Heaven's Light is Our Guide

DEPARTMENT OF ELECTRONICS & TELECOMMUNICATION ENGINEERING

Rajshahi University of Engineering & Technology, Bangladesh

A 24-Pulse Rectifier with Passive Current Injection Method Based on Dual Auxiliary Transformers.

Author

Mustafizur Rahman

Roll: 1804042

Supervised by

Shuvra Prokash Biswas

Assistant Professor

Heaven's Light is Our Guide

DEPARTMENT OF ELECTRONICS & TELECOMMUNICATION ENGINEERING
Rajshahi University of Engineering & Technology, Bangladesh

A THESIS REPORT ON

A 24-Pulse Rectifier with Passive Current Injection Method Based on Dual Auxiliary Transformers.

This thesis report is presented to Rajshahi University of Engineering & Technology's (RUET) Department of Electronics & Telecommunication Engineering in partial completion of the requirements for the degree of Bachelor of Science in Electronics & Telecommunication Engineering.

Supervised by,

Shuvra Prokash Biswas
Assistant Professor
Dept. of Electronics & Telecommunication Engineering
Rajshahi University of Engineering & Technology

Prepared by,

Mustafizur Rahman
Roll No.: 1804042

Acknowledgment

I would like to begin by expressing my sincere appreciation to the All-Powerful God, the creator of everything, for giving me the patience and fortitude that helped me go through my B.Sc. journey. This milestone would not have been attainable without His heavenly direction.

To begin with, I would like to sincerely thank my thesis supervisor Shuvra Prokash Biswas, an assistant professor at the Rajshahi University of Engineering & Technology in the Department of Electronics & Telecommunication Engineering, who oversaw my thesis. His constant advice and assistance were crucial to my thesis's accomplishment. His guidance, perceptive criticism, and support not only enhanced my work but also broadened my viewpoint as a researcher. I feel very fortunate to have had the chance to work under his guidance, and I believe that the information and abilities I have gained will provide a strong basis for my future aspirations.

My appreciation also goes out to the committed instructors of Rajshahi University of Engineering and Technology's Department of Electronics & Telecommunication Engineering. Their dedication to creating a supportive learning atmosphere and dispensing a variety of information really benefited my academic path.

The finalization of this thesis book would not have been possible without the combined encouragement, support, and direction of these remarkable people. I am very appreciative of their priceless contributions to both my academic and personal development. Finally, I would like to express my sincere gratitude to my parents and all of my well-wishers for their steadfast support, presence, and encouragement at every stage of my scholastic journey.

Date: January, 2024.
RUET, Rajshahi

Heaven's Light is Our Guide

DEPARTMENT OF ELECTRONICS & TELECOMMUNICATION ENGINEERING

Rajshahi University of Engineering & Technology, Bangladesh

CERTIFICATE

*This is to certify that the thesis paper entitled " **A 24-Pulse Rectifier with Passive Current Injection Method Based on Dual Auxiliary Transformers**" has been done by **Mustafizur Rahman** under **Shuvra Prokash Biswas**, Assistant Professor, Department of Electronics & Telecommunication Engineering, Rajshahi University of Engineering & Technology.*

Supervisor	**External Examiner**
--------------------------------------	------------------------
Shuvra Prokash Biswas	
Assistant Professor	
Dept. of ETE, RUET	Dept. of ETE, RUET
Rajshahi-6204, Bangladesh	Rajshahi-6204, Bangladesh

Head

Dr. Mst. Fateha Samad

Professor

Dept. of ETE, RUET

Rajshahi-6204, Bangladesh

ABSTRCT

This thesis addresses the power quality challenges associated with converters, commonly known as rectifiers, that are typically fueled from three-phase AC supplies. These converters often introduce harmonics into the power supply, resulting in poor power factor, AC voltage distortion, and ripple in DC outputs. To mitigate these issues, multi-pulse converters are employed, offering more than six pulses of DC voltage per cycle or featuring more stages in AC input current than traditional six-pulse rectifiers. The research in this thesis concentrates on investigating various multi-pulse techniques, utilizing phase-shifting transformers and diverse passive injection methods. In particular, to enhance harmonic mitigation in a 12-pulse rectifier, a novel approach is proposed: a series-connected 24-pulse rectifier with a passive current injection circuit based on dual auxiliary transformers (PCIC-DAT). This innovative solution incorporates a circulation current forming circuit, a dual auxiliary transformer (DAT), and an auxiliary single-phase full-bridge rectifier (ASFR). The PCIC-DAT, installed on the DC side of the proposed rectifier, generates a specific square-wave current injected into the connection point of two three-phase bridge rectifiers (TPBRs). This augmentation increases the working modes of the TPBRs, transforming the series-connected 12-pulse rectifier into a new 24-pulse rectifier. The resulting rectifier exhibits an approximately sinusoidal input current (THD $<$ 5%) and a reduced ripple output voltage. The proposed scheme features a straightforward circuit configuration, modest kVA rating, and minimal conduction loss, making it well-suited for industrial applications. The rectifier is meticulously analyzed, designed, and simulated in the MATLAB software environment, with simulation results verifying compliance with IEEE-519 standards. The insights derived from this research have the potential to substantially enhance power quality by minimizing harmonic distortion in input current and output voltage across various loads, impacting our day-to-day lives positively. Researchers, engineers, and designers working in the field of multi-pulse converters can benefit from the broad perspectives offered in this study.

Contents:

List of Figures:

List of Tables:

Chapter 1

Introduction

1.1 Introduction

Solid state ac–dc converters find extensive application in various fields including adjustable speed drives (ASDs), high voltage dc (HVDC) transmission, electro-chemical processes like electroplating, telecommunication power supplies, battery charging, uninterruptible power supplies (UPS), high-capacity magnet power supplies, high-power induction heating equipment, aircraft converter systems, and converters for renewable energy conversion systems. These converters, often referred to as rectifiers, typically receive power from a three-phase AC supply with a power rating over a few kilowatts. They encounter issues related to power quality, such as the injection of harmonics, resulting in a poor power factor, distortion of AC voltage, and the production of rippling DC outputs. The use of a passive ripple injection technique in a current-fed 12-pulse series-configured rectifier is proposed as a unique method to improve rectifier performance and reduce input current harmonic pollution. This technique aims to achieve input current quality similar to that of a 24-pulse system. By using a minimal number of components and a straightforward configuration of the primary transformer winding, this technique provides an effective solution while ensuring strong resistance to imbalances in rectifiers. The design removes the requirement for active devices, offering a simple and cost-effective method to expand the 12-to-24 step input current. Incorporating an auxiliary single-phase full-bridge rectifier (ASFR) in ACIC saves stress on auxiliary diodes and prevents the usage of large inductors on the input side [1]. A realistic and cheap method to raise the performance of rectifiers utilizing simply two tiny auxiliary single-phase full-bridge rectifiers (ASRs) with a limited set of passive components. This meticulously designed methodology effectively mitigates input current harmonics, circumventing the complexities associated with the incorporation of bulky inductors on the rectifier's input side and constitutes a succinct and efficient avenue for enhancing the operational characteristics of rectifiers within a cost-effective framework [2-3]. There are various processes of reducing harmonics and various applications of rectifiers in drive application. A hybrid active filter intended for minimizing the line-side harmonic currents of a three-phase 12-

pulse diode rectifier utilized as the front end of a medium-voltage high-power motor drive [4]. The fundamental process within rectification systems involves the utilization of a three-phase AC supply directed towards multi-phase transformers. The resulting output from these transformers is subsequently channeled into a bridge or series-connected rectifier, effecting the conversion from AC to DC power. The pivotal task of ameliorating harmonics in the input current and mitigating ripple on the DC output voltage often revolves around strategies such as augmenting the phase distribution of multi-winding transformers to elevate the pulse count in the DC output voltage. Additionally, the incorporation of active or passive voltage/current injection techniques at the latter stages of the rectifier system, employing methods like pulse doubling or tripling, further amplifies the pulse count. Employing filters to refine the DC output is commonplace, and the tailored utilization of these outputs is contingent upon specific requirements such as motor drives. The intricacies associated with the design of phase shifting transformers render them complex, tricky, and financially demanding. As an alternative, the pragmatic choice for AC-DC power conversion involves the design of multi-pulse rectifiers, employing either active or passive injection techniques. However, the utilization of active components in the injection circuit proves to be less effective. Consequently, the more viable option entails the utilization of passive injection techniques in conjunction with a multi-pulse rectifier system.

1.2 Power Source Representation

Power source representation involves the characterization and modeling of electrical power sources to analyze their behavior in various systems. It provides a structured way of understanding and simulating power sources for diverse applications in electrical engineering.

1.2.1 Voltage Vector Representation

In a three-phase system with balanced symmetrical voltages the sequence is defined as positive when the vectors reach their peak amplitudes in order A, B, C. If with same counterclockwise rotation, vectors reach their peaks in order A, C, B the sequence is defined as negative as in figure 1.1. An important property of these voltage sets is that if a positive-sequence set experiences phase shift Φ in passing through transformer then negative-sequence set will undergo phase shift $-\Phi$. The relative phase each vector conveniently defined respect reference phase angle $\omega t = 0$. All vectors can be expressed respect reference including different frequency (harmonic) vectors. However, vectors rotate do so different rates.

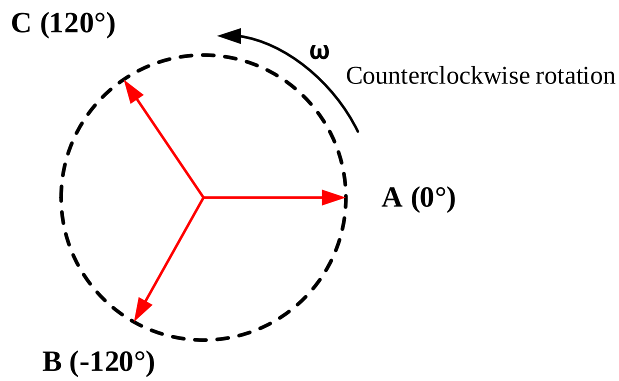

Figure 1.1: Voltage vector representation.

Here, the voltage equations are referred as,

$$V_A = V \sin(\omega t) \tag{1.1}$$

$$V_B = V \sin(\omega t - \frac{2\pi}{3}) \tag{1.2}$$

$$V_C = V \sin(\omega t + \frac{2\pi}{3}) \tag{1.3}$$

1.2.2 Preexisting Harmonic Voltage

Harmonics are the sinusoidal components of a waveform that have frequencies that are integer multiples of the fundamental frequency. Harmonics refer to the deviations in voltage or current waveform from the smooth sinusoidal pattern found in electrical power systems. These aberrations result in the production of additional frequency components that are integer multiples of the fundamental frequency (2, 3, 4, 5 etc.). On the other hand, preexisting harmonics in voltage are those harmonic elements that naturally exist in the voltage waveform due to various power system characteristics [5].

In general, the power system is at least expected to contain harmonic voltage related to characteristic harmonics ($6k \pm 1$) of 6 pulse rectifiers and (12 ± 1) for 12 pulse rectifiers. Thus the general phase voltage V_A can be represented by

$$V_A = V_i \sin\ \omega t + \sum_{k=1}^{\infty} V_{(6k+1)} \sin\left[(6k+1)\omega t + \varphi_{(6k+1)}\right] \tag{1.4}$$

Where k is the positive integer.

