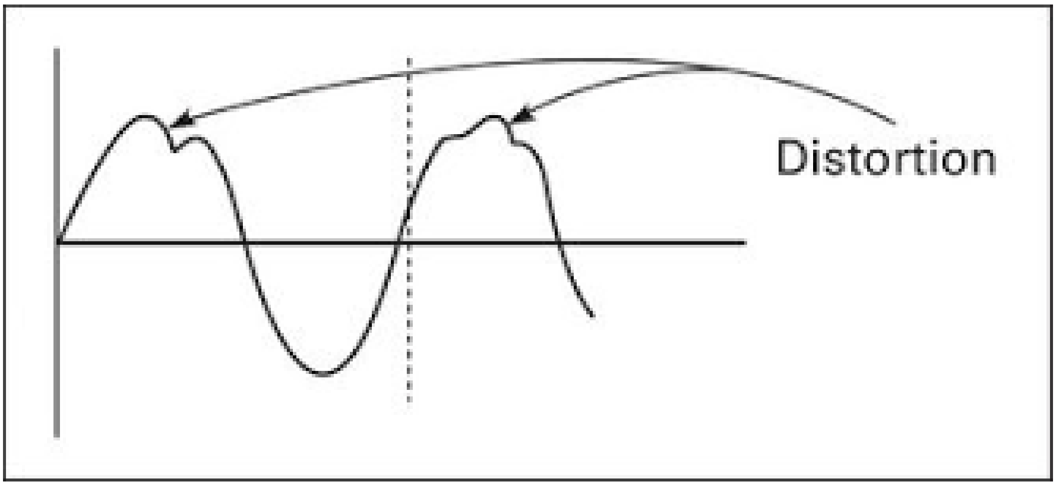

Figure 2.2 Distorted Waveform

The total harmonic distortion (THD) is a fundamental metric used to quantify the presence of harmonic distortion in electrical systems. According to the IEEE-519 2014 Standard, THD is defined as the proportion of the root mean square of harmonic distortion, including harmonic frequencies up to the 50th order, in relation to the fundamental frequency. If necessary, higher frequencies (harmonics beyond the 50th order) can also be considered [5]. Another important metric associated with harmonic distortion is the total demand distortion (TDD), which represents the proportion of the root mean square of harmonic distortion, including harmonic components up to the 50th order, expressed as a percentage of the peak current [5]. TDD provides insights into the overall impact of harmonic distortion on the electrical system and its load.

In practical terms, harmonics introduce pollution into the electrical distribution system, resulting in alterations to the waveform of the utility supply. Although the magnitude of harmonics may vary over time, there is always a certain level of pollution present. This persistent pollution can have detrimental effects on the system's performance, including an increase in the utility's apparent demand for power supply, elevated line losses, and a degradation of the power factor. Therefore, it becomes essential to accurately measure and thoroughly analyse harmonics to mitigate their negative impacts [17].

To address the challenges posed by harmonic currents, various standards and recommendations have been developed to assess and manage harmonics in electrical systems. The International Electrotechnical Commission (IEC) has played a significant role in establishing standards for the measurement and calculation of harmonic currents. Notably, IEC 61000-3-2 focuses on low-voltage systems, while IEC 61000-3-12 is designed for high-voltage systems [18], [19]. These standards provide comprehensive guidelines for measuring harmonic distortion and define limits on the maximum allowable levels of harmonic currents for different types of systems.

The presence of harmonic phenomena is not limited to electrical systems alone; it can be observed in various fields and can impact systems in both positive and negative ways. This broad applicability has made the measurement and control of harmonics an important aspect of many technical fields. Consequently, numerous standards and guidelines have been developed to assess harmonic distortion and establish best practices for managing harmonics effectively. By adhering to these standards, engineers and technicians can ensure the optimal performance and reliability of electrical systems, while minimizing the adverse effects caused by harmonics.

2.3 Problems Caused by Harmonics

One of the primary factors contributing to poor power quality is the presence of harmonics within the power grid. Harmonics occur when non-linear loads are connected, resulting in the flow of harmonic currents throughout the power system [20]. This phenomenon leads to distortion in the source voltage signal at the point of common coupling (PCC) due to source impedance [21]. To illustrate this, Figure 2.3 depicts a circuit featuring a sinusoidal voltage source and a nonlinear load. The presence of harmonics can give rise to several issues, including increased power losses, equipment overheating, and voltage distortion [3].

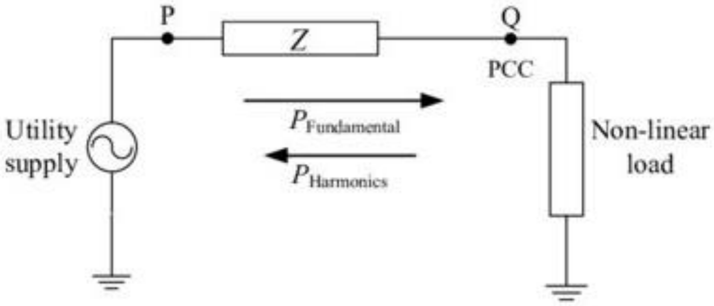

Figure 2.3 Circuit with sinusoidal voltage source and nonlinear load

One significant consequence of harmonic currents is the escalation of power losses. The additional current introduced into electrical systems by harmonics results in heightened power losses. Consequently, this leads to increased energy costs and reduced overall system efficiency. Indeed, research carried out by the Electric Power Research Institute (EPRI) has unveiled that harmonics in a standard distribution system can lead to power losses ranging from 1% to 5% of the total system power

[22]. Such losses can significantly impact the efficiency of the system and contribute to elevated operating costs.

Furthermore, harmonic currents can cause overheating of electrical equipment due to the increased heat generated by the heightened current flow. This heightened temperature can trigger premature failure of the equipment and potentially create hazardous situations. Additionally, the excess heat generated by harmonics can subject electrical components to thermal stress, resulting in a reduced lifespan for these components and increased maintenance costs [23].

In addition to power losses and equipment overheating, harmonics also induce voltage distortion. Voltage distortion refers to the deviation of the voltage waveform from its ideal sinusoidal shape [24]. his distortion poses challenges to the operation of various electrical devices, such as motors and power factor correction capacitors, and leads to increased losses within the system. For example, voltage distortion can cause motors to operate with reduced efficiency, resulting in higher energy consumption and decreased performance. Moreover, voltage distortion can push power factor correction capacitors beyond their rated range, leading to diminished lifespan and increased maintenance costs.

The detrimental effects of harmonics extend to the loads connected to the point of common coupling (PCC) in various ways, making it a significant side effect. The presence of current harmonics in conductors amplifies Joule effect losses, thereby further exacerbating the energy losses in the system [21]. In electrical motors, harmonics can hamper performance and decrease functional torque. Additionally, harmonics can cause sudden activation of circuit breakers and other protective mechanisms, impacting the overall stability and reliability of the system [21]. Moreover, communication systems are also susceptible to the undesirable effects of harmonics. Depending on the frequency, strength of coupling, and sensitivity of the equipment, certain harmonics can cause distortion or interference in communication lines. This interference can disrupt the proper functioning of communication systems, leading to compromised signal quality and data transmission integrity. Furthermore, harmonics can have even more severe consequences, including blackouts, failures in interconnected systems, and propagation through connected electrical subgrids [25]. These outcomes can result in substantial increases in energy costs, reduced equipment lifespan, and higher maintenance expenses.