The key aspects of this analysis may be shown by studying simply the first two of these typical harmonics, namely, the 5th and 7th. These arise when k = 1, and in this scenario

$$V_A = V_1 \sin\ \omega t + V_5 \sin\ (5\omega t + \phi_5) + V_7 \sin\ (7\omega t + \phi_7) \tag{1.5}$$

The converter dc output is similarly affected by harmonic voltage in each ($\frac{2\pi}{3}$) conduction period; thus,

$$V_{dc} = \frac{3}{\pi} \int_{\pi/6}^{5\pi/6} [V_1 \sin\ \omega t + V_5 \sin\ (5\omega t + \phi_5) + V_7 sin(7\omega t + \phi_7)]\, d\omega t \tag{1.6}$$

Completing this integration leads to,

$$V_{dc} = \frac{3\sqrt{3}}{2\pi} V_1 \left(1 - \frac{1}{5}\frac{V_1}{V_5} \cos\ \phi_5 - \frac{1}{7}\frac{V_7}{V_1} \cos\ \phi_7\right) \tag{1.7}$$

1.2.3 Harmonic Effects on Multi-pulse Converter

Multipulse converters employ phase-shifting transformers to allow the cancellation of certain harmonic currents. The transformers also alter the phase of power source line voltage harmonics, but in an adverse way. For example, assume the 5th harmonic voltage at the source is at an angle of 0°. For a 12-pulse system with a second converter supplied at +30°, the 5th harmonic in the supply for the second converter will be at (−5 × 30) − 30, that is, −180°. (Advance phase A basic in **Figure 2-1** by π/6 to see this). A 2.5% 5th harmonic voltage will cause the dc output of the first converter to reduce by 0.5% and the second converter to rise by 0.5%. If, for example, two 620 V dc converters are paralleled, there will be a dc voltage imbalance of 6.2 V. If this voltage is not rectified by rectifying measures, it will produce a severe current imbalance. In turn this introduces

6 pulses harmonics to the line currents. The 7^{th} harmonic causes even further unbalance if it has the same phase shift ϕ.

In practice the harmonic voltage phase angle is difficult to define, because it is a function of converter design and system parameters. The precise phase relationships of various harmonics are not known exactly [5].

1.3 Multipulse Methods and Transformers

1.3.1 Rectifier Topology and Multipulse Methods

The word "multipulse" lacks a specific meaning, although in the context of power electronics, it often means converters running in a three-phase system, producing more than six pulses of direct current (DC) every cycle. Multipulse techniques include joining many converters in a way that balances out the harmonics generated by one converter with those produced by others. This technology successfully removes particular harmonics related with the number of converters, leading to enhanced power supply quality. Multipulse converters provide a basic and economical technique to minimize harmonics in power electronic converters, finding wide applications in high-power electrochemical systems. The rising employment of power converters for adjustable-frequency AC controllers has led to the development of multipulse approaches adaptable to lower power ratings, down to 100 HP and below.

Understanding the essential function of multipulse converters presupposes that the DC circuit is appropriately filtered, guaranteeing that any ripple caused by the DC load has negligible influence on the DC current. This is true for passive loads and most converters sending DC power to voltage-source inverters. However, it may be less appropriate to inverter loads of the current-source kind, where filtering and controls may be inadequate to prevent the DC load ripple from impacting the total ripple. In such instances, the AC line input current may cover a broad range of harmonics, including subharmonics that are not integer multiples of the source frequency. Conventional multipulse techniques may struggle to remove these non-integer harmonics.

Multipulse systems give two key benefits simultaneously:

1. Reduction of AC Input Line Current Harmonics
2. Reduction of DC Output Voltage Ripple

Multipulse methods are characterized by the use of multiple converters, or multiple semiconductor devices, with a common dc load. Phase-shifting transformers are an essential ingredient and provide the mechanism for cancellation of harmonic current pairs, for example, the 5th and 7th harmonics, or the 11th and 13th, and so on. First technique of multipulse methods is to use separate load for the converters.

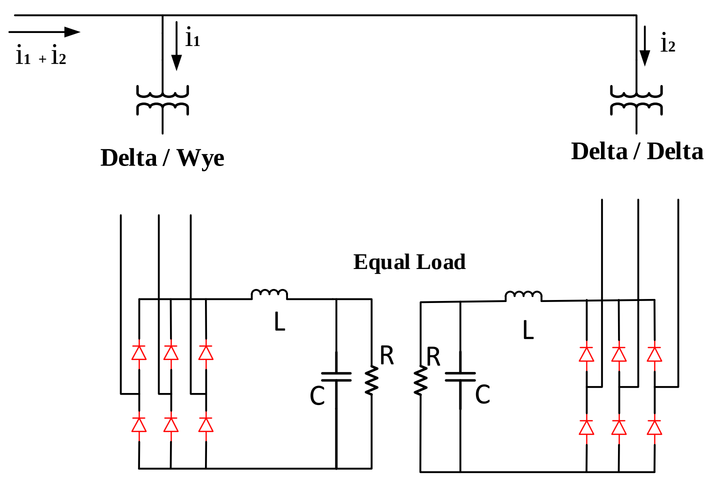

Figure 1.2: Two separate 6-pulse combined 12-pulse rectifier with separate load.

Here, in figure 1.2 two separate loads are fed through a transformer that produces a 3-phase set of secondary voltage shifted by 30^0 w.r.to the primary voltage. The other converter bridge is fed by secondary voltage from the delta/delta transformer, which have 0^0 phase shift. There is another method of creating multi pulse as like combining more than one converters within a single equipment and a single dc load. Here, the figure 1.3 shows two 6-pulse rectifier combined with a single shared load.

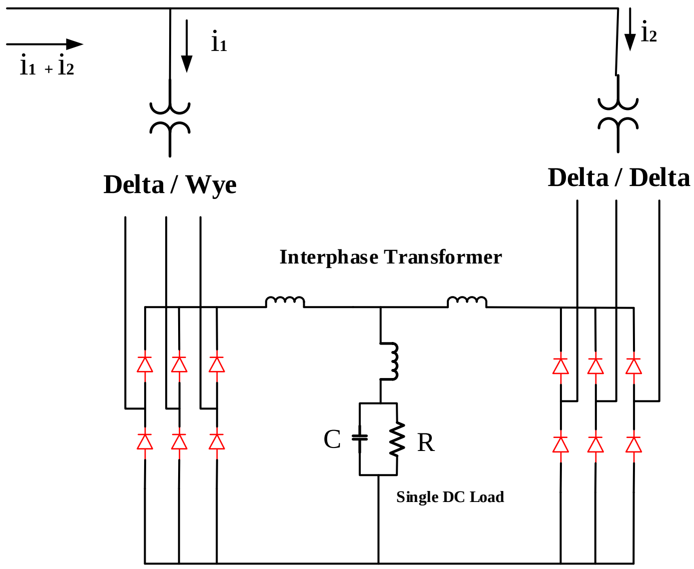

Figure 1.3: Two separate 6-pulse combined 12-pulse rectifier with combined load.

In figure 1.4, it is shown that to create 18 pulse DC output 3 full bridge rectifiers are combined in series with a single side load and therefore they are creating 18 pulse system. There is having another way of creating multipulse is to combine rectifiers in parallel with a single side load and hence create multipulse rectifier.

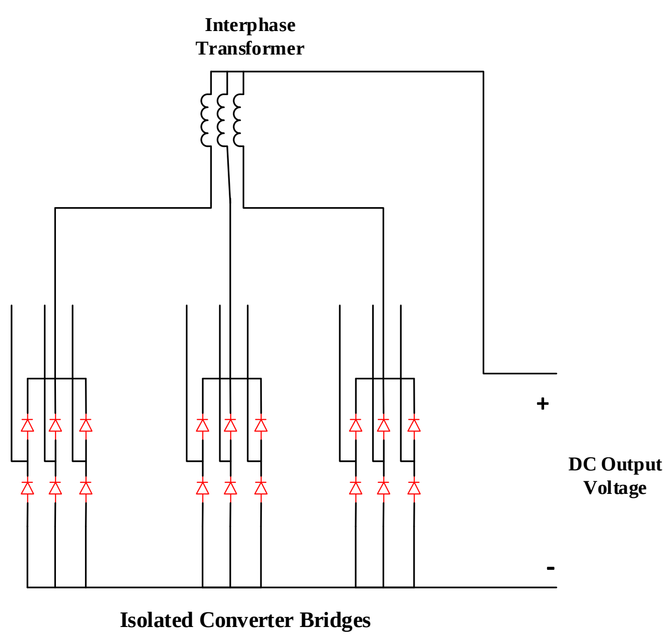

Figure 1.4: Three 6-pulse circuit combined as 18-pulse rectifier into a single DC load.

1.3.2 Multipulse Transformers

Phase shifting transformers are essential components in electrical power systems since they provide precise control over the phase angle connection between voltage waveforms. These transformers provide the manipulation of the phase shift in the output voltage compared to the input voltage, allowing for the management of power transmission and voltage levels within the system. Operators may enhance power flow and system stability by strategically positioning phase shifting transformers to precisely change phase angles. Phase shifting transformers are often supplied with tap changers or other control systems that enable operators to adjust the phase shift as needed for the system. Furthermore, these transformers are used in load balancing and power distribution scenarios, where the manipulation of phase angles aids in the regulation of voltage levels and the reduction of losses. Designing and operating phase shifting transformers need meticulous deliberation. To achieve best performance and dependability, it is crucial to consider factors such as the impedance of the transformer, load circumstances, and cooperation with other transformers.

1.3.3 Dot Convention representation of transformers

A standardized technique for representing the phase relationship and winding arrangement in transformers, particularly phase-shifting transformers, is the dot convention. To show the relative polarity of each winding in the transformer, a dot is placed on each winding. The precise placement of the dot, which is often positioned close to the winding's end, is crucial for figuring out the phase connection. If both dots have the same polarity (both on the top or bottom), the dot on one winding is said to be in phase with the equivalent dot on the other winding. If there are two dots with opposing polarities (one at the top and the other at the bottom), they are said to be out of phase. Understanding the desired phase shift between the main and secondary windings of a phase-shifting transformer depends on the use of the dot convention. Engineers can forecast whether the transformer will create a leading or lagging phase shift between the input and output voltages by using the dot standard [5].

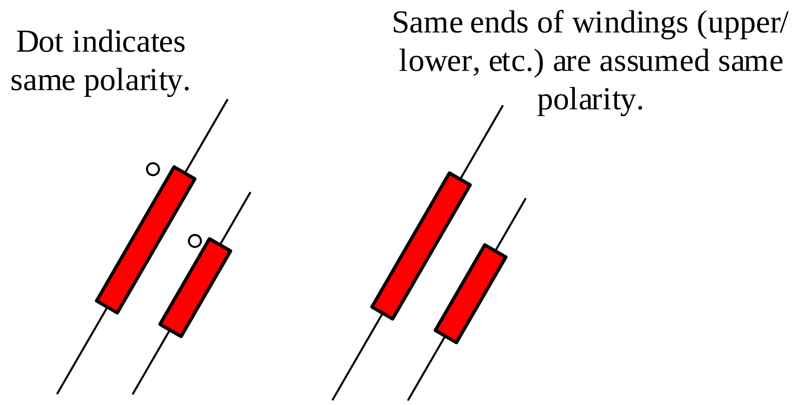

Figure 1.5: Interpretation of transformer polarity.

1.3.4 Isolated Transformers

Wye-wye (Y-Y):

Two Y-shaped windings, the primary and secondary, are connected in a Y-Y (Wye-Wye) configuration in a three-phase transformer. This indicates that a Y is formed by three linked coils on each winding. The three windings of the connection come together at a single point called the neutral, which defines the connection. This neutral point serves as the system's main point of reference. The Y-Y connection's neutral point is one of its noteworthy features. This makes connecting single-phase loads easy and may be helpful for grounding. The voltage in the main and secondary windings may be changed thanks to the Y-Y connection. The phase voltage on both the main and secondary sides is √3 times the line voltage. Phase shifts between the main and secondary voltages are not naturally introduced by the Y-Y connection. It is appropriate for applications where keeping certain phase connections is essential because of this feature. Distribution systems often employ the Y-Y connection, especially when the neutral point is needed for grounding and to serve both single-phase and three-phase loads. A certain amount of harmonic suppression occurs in the system as a result of the Y-Y connection's inherent high resistance to the passage of third harmonics [5].

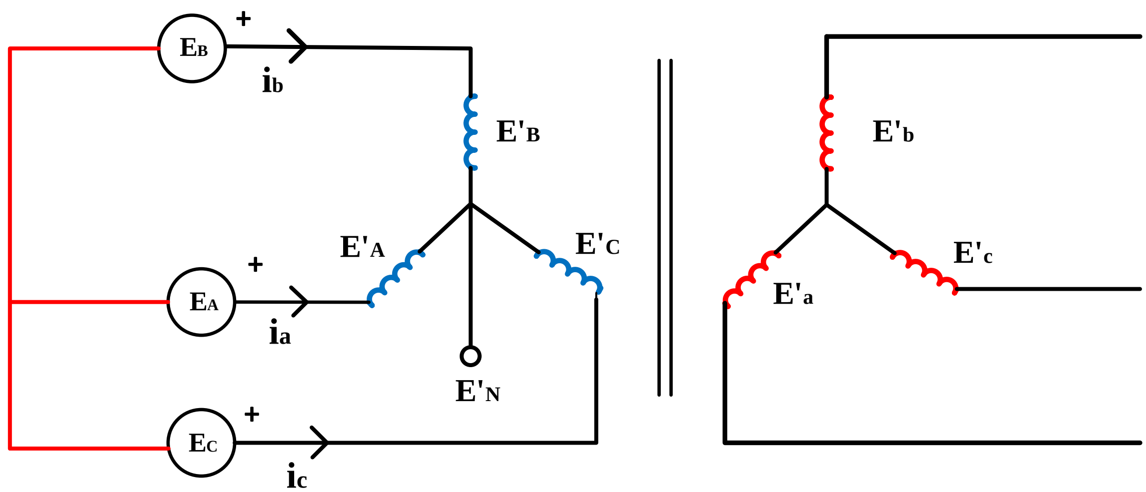

Figure 1.6: A simple connection of Y-Y transformer [6].

Wye-delta (Y- Δ):

A 3-phase transformer with a wye-delta (or star-delta) connection has a primary winding arranged in a wye (Y) shape and a secondary winding arranged in a delta (Δ) shape. When exact phase connections are crucial. There are two possible d connections for the transformer's secondary three-phase windings. There is a distinct phase-shifting with these two d connections. A positive 30° phase-shifting is produced via the Y- Δ 1 connection, meaning that the secondary VAB voltage trails the main VAB voltage by 30°. In contrast, a negative 30° phase-shifting is produced by the Y- Δ 2 connection, meaning that the secondary VAB voltage lags the main VAB voltage by 30°.The line-to-line voltage on the secondary side (Δ connection) is √ 3 times the phase voltage, it is equal to the phase voltage on the main side (Y connection). On the main side, the line-to-line current equals the phase current, while on the secondary side, it is three times more. There is no difference in the kVA rating between the main and secondary sides. Nonetheless, the secondary delta winding's current is about three times more than the main wye winding's current, which impacts the windings' ability to transport current [6].

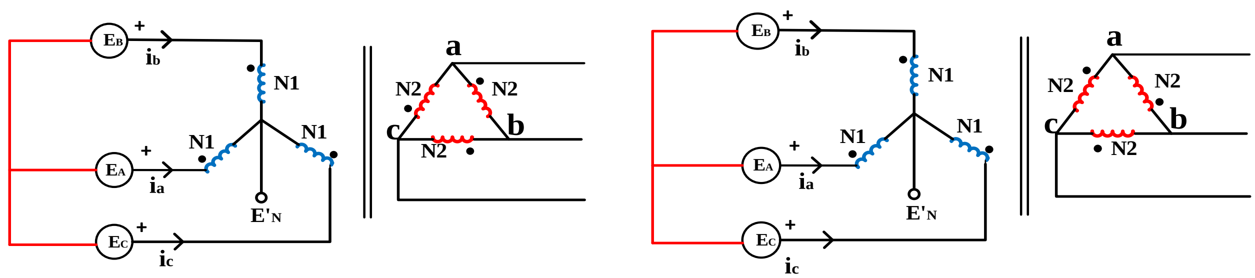

Figure 1.7: Two Δ connection of transformer secondary windings (a) Y- Δ1 and (b) Y- Δ2 [7].

Wye-zigzag (Y-Z1 and Y/Z2):

There are two alternative configurations for the secondary three-phase transformer windings Z connection. Figure 1.8 illustrates both of these z relationships. The Y-Δ connection has been shown to produce a continuous phase-shift of ±30° in the past. It is shown that by varying the voltage ratios of the secondary windings N2 and N3, variable phase-shifting for the Y-z connection might be achieved.

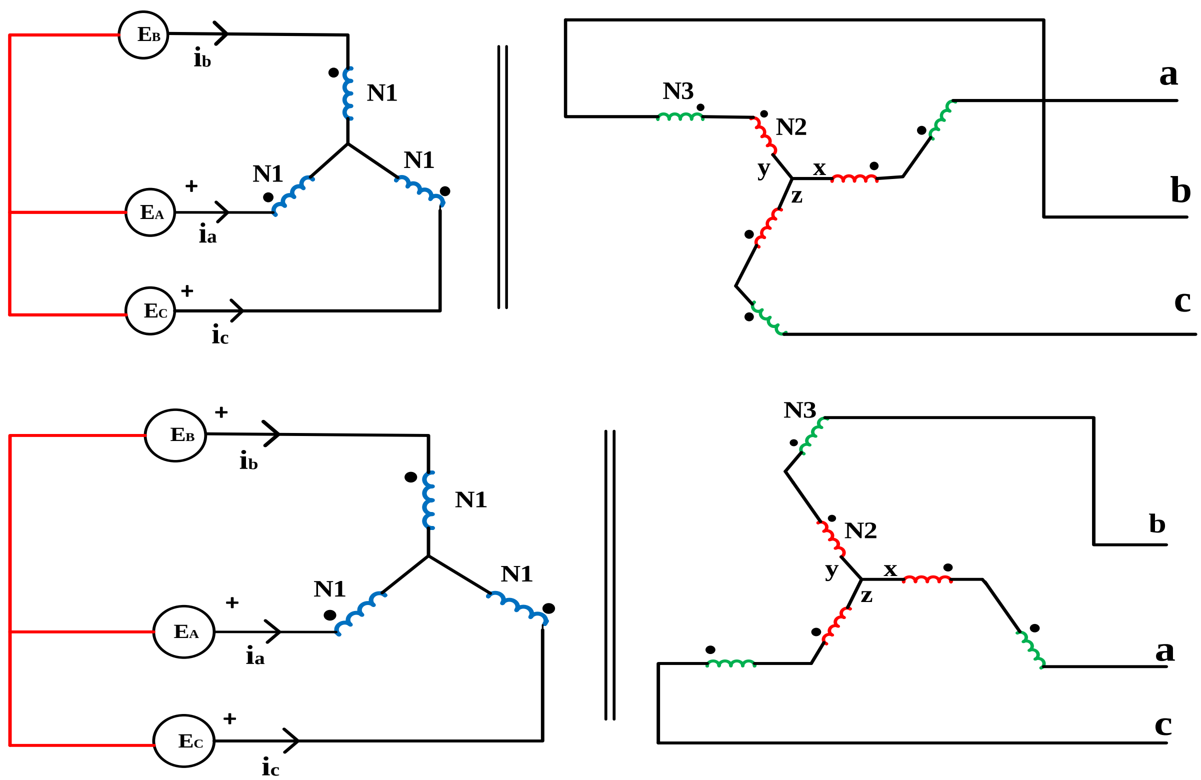

Figure 1.8: Two Z connection of transformer secondary windings (a) Y-Z1 and (b) Y-Z2 [7].

Figure 1.8 shows how the transformer's phase-shifting is varied as a consequence of this voltage ratio. The phasor diagram of the secondary windings of the Y-z1 transformer to the primary voltage VAB are shown in Figure 1.8 (a). As a result, the phase-shifting angle and the voltage ratio V_{N2}/V_{N3} of the secondary windings of the Y-z1 transformer are inversely related. For the Y-z2 transformer, the same conditions and guidelines are used, as Figure 1.8(b) illustrates.

The voltage ratio V_{N2}/V_{N3} has to be adjusted to a minimum and maximum in order to define the phase-shifting range for the Y-z1 and Y-z2 transformers. Consequently, the Y-z1 transformer's phase-shifting range is 0° to 60°, whereas the Y-z2 transformer's phase-shifting range is -60 - 0° [6].

1.3.5 Autotransformer:

The autotransformer is both the simplest basic and the most intriguing of the connections using two windings. It is used relatively frequently in bulk power transmission networks because of its ability to double the effective KVA capacity of a transformer. The autotransformer is a kind of transformer where the main and secondary windings share a part of the same winding, unlike ordinary transformers where the windings are distinct. In an autotransformer, a section of the winding functions as both the main and secondary winding. The shared winding normally consists of a common part and two extra sections that operate as the main and secondary windings.

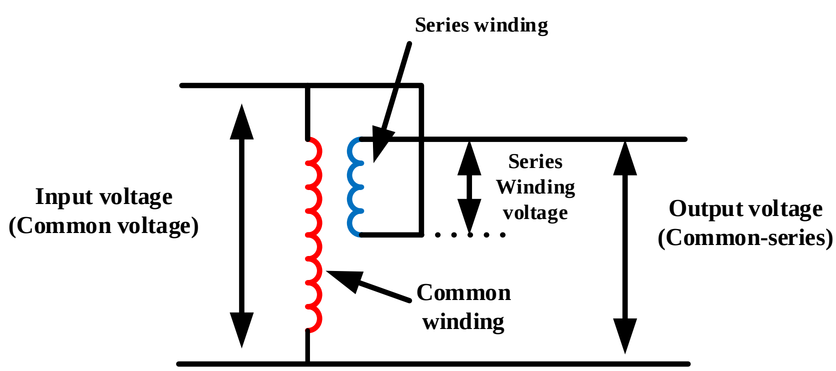

Figure 1.9: A simple autotransformer connection [7].

Here is a simplified structure of autotransformer in figure 1.9**.** Autotransformers feature a single winding with a tapping point, which minimizes the amount of copper and iron consumed compared to dual-winding transformers. The tapping point allows for variable voltage output by altering the connecting point along the common winding. Autotransformers may step up or step-down voltages dependent on the location of the tapping point. Due to the shared winding, autotransformers are frequently more efficient than conventional transformers, since they have smaller copper losses [7].

1.4 Harmonic Standards and Requirements

The THD is defined as the ratio of the RMS value of the harmonics (i.e. exclusive of fundamental) to the RMS value of the fundamental. The THD is formulated in equation (8) as,

$$\text{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_L} \tag{1.8}$$

Here,

I_n = n^{th} harmonic RMS current.

I_L = Maximum demanded load current (Fundamental frequency component).

n = Number of harmonics.

The system harmonic current limits recommended in **IEEE Std 519-1992** are shown in table-1.1 for a 6-pulse system.

Table 1.1: Harmonic current limits recommended in IEEE Std 519-1992.

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{sc} / I_L	**<11**	**11≤ n ≤ 17**	**17≤ n ≤ 23**	**23≤ n ≤ 35**	**35≤ n**	**THD**
< 20*	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0

50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.
Even harmonics are limited to 25% of the odd harmonic limit above						

Where,

I_{sc} = Maximum short circuit current in RMS.

I_L = Maximum load current (Fundamental frequency component).

1.5 Principal Objectives of the Thesis

The primary objectives behind this thesis can be summarized as follows:

- To offer a comprehensive overview of multipulse converter technology with a focus on passive current injection scheme.
- To conduct detail analysis of cost-effective, high reliability, reduced complexity, low component count operation based on multipulse rectifier system.
- To address the limitations of passive harmonic suppression scheme and propose solutions to overcome shortcomings ensuring effectiveness of harmonic mitigation methods.
- To optimize and enhance AC current profile and DC output voltage for various load contributing improved over all power quality.
- To propose an efficient method for enhancing input power quality in three-phase supply systems that aligns with regulatory standards and requirements.

1.6 Motivation

The imperative obligation to solve the ever-increasing problems in power electronics and improve the power quality in a variety of industrial applications drives the investigation of multipulse rectifiers. Reduced values' pulse arrangement is crucial in determining the output waveform's harmonic content, which in turn affects Total Harmonic Distortion (THD), efficiency, and system performance as a whole. AC-DC converters are crucial parts of a wide range of applications, including motor drives, renewable energy systems, and the power supply for electronic devices. A superior power output is necessary to guarantee reliable operation.Computers, medical equipment, and communication systems are examples of sensitive electronic equipment that needs clean power free from harmonics and voltage swings. Voltage waveform distortion may occur due to harmonics produced by non-linear loads and converters. So the problem of harmonics need to fix somewhat. Figure 1.10 provides a thorough overview of various multipulse rectifier, highliting the particular THD value and KVA ratings in recent days [8].

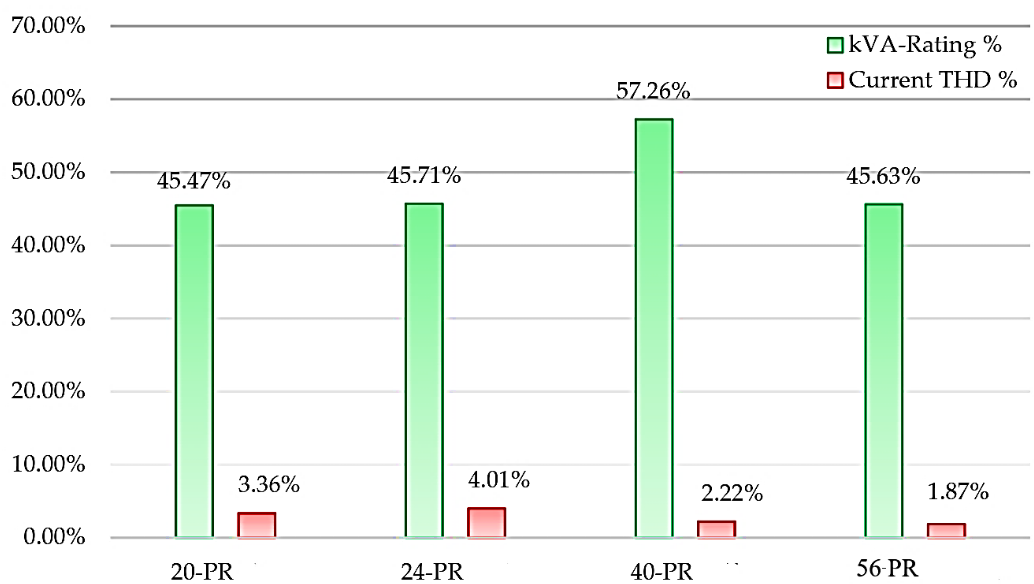

Figure 1.10: Various pulsing rectifier and their current THD including KVA ratings [8].

To maintain stable and reliable power conversion it is needed to reduce input line current THD thus enhancing the output power quality. So, the primary motivations of this thesis are given as following:

- **Compliance with Standards:** In an effort to meet strict requirements like IEEE-519 and get even lower THD levels, pulse combinations other than the traditional 12 pulses are being pursued. In order to push the envelope in terms of harmonic mitigation, it is critical to investigate higher pulse designs as industries want cleaner and more reliable electricity. Thus, exploring the higher pulse design is one of the important motives of this thesis.

- **Adaptability to Varied Loads:** Different load characteristics are seen in different industrial applications. It is possible to customize the rectifier's response to certain load situations by researching multipulse rectifiers with different pulse designs. This flexibility guarantees that gains in power quality are robust against dynamic and changing loads in addition to being successful in the best of circumstances.

- **Industrial Application and Economic Impact:** This field's diverse research has practical implications for sectors outside of the academic sphere. Reducing downtime, extending equipment life, and eventually saving industries money are all benefits of efficient and harmonically pure power systems. An effective way to accomplish these useful advantages is to do research in this broad area.

1.7 Contribution of Thesis

The main contribution of this thesis is elaborated on in the following section:

- One of the primary contributions of this thesis is the development of a new 24-pulse rectifier. This involves the design, analysis, and implementation of a rectification system that offers improved harmonic mitigation and enhanced performance compared to traditional rectifiers. The innovation lies in the incorporation of a passive current injection circuit based on dual auxiliary transformers;
- This study introduces the integration of DAT (Dual Auxiliary Transformer) for improved performance. This dual transformer setup is a novel approach aimed at achieving better control over the rectification process and optimizing the performance of the 24-pulse rectifier. The integration of dual transformers adds a unique dimension to the passive current injection circuit;
- The proposed scheme in this article is a current injection scheme, not a voltage injection scheme, so it does not need to connect large inductors in series on the input side,

avoiding the negative impact caused by these large inductors. This contribution directly impacts power quality, leading to a more stable and efficient three-phase supply system;

- In this study, a comprehensive design is proposed with PACIC (Passive Auxiliary Current Injection Circuit) and without using IPR (Interphase Reactor) and simulated in MATLAB that ensures the robustness and applicability of your proposed rectifier in real-world scenarios;
- The performances of the proposed rectifier converter are examined in terms of load variation, conduction loss, KVA rating of the PST (Phase Shifting Transformer), THD (Total Harmonic Distortion) of input side current, DC output voltage and total power that ensures the deployment of the new rectifier converter in real-world scenarios;

1.8 Thesis Organization

The outline of the thesis is shown as follows:

- Chapter 1 represents an introductory part of this thesis by giving some basic ideas of multipulse method. In addition, it also introduces with some basic transformer that is used in multipulsing method and in this chapter, it also presents the principal objectives this thesis and contributions through this thesis.
- Chapter 2 of this thesis includes an in-depth study of the theoretical framework that is important to the investigation. In addition, this chapter includes an in-depth overview of the available literature relevant to the unique multipulsing techniques.
- Chapter 3 provides a comprehensive analysis of the multipulse structure and configuration of various phase shifting transformer. This chapter gives, the basic theory related to multipulsing method and showcasing existing topology. This chapter discusses all the part of uncontrolled rectifier that is being used for AC-DC conversion.
- Chapter 4 explains the proposed multipulse rectifier. In-depth discussion a novel current injection technique to obtain 24-pulse at the dc side along with minimized THD is discussed in this chapter.
- Within Chapter 5, the performance of the proposed rectifier is analyzed. In this chapter, the result discussion of the proposed 24-pulse rectifier with and without passive current injection is given.

- Chapter 6 serves as the platform for presenting concluding remarks and outlining potential areas for future improvement of 24-pulse rectifier within the proposed passive current injection.

1.9 Conclusion

This chapter provides a thorough synopsis of the core concepts covered in the thesis book. This subject covers the representation of voltage vectors, an introduction to power system harmonics, a variety of multipulse techniques, distinct PST categories, and worldwide harmonic standards. Additionally, a basic summary of the thesis concerns is presented in this chapter. But the purpose of this chapter is to provide readers a thorough overview so they are familiar with the book's material. The next parts will expound on the fundamental ideas and objectives of the thesis. The chapter ends with a summary of the thesis book's organization and structure, highlighting its significance.

Chapter 2
Theoretical Foundation and Literature Review

2.1 Theoretical Foundation

The theoretical foundation of this thesis is rooted in the fundamental principles of power electronics, rectification technology, and harmonic mitigation strategies. The foundation begins with an exploration of multipulse rectifiers, understanding their significance in reducing harmonic distortions and improving power quality. The concept of multipulse rectifiers was introduced to mitigate harmonic distortions in power systems. Initially, the focus was on reducing harmonic content generated by rectifiers with six pulses per cycle. In the mid-20th century, the 12-pulse, 24-pulse rectifier became a standard method for harmonic reduction [9-12].

In the 21st century, there has been a continued focus on improving the efficiency, reliability, and cost-effectiveness of multipulse rectifiers. Researchers explored novel transformer configurations, such as the use of dual auxiliary transformers, to enhance harmonic suppression. Additionally, advancements in semiconductor technology have facilitated the development of more compact and efficient rectifiers. The principles of multipulse converter technology, highlighting the need for sophisticated rectification systems to address the challenges posed by harmonics in modern power systems. Recent innovations in multipulse methods include the integration of passive current injection techniques. This involves the use of auxiliary circuits to inject specific currents and manipulate the harmonic profile of the rectifier output. These methods aim to achieve harmonic reduction without relying solely on active control elements [13-14].

Analysis of the effects of three phase uncontrolled bridge rectifiers on the power system can be found in many standard textbooks. However, most of the analysis are conducted with the assumption of a balanced input power supply condition. This condition is not necessarily true in many practical industrial systems, particularly in the presence of other nonlinear loads. Paper [15-16] the common proposition lies in their emphasis on innovative approaches to power systems. Both papers contribute to advancing power system technologies, showcasing inventive methodologies for efficiency improvement and fault protection in different contexts.

In [17-18] it introduces new methodology for 18-pulse and 24-pulse rectifier and also introduces autotransformer in order to enhance the reliability and easy implementation of transformer and rectifier units.

Over time and based on real world scenarios introduces many more method of multipulse rectifier nowadays to improve power quality to ensure efficient power transfer between electronic devices.

2.2 Literature Review

The field of study has been characterized in recent years by a passionate investigation of phase-shifting transformer-based multipulse rectifier systems. An increasing number of applications, such as industrial processes, renewable energy integration, and aerospace technologies, need for dependable and efficient power electronic systems, which has prompted this coordinated effort. Research on multipulse rectifier systems using phase-shifting transformers is an important field that has attracted a lot of attention from engineers and academics. Phase-shifting transformers provide a new dimension to these systems by enabling modulation of the rectified output and control over the firing angles. Because it is essential to obtaining higher power quality, lower harmonics, and overall system efficiency, this control flexibility has been the focus of many recent research. With the ultimate objective of satisfying the changing needs for dependable and efficient energy conversion systems in a range of applications, the literature demonstrates a dedication to the advancement of power electronics technology. In addition to improving multipulse rectifiers' performance, researchers' efforts have shaped this important field of study's future and opened the door for future innovation.

2.2.1 Literature Review on Multipulse Rectifier System with Passive Injection Technique

Multipulse rectifiers (MPRs) coupled in series are used to provide high-quality electricity for high-voltage and high-power events. Two common topologies serve as the theoretical basis for both passive and active harmonic reduction processes, as well as for the design and construction of unique harmonic reduction circuits (HRCs) [19]. In [20] author proposed a pulse doubling technique utilizing a ZSBT(zero sequence blocking transformer) .The addition of a pulse-doubling circuit, inherently a tapped inter-phase transformer(IPT), facilitates the attainment of a 40-pulse output that shows 4.3% THD of input line current attaining efficiency of 97.2% at full load. Due to the high current operation of the rectification devices, it is necessary to take into account the conduction losses. In addition to assessing power quality and conduction losses, KVA ratings of transformer, the weight and volume of the rectifiers are also factored in. But the drawback of the large current rectifier is that the load voltage cannot be changed and active component draw large current. [21].

Table 2.1: Literature review on multipulse rectifier converter.

Reference No	Achievement	Limitation
[22]	• Flexible load configuration. • Low KVA rating (1.16%) inverter needed. • Input line current THD less than 2%.	• 3 additional current sensors. • Active IPT scheme is used.
[23]	• Compromising input line current THD only 1.39%. • Adaptable load variation facility.	• Complex autotransformer configuration. • Additional two-stage auxiliary circuit.
[24]	• No commutation over-lap in the pulse multiplication circuit. • Depressed ripple co-efficient (4.19×10^{-3}) of load voltage.	• Existence of leakage inductance in main transformer.
[25]	• No requirement of additional IPR and ZSBT. • Lower volume and higher power density of rectifier.	• Increased KVA ratings of transformer (28.5% of load power).
[26]	• Less conduction loss in IPR. • Input current THD less than 5%.	• Additional inductor required with the source. • Bulky auxiliary circuit.

[27]	• Expelled ZSBT in zigzag configured autotransformer. • Minimized input current THD of 3.12%. • The magnetic ratings of the system is only 30.3%.	• Complex connection of transformer.
[28]	• Improved input power factor. • Simple method and easy to realize. • Input line current THD of 6.58%.	• Leakage inductance and commutation process ignored.
[29]	• Expelled the use of active filter. • Simple and inexpensive auxiliary supply. • Evolved input current THD of 4.9%	• Additional PWM inverter.
[30]	• Exploit dc side filter. • Simple integration of dc energy storage.	• High leakage inductance of transformer. • High equivalent series resistance of transformer.
[31]	• Combine active and passive injection method. • Remarkable harmonic suppression effect.	• Complex operation. • Bulky circuit system.
[32]	• Overall weight and size of circuit comparatively low. • Hybrid injection method.	• Switch synchronization requires additional sensing device. • Low current ratings of active device.

[33]	• Provide comprehensive balancing strategy of capacitor voltage. • Propose multilevel inversion and reduced split dc link.	• Required additional bidirectional switch.
[34]	• Present a improved power factor enhancing power quality system. • Offer low cost, better performance harmonic reduction mechanism.	• Need of additional input side inductor.
[35]	• Low component count, better performance. • Good power factor (0.991). • High immunity to imbalanced problems of rectifiers.	• High supply frequency (400Hz).
[36]	• Sensitive to variation of input voltage. • Better performance, good ripple factor (1.88×10^{-3}). • Minimized input line current THD (5.04%).	• Complex multi winding IPR configuration. • Bulky circuit.

2.3 Chapter Summary

In this chapter, a potential investigation has been conducted to give a optimized overview of the different multipulse ac-dc converters utilizing different passive injection method used in versatile area of power system. The advanced multipulse rectifier techniques have proved to be more effective than the conventional multipulse converters ensuring precise improved power factor, minimized THD of input line current and conduction loss, compromised supplementary circuit and hence provide better performance and improved power quality to the system. This chapter is primarily dedicated to a review of literature of the existing topology that highlights their achievements and limitations. With conclusion of this segment, the integration of currently available rectifier converter familiarization is done in the literature.

Chapter 3
Modeling of Multipulse Rectifier Converter

3.1 Dynamics of AC-DC Multipulse Rectifier Converter

AC-DC multipulse rectifier converter contributes in providing sustainable, reliable and efficient conversion of electric power. Its primary purpose is to ensure mitigation of harmonic distortion by eliminating higher frequency components from electrical supply leads to stable operation of various load as well as compliance with power quality standards and thus provide an expansion in the power system. In this section, a comprehensive, reliable and efficient modelling of multipulse rectifier will be conducted. It includes the representation of standard power supply units, energy-efficient and high-performance PST (Phase Shifting Transformer), bridge rectifier units, passive injection units, filtering and load units. An examination of existing 24-pulse rectifier with passive auxiliary current injection circuit at DC side model will be illustrated in this part and the difficulties of modelling passive injection will be depicted. A basic block of multipulse rectification method with passive injection is shown in figure 3.1.

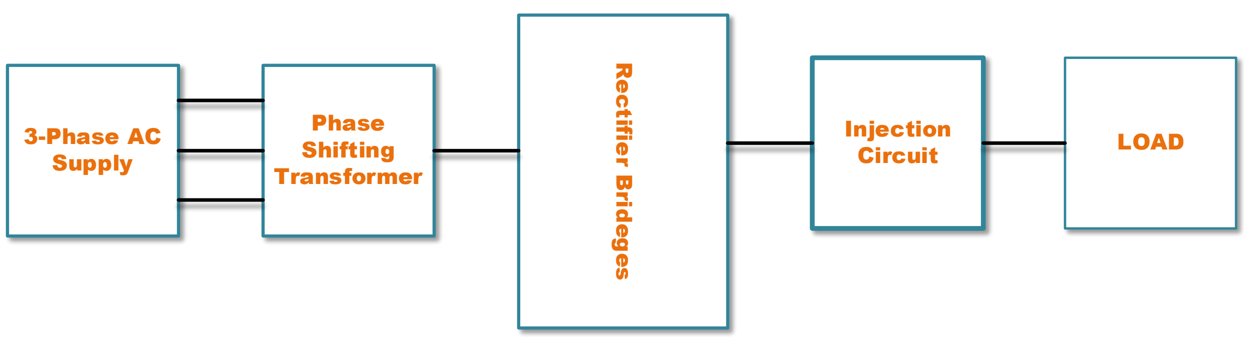

Figure 3.1: A basic block diagram of a AC-DC rectifier converter.

3.2 Power Supply

In electrical power systems, three-phase alternating current (AC) is a common and efficient method of distributing electrical power. It involves three sinusoidal waveforms, each phase-shifted by 120 degrees from the other, providing a continuous and balanced power supply.

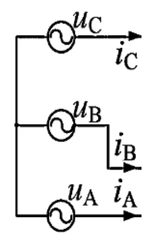

Figure 3.2: A balanced 3-phase AC supply system.

Figure 3.2 shows a basic representation of a balanced three phase AC supply. General representation of phase voltages V_A, V_B, V_C are configured at chapter 1 in equation (1.1), (1.2) and (1.3). The line-line voltage of this balanced system is expressed as,

$$v_{LL}(t) = \sqrt{3} \times v_{ph}(t) \tag{3.1}$$

Where V_{ph} is the phase voltage. In balanced power supply line current I_L and the phase current I_{ph} are expressed by the relationship as,

$$I_L(t) = I_{ph}(t) \tag{3.2}$$

There are some power supply considerations to design a multipulse rectifier converter that comply with relevant standards such as IEEE-509. There is also some parameters i.e. power factor, input line current THD that must be considered. A basic equation of power factor (PF) for a 3-phase balanced supply can be expressed as,

$$\text{PF} = \cos\varphi \tag{3.3}$$

Where, φ is the phase angle between voltage and current waveform. For a balanced three-phase system with a purely resistive load, the power factor is unity (PF=1), and the phase angle (ϕ) is 0 degrees. In situations where the load is not purely resistive (e.g., with inductive or capacitive components), the power factor may be less than 1, indicating a phase shift between voltage and current.

3.3 Transformer Models

Within the domain of transformers, there are several distinct types, each designed to serve specialized purposes. This study focuses on the investigation of commonly used transformer types in power electronic converters. Notable examples of these transformers include the modified star configuration transformer, zigzag-configured transformer, autotransformer, hexagonal transformer, fork transformer, polygon autotransformer, delta-star/double-star transformer, star-delta/extended delta transformer, isolated transformer, and others. The main emphasis is on comprehending and enhancing the efficiency of these transformer setups in the setting of power electronic converters. Among them some of the transformers are discussed in the next section.

3.3.1 Delta / Delta-Wye (Δ / Δ-Y) Transformer

A Delta/Delta-Wye transformer, also known as a "Scott-T transformer" is a specialized configuration used for transforming electrical voltage in power systems.

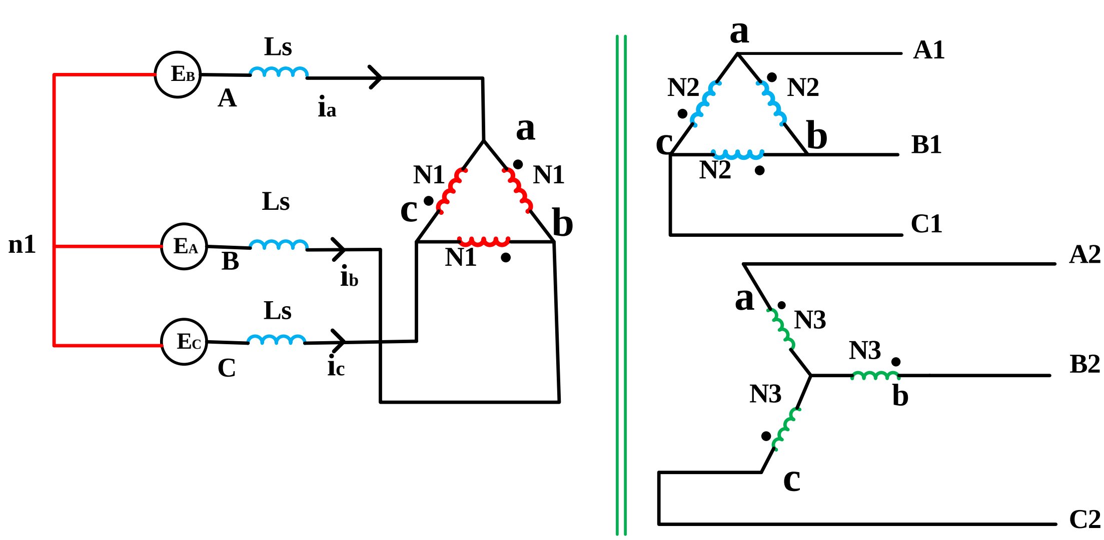

Figure 3.3: A delta / delta-wye (**Δ / Δ-Y**) transformer connection [37].

The primary purpose of the Delta/Delta-Wye transformer is to introduce a 30-degree phase shift between the primary and secondary voltages [37]. The primary winding on the high-voltage side of the transformer is configured in a delta (Δ) arrangement. This arrangement provides a phase-to-phase voltage that is equal to the line-to-line voltage. Here the input voltages for the transformer are denoted by u_{an1} , u_{bn1} , u_{cn1} and expressed as,

$$u_{an1} \approx \frac{\sqrt{2}E}{K} \sin\left(wt - \phi\right) \tag{3.4}$$

$$u_{bn1} \approx \frac{\sqrt{2}E}{K} \sin\left(wt - 2\pi/3 - \phi\right) \tag{3.5}$$

$$u_{cn1} \approx \frac{\sqrt{2}E}{K} \sin\left(wt + 2\pi/3 - \phi\right) \tag{3.6}$$

Where, ϕ is the phase difference between ac voltage sources and input currents, ω is the angular frequency, k is the ratio coefficient of the Δ / Δ-Y transformer and E is the RMS value of the input voltages. The secondary winding on the low-voltage side is also arranged in a delta configuration. This maintains the phase relationship between the primary and secondary voltages. The tertiary winding, often referred to as the "teaser" winding, is arranged in a wye (Y) or star configuration. The wye configuration involves connecting one end of each winding together to form a common neutral point, while the other ends remain separate. This provides a neutral point **n_2** for grounding purposes and allows for the creation of a phase shift. The relationship between primary and secondary side voltages of the phase-shifting transformer satisfies that,

$$u_{an1} = \frac{1}{\sqrt{3}} u_{A1B1} \angle -\frac{\pi}{6} \tag{3.7}$$

$$u_{A1B1} = u_{AB} = \sqrt{3} u_{A2n2} \tag{3.8}$$

$$u_{B1C1} = u_{BC} = \sqrt{3} u_{B2n2} \tag{3.9}$$

Where, u_{A1B1} , u_{B1C1} are the line-line voltage for the Δ configuration of secondary windings and V_{AB}, V_{BC} are the line voltage of the AC supply and u_{A2n2} , u_{B2n2} are the phase voltage for the secondary winding Y configuration. The turns ratio of the Δ/Δ/Y phase-shifting transformer is expressed as

$$N1 : N2 : N3 = K\sqrt{3} : \sqrt{3} : 1 \tag{3.10}$$

Here, N1, N2, N3 are the turns ratio of Δ/Δ/Y transformer.

3.3.2 Delta/Zigzag (Δ / Z_1-Z_2) Transformer

A zigzag transformer, frequently referred to as a Delta/Zigzag (Δ/Z1-Z2) transformer. In this transformer, a secondary winding with a zigzag configuration (Z1-Z2) is combined with a delta (Δ) primary winding [38-41]. A phase-to-phase voltage matching the line-to-line voltage is provided by the main side setup. A zigzag configured model is shown in figure 3.4.

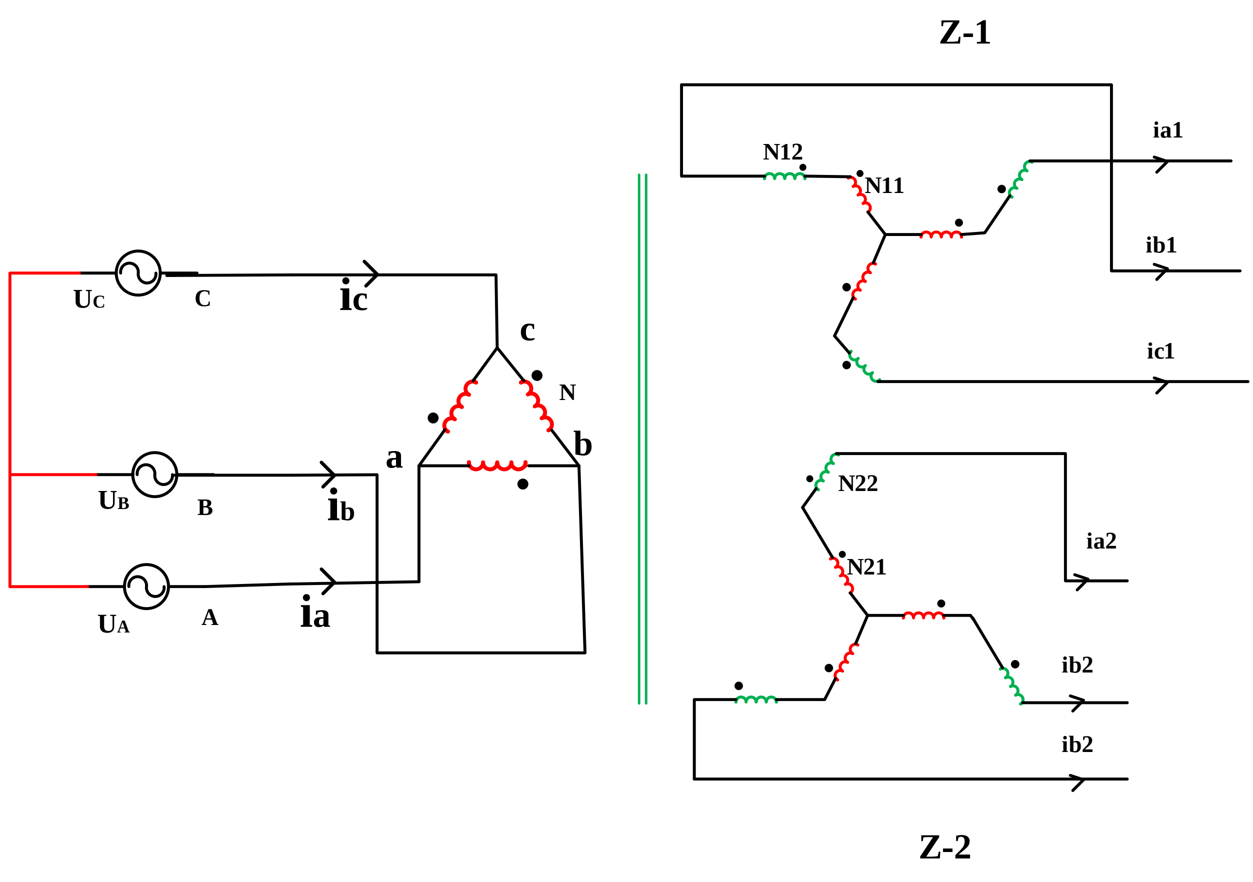

Figure 3.4: A delta / Zigzag (**Δ / Z1-Z2**) transformer connection.

There are zigzag patterns on the secondary winding. This entails zigzagging three windings together to form two "zigzag" pathways that are designated Z-1 and Z-2. A phase shift of thirty degrees is introduced between the main and secondary voltages by the zigzag arrangement. The turns ratio of the primary and secondary windings of the zigzag phase-shifting transformer in figure 3.4 is denoted by the ratio as,

$$N : N11 : N12 : N21 : N22 = \sqrt{3}: k: \frac{\sqrt{3}-1}{2} k: k: \frac{\sqrt{3}-1}{2} k \tag{3.11}$$

Where, N refers to the number of turns in primary windings, N11 and N21 are the numbers of turns of the long winding of the secondary windings, and N12 and N22 are the numbers of turns of the short windings of the secondary winding and the k refers to the ratio co-efficient of this phase shifting transformer. The voltage relationship between primary side to secondary side of this zigzag configured transformer can be expressed as,

$$V_{sZ1} = \frac{V_P}{\sqrt{3}} \tag{3.12}$$

$$V_{sZ1} = \frac{V_P}{\sqrt{3}} \tag{3.13}$$

Where, V_P denotes phase voltage in **Δ** windings, V_{sZ1} and V_{sZ1} voltage in the secondary zigzag windings for Z-1 and Z-2 respectively. The ability of the Zigzag transformer to ground is one of its main benefits. A neutral point that can be linked to the ground may be created through the use of the zigzag winding. Because of its ability to suppress harmonics, the zigzag design is useful in situations where a decrease in harmonic content is crucial.

3.3.3 Zero Sequence Blocking Transformer (ZSBT)

The zero-sequence components found in a three-phase system are blocked by zero-sequence blocking transformers (ZSBTs), which are typically constructed by wrapping the three phases around the same core limb. By restricting the zero-sequence current path, the ZSBT helps maintain a balanced system, prevents false tripping of protective relays, and enhances the overall reliability of the power distribution system. The zero-sequence current is blocked or severely hindered under typical working circumstances, while the positive and negative sequence currents pass through the series-connected windings. It is possible to stop the uncontrolled flow of current via the neutral and ground by selectively blocking zero-sequence current [42]. In order to create a multipulse system, phase-shifted rectifier units supplied by autotransformers are usually connected in parallel using ZSBTs. In particular, there is a possibility that large currents will reach fault levels if the converter in figure 3.5 is connected to an open winding three-phase output transformer with a low zero-sequence impedance (such as one that is wound on a three-limb core, has a zig-zag configuration, or has an auxiliary delta winding). Zero-sequence currents are often stopped from flowing in these situations by the circuit's ZSBT. This specialized transformer plays a crucial role in maintaining system balance and preventing undesirable consequences associated with uncontrolled zero-sequence currents.

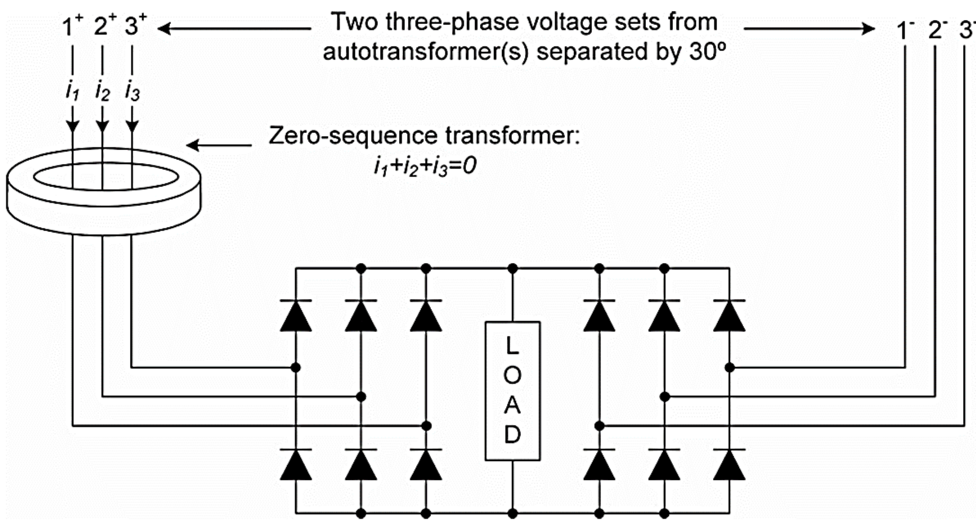

Figure 3.5: A basic ZSBT structure [42].

3.4 Multipulse Rectifier Design

Direct current (DC) is produced from alternating current (AC) by use of a power electronic converter called a multipulse rectifier. The rectifier's configuration, which uses many phases in its construction, is referred to as "multipulse". In high-power applications where harmonic distortion and power quality are crucial factors, these rectifiers are often used. In order to mitigate the harmonic distortion produced by traditional rectifiers, multipulse rectifiers were created. They do this by using the rectification process's many stages. Typical topologies for rectifiers include 6, 12, and 24-pulse, where the number denotes the number of pulses per cycle. Reducing the harmonic content of the input current and enhancing power quality are the main objectives of multipulse rectifiers. These rectifiers may significantly reduce harmonic interference by using phase-shifting methods and distributing the harmonic orders across many phases. A model of 24-Pulse Rectifier with a Passive Auxiliary Current Injection Circuit at DC Side is conducted in MATLAB Simulink environment and operations of the model are illustrated in this section.

3.4.1 Three Phase Uncontrolled Rectifier Design Methodology

Rectifier circuit nomenclature is based on descriptive name given in the following order:

- The connection of the transformer alternating-current windings.
- The number of pulses of the rectifier unit.
- The connection of the transformer direct-current windings and rectifying elements; and
- Type of circuit (single-way or double-way). In describing multiple rectifiers, the prefixes double, triple, and quadruple are used to indicate the number of component simple rectifiers, and the names diametric, wye, cross, star, fork, zig-zag, etc. are used to denote the connection of each component simple rectifier.

There are some terms that are related to the properties of rectifier circuit and terminologies that are that are depicted as:

- **Cascade rectifier:** a rectifier made up of two or more simple rectifiers coupled such that their commutations do not coincide but their direct voltages accumulate.
- **Commutation:** The transfer of unidirectional current between consecutively conducting components in a rectifier circuit is known as commutation.
- **Full-wave rectifier:** a rectifier that uses both halves of each cycle to convert single-phase alternating electricity into pulsing unidirectional current.
- **Half-wave rectifier:** A rectifier that uses just half of a cycle to convert single-phase alternating electricity to pulsing unidirectional current.
- **Mode of operation:** A rectifier circuit's mode of operation is its distinctive pattern of operation, which is established by the order and length of conduction and commutation.

- **Rectifier transformer secondary coupling factor (Ks):** A way to indicate how much a 3-winding rectifier transformer's secondary winding are mutually coupled. Ks = 0 denotes completely uncoupled secondaries, which is the same as connecting two independent transformers with two windings each. A rectifier unit's short circuit current and voltage regulation are significantly influenced by the transformer Ks factor.
- **Displacement power factor:** The displacement component of power factor is calculated by dividing the fundamental wave's apparent power (volt-amperes) by its active power (watts), which includes the rectifier transformer's stimulating current.
- **Form factor:** A periodic function's form factor may be defined as the ratio of the root mean square value to the average absolute value, averaged during the function's whole period.
- **Ripple voltage or current:** The alternating component of a pulsing unidirectional voltage or current, whose instantaneous values represent the difference between their average and instantaneous values.
- **Total voltage regulation:** When rated sinusoidal alternating voltage is applied to the alternating-current line terminals and the load current is reduced from a certain value to zero, or light transition load for multiple rectifier circuits, the total voltage regulation of a rectifier unit is the change in output voltage, expressed in volts. The rectifier transformer must be on the rated tap in order for the effect of the alternating-current system source impedances to be seen from the rectifier primary terminals as if they were inserted between the line terminals and the transformer. The corrective action of any automatic voltage regulating means is not included in this.
- **Rated load of a rectifier unit:** The output power in kilowatts that can be consistently supplied at the output voltage specified. It might also be referred to as the unit's full load rating or 100 percent load.
- **Rated output voltage of a rectifier unit:** A rectifier unit's rated output voltage is the voltage that is used as the foundation for its rating. It is the average direct voltage at rated direct current between the assembly's or piece of equipment's dc terminals.

3.4.2 Design of a AC-DC Multipulse Converter

An existing model of a basic 24-pulse rectifier linked in series, together with a passive auxiliary current injection circuit (ACIC), is simulated using Simulink. The rectifier comprises a 12-pulse rectifier and an ACIC. The ACIC comprises a circuit that generates a circulating current, an auxiliary transformer known as the single-phase transformer (AST), and an auxiliary full-bridge rectifier referred to as the single-phase auxiliary full-bridge rectifier (ASFR). The ASFR device retrieves an alternating square-wave current from the direct current (dc) side and introduces it into the outputs of three-phase rectifier bridges in order to enhance the output state of these bridges [43].

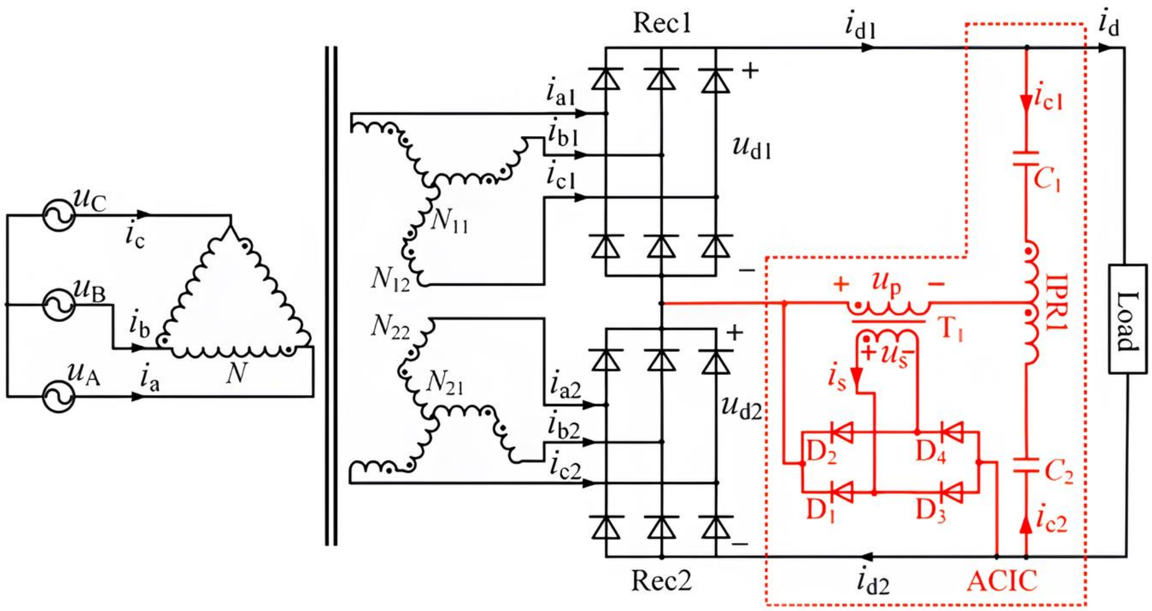

Figure 3.6: An existing model of 24-pulse rectifier converter [43].

3.4.3 Operating Modes

In figure 3.6, in accordance with the relationship between the input voltage us of ASFR in ACIC and the output voltage u_{d2} of Rec2, the proposed rectifier has four operating modes, namely O1-mode, O2-mode, N-mode, and P-mode.

O1-mode:

When $u_s<u_{d2}$, the proposed rectifier works in O1-mode. In this mode, the ASFR in ACIC is reverse-biased and switched OFF, and its input current is = 0. The current flowing through C1 and C2 in the circulation current forming circuit is also zero. At this time, the proposed rectifier works as a series-connected 12-pulse rectifier.

P-Mode:

In this mode, when $u_s>u_{d2}$ diodes D2 and D3 in ASFR are reverse-biased and switched OFF, whereas diodes D1 and D4 in ASFR are switched ON.

O2-mode:

In this mode, when $-u_s < u_{d2}$ the diodes in the ASFR are reverse-biased and OFF, the input current of ASFR is 0, and the current flowing through C1 and C2 is also zero. Under this mode, the proposed rectifier behaves as a conventional 12-pulse rectifier.

N-mode:

In this mode, when $-u_s > u_{d2}$ diodes D1 and D4 in ASFR are reverse-biased and switched OFF, whereas auxiliary diodes D2 and D3 in ASFR are switched ON. The input current -is is greater than 0. Rec1 is turned ON, and its output current id1 is greater than 0. Meanwhile, Rec2 is turned OFF, and its output current id2 is 0. The currents flowing through C1 and C2 in the circulation current forming circuit are greater than zero.

3.4.4 Design of Auxiliary Current Injection Circuit (ACIC)

The analysis of AST, ASFR, IPR1, C1, and C2 parameters is conducted in order to develop an ACIC. Under the optimal turns ratio, the RMS value of primary winding voltage U_p is expressed as,

$$U_{p-rms} = \sqrt{\frac{3}{\pi}\int_0^{\frac{\pi}{3}} u_p^2 \, d\mathrm{wt}} = 0.0143U_d \tag{3.14}$$

The RMS voltage of the secondary winding output U_s is

$$U_{s-\mathrm{rms}} = mU_{p-\mathrm{rms}} = 0.409U_d \tag{3.15}$$

Under the optimal turn ratio condition, the (RMS) value of interphase reactor voltage U_{IPR} is referred as,

$$u_{IPR\_rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} u_{IPR}^2 \, dwt} \tag{3.16}$$

It is noticed that the capacity of the IPR is only 0.092% of the output power. Capacitors C1 and C2 are used to block direct current, and together with AST, they make up a high-pass filter, which provides a path for the injected square-wave current i_p. The high-pass filter composed of C1 and C2 and AST should smoothly pass the fundamental component of i_P that is,

$$\frac{1}{2\pi R_{p1} C_p} = f_z < \frac{f_{p1}}{5} = \frac{6f}{5} \tag{3.17}$$

The values of C1 and C2 in ACIC can be obtained as,

$$C_1 = C_2 \geq 5.73 \frac{I_d}{U_{d_f}}$$

3.5 Load

To clarify the harmonic suppression performance of the rectifier under different load conditions, the input current THD of the rectifier when the load current is 1, 2.1, 3, 4.2, 5, and 6 A is classified. To describe the input current THD changing with load reasonably, the load factor k is defined as,

$$k = \frac{I_d}{I_{d-rated}} \tag{3.18}$$

Where, I_d is the actual load current, and $I_{d-rated}$ is the rated output current. When the load factor more than 0.5, the input current THD of the proposed rectifier can be less than 5%, which can fulfill the requirements of most industrial applications. To effectively suppress the impulse current generated when the rectifier starts in practical application, a starting resistor can be connected in series on the output dc-bus of the proposed rectifier, and the starting resistor can be cut off after the capacitors C1 and C2 are basically charged.

3.6 Chapter Summary

This chapter appears into the intricate details of multipulse rectifiers, addressing their design, the relevance of phase-shifting transformers, and considerations for power supply and load circumstances. It starts with an investigation of the power supply segment, highlighting the relevance of harmonics in power systems and the requirement for rectifiers that may attenuate these distortions. The subject then expands to numerous sorts of phase-shifting transformers and their specific uses in multipulse rectifiers. The chapter continues by discussing the design characteristics of multipulse rectifiers, reviewing essential factors for optimum performance, and assessing their behavior under varied load scenarios.

Chapter 4

Design of Proposed Rectifier

4.1 Proposed Multipulse Rectifier Converter

A proposal is made to improve the ability of the 12-pulse rectifier to reduce harmonics by using a 24-pulse rectifier linked in series. This 24-pulse rectifier includes a passive current injection circuit based on dual auxiliary transformers (PCIC-DAT). A novel method called PCIC-DAT (Passive Current Injection Circuit based on Dual Auxiliary Transformers) is developed, which involves a 24-pulse rectifier technology. This technology is shown in figure 4.1. The PCIC-DAT is put in parallel with the intended rectifier on the direct current (dc) side. The PCIC-DAT initially produces a square-wave current, which is then injected into the connection point of two three-phase bridge rectifiers (TPBRs). This injection enhances the operating modes of the TPBRs, resulting in the conversion of the series-connected 12-pulse rectifier into a new 24-pulse rectifier.

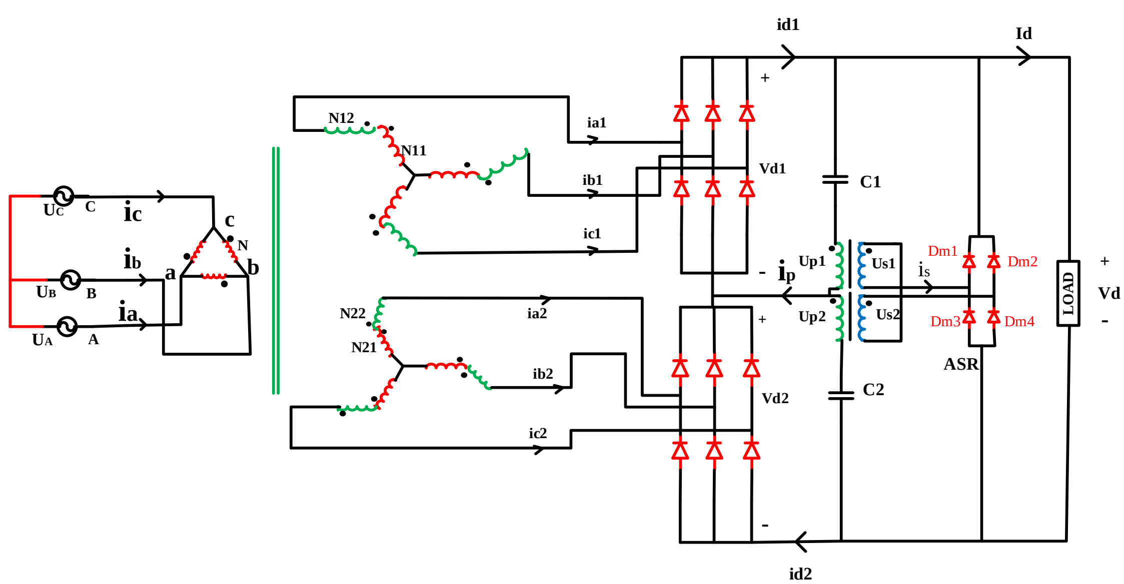

Figure 4.1: Proposed 24-pulse rectifier model.

This proposed approach utilizes a current injection method rather than a voltage injection method. As a result, it eliminates the necessity for connecting bulky inductors in series on the input side, hence avoiding the adverse effects produced by these huge inductors and the proposed scheme is designed with interphase reactor (IPR) and this is the main modification with the existing method.

4.1.1 Design of PST

A phase shifting transformer (PST) is included in the proposed multipulse converter along with two three phase bridge rectifiers (TPBR) connected in series in figure 4.1. The phase shifting transformer is a convention connection of delta/ zigzag isolated transformer. The Zigzag-configured PST is constructed with a certain winding turns ratio in order to create a phase shift of 30 degrees.

$$N : N11 : N12 : N21 : N22 = \sqrt{3}: k: \frac{\sqrt{3}-1}{2} k: k: \frac{\sqrt{3}-1}{2} k \tag{4.1}$$

N represents the quantity of rotations in the main windings. N11 and N21 represent the quantities of turns in the long winding of the secondary windings, whereas N12 and N22 represent the quantities of turns in the short windings of the secondary winding.

4.1.2 Design of the Proposed Rectifier

The suggested rectifier has three modes (mode-p, mode-q, mode-r) based on the relationship between the ASR input voltage (Us) and the output voltage (Vd). To describe the working modes of the rectifier conveniently, defined Up as the difference between the primary winding voltages Up1 and Up2 of two ASTs (auxiliary single-phase transformer), and Us as the difference between the secondary winding voltages Us1 and Us2 of two ASTs, which is,

$$Up = Up1 - Up2 \tag{4.2}$$

$$Us = Us1 - Us2 \tag{4.3}$$

Mode-P:

when |Us| < Vd, all diodes in the ASR are reverse-biased; that is, the ASR does not work, the input current of the ASR is zero, the PCIC-DAT has no modulation effect, and TPBR1 and TPBR2 work at the same time.

Mode-Q:

when Us > Vd, Dm2 and Dm3 in ASR are OFF, and Dm1 and Dm4 are ON. The input current is of ASR is greater than zero. At this moment, TPBR1 and ASR jointly supply power for the load, the output currents of TPBR1 and TPBR2 meet id1 > 0 and id2 = 0.

Mode-R:

When the value of −Us is greater than Vd, the topology being discussed functions in mode-R. In the state, TPBR2 plays a major role because of the modulation impact of PCIC-DAT. The TPBR2 and ASR deliver electricity to the load jointly. The output current id2 of the TPBR2 is larger than zero, whereas the output current id1 of the TPBR1 is equal to zero. The diodes Dm2 and Dm3 in the ASR are triggered and switched on, and the input current of the ASR is < 0.

This part also evaluates the kVA ratings of the ASTs in PCIC-DAT and the voltage and current levels of diodes in ASR, giving a reference to the implementation of PCIC -DAT. Some basic equation used to design 24-pulse rectifier. The rms value of the current which flows through the primary windings of T1, can be expressed as

$$I_{p1\_rms} = 0.0241\ I_d \tag{4.4}$$

The rms current that flows through the secondary windings of the transformer expressed as

$$I_{s1\_rms} = 0.683\ I_d \tag{4.5}$$

The rms value of U_{p1} can be calculated as

$$U_{p1\_rms} = 0.0144\ V_d \tag{4.6}$$

The rms value of U_{p1} can be calculated as

$$U_{s1\_rms} = 0.049\ V_d \tag{4.7}$$

The KVA ratings of the auxiliary transformer P is referred as

$$P=\frac{1}{2}\left(U_{P1\_rms}\times I_{p1\_rms}+U_{s1\_rms}\times I_{s1\_rms}\right) \tag{4.8}$$

It is recommended to choose the equivalent capacitance Cp in accordance with one-half of the crucial cut-off frequency, or Cp = C1 = C2, taking into account the cost constraint. The load here is used an R-L type. The basic parameters and values that are used in the modeling are given in a table-4.1.

Table-4.1: Parameter values used in the 24-pulse rectifier designing.

Components	Design Values
Power Supply	310V
Capacitor (C1= C2)	≥ 2500 uF
Trans ratio of the zigzag transformer	6.928:1:0.366:1:0.366
Rated output voltage, V_d.	250V
Rated output current, I_d	6A
Load filtering inductance	15mH

The primary passive components of the suggested diode rectifier are diodes and PST and no further control or driving circuits are needed. The proposed model is first simulated without PCIC-DAT and hence it worked as conventional 12-pulse rectifier. Then it is simulated using PCIC and as a result it has worked as 24-pulse rectifier and desired THD value has been found that is less than 5%. The performance of the designed rectifier is depicted in the next chapter.

4.2 MATLAB Model of 24-pulse Multipulse Rectifier

A MATLAB Simulink model of the proposed model is shown in figure 4.2.

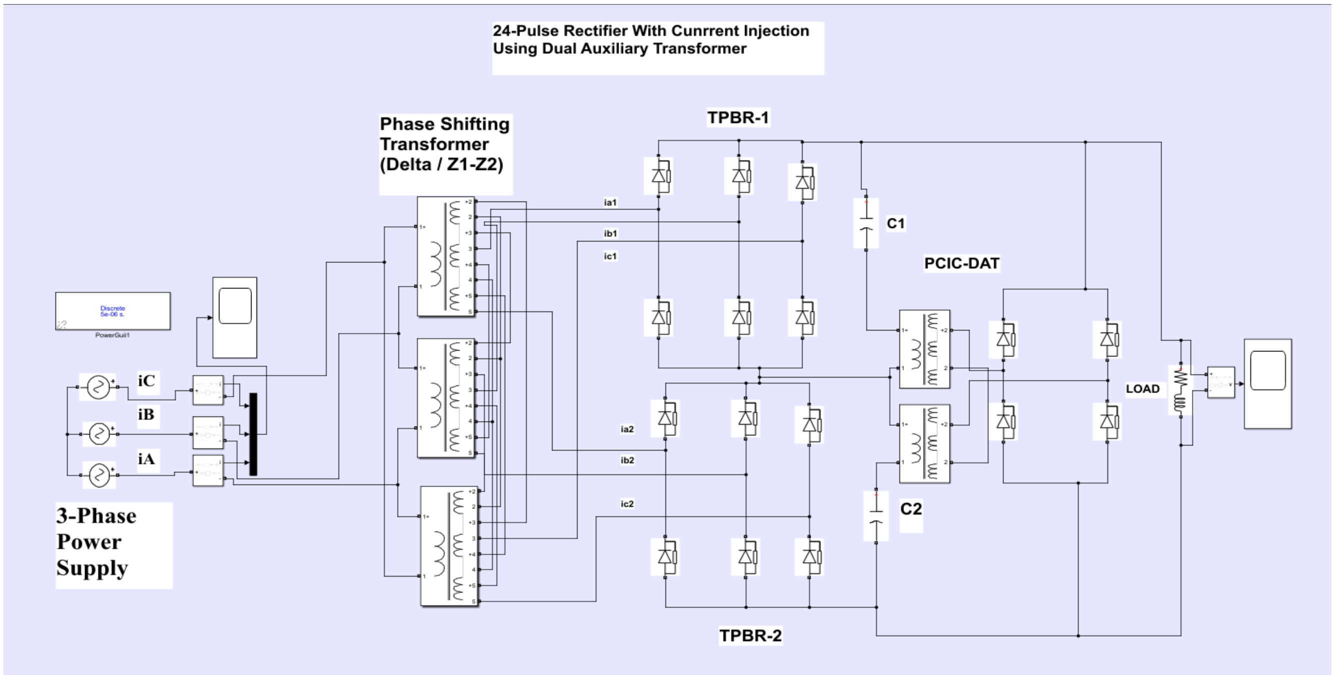

Figure 4.2: Proposed 24-pulse rectifier Simulink model.

4.3 Chapter Summary

In this chapter, a proposed design of 24-pulse rectifier with passive current injection mechanism using a dual auxiliary transformer and a single-phase bridge rectifier is discussed. In this section, the mechanism and operating mode of current injection technique is introduced. With phase shifting zigzag configured transformer 30-degree phase shifting is obtained for 12-pulse operation later using current injection technique 24-pulse is obtained and desired THD is found for the input line current and voltage ripple in the output section is also reduced.

Chapter 5

Performance analysis of proposed Multipulse Rectifier

5.1 Simulation Analysis of Proposed 24-Pulse Rectifier

In this section the simulated result of 24-pulse rectifier with PCIC-DAT and without PCIC-DAT are presented. Step by step the response from the rectifier in terms of input current profile, output load voltage and finally total harmonic distortion factor is shown in this chapter.

5.1.1 Response of the Designed Rectifier without PCIC-DAT

In figure 5.1, the input line current of the proposed 24-pulse rectifier without PCIC-DAT is shown. Without PCIC the rectifier act as 12-pulse rectifier. The level of input current can be seen from the wave form.

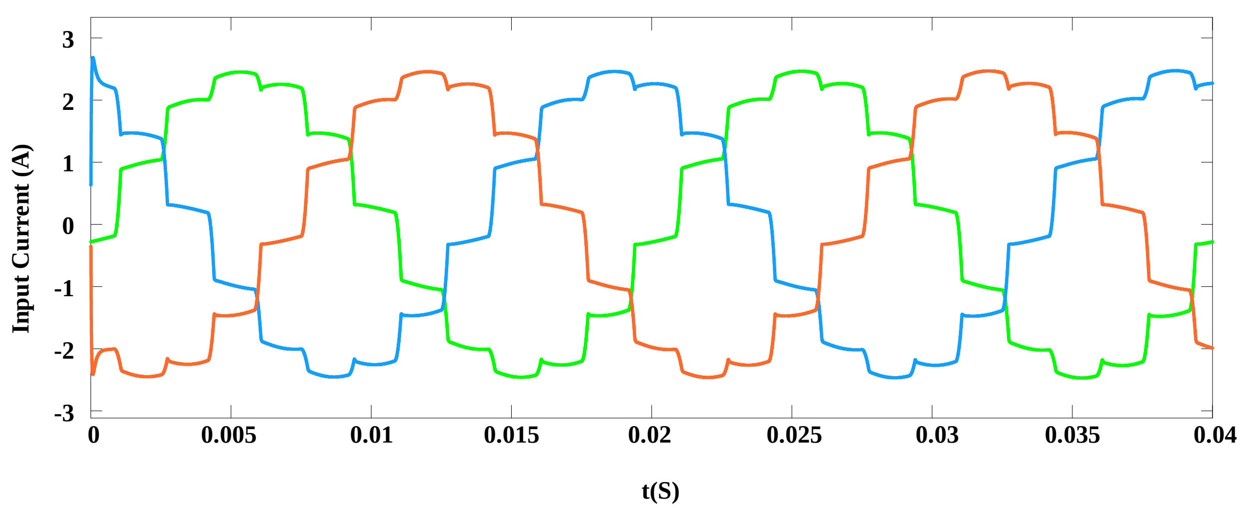

Figure 5.1: Input line current of 12-pulse operation of designed rectifier without PCIC-DAT.

In figure 5.2, the output voltage waveform is shown. It can be seen that without PCIC-DAT act as conventional 12-pulse rectifier.

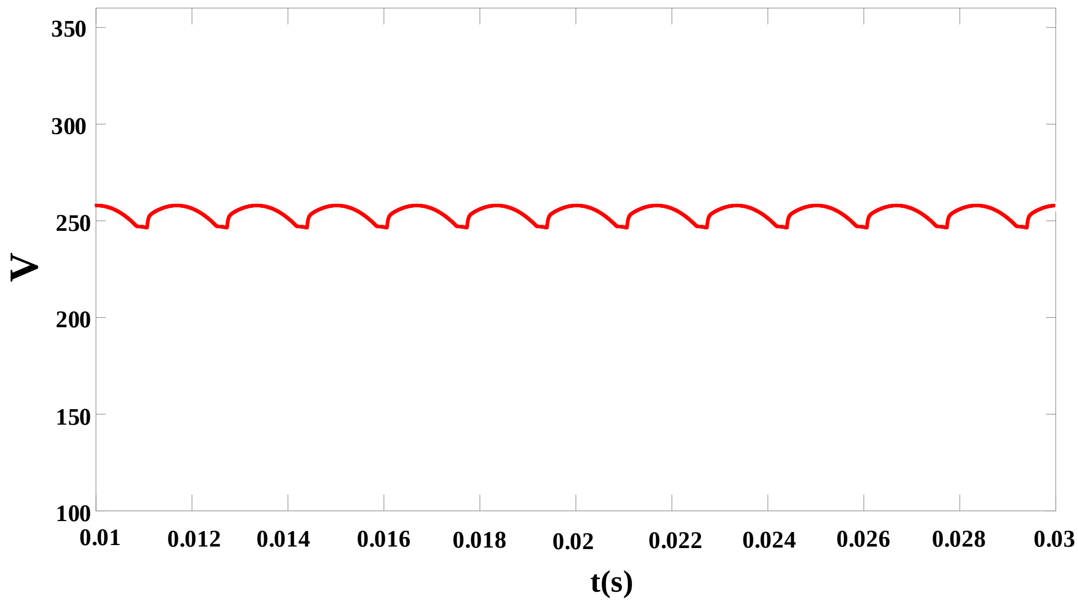

Figure 5.2: Output voltage of 12-pulse operation of designed rectifier without PCIC-DAT.

In figure 5.3, it can be seen that total harmonic distortion (THD) of input line current of 12-pulse operation of designed rectifier can be found 11.85% and which is greater than the IEEE-509 standards when it eliminates 11th and 13th harmonics.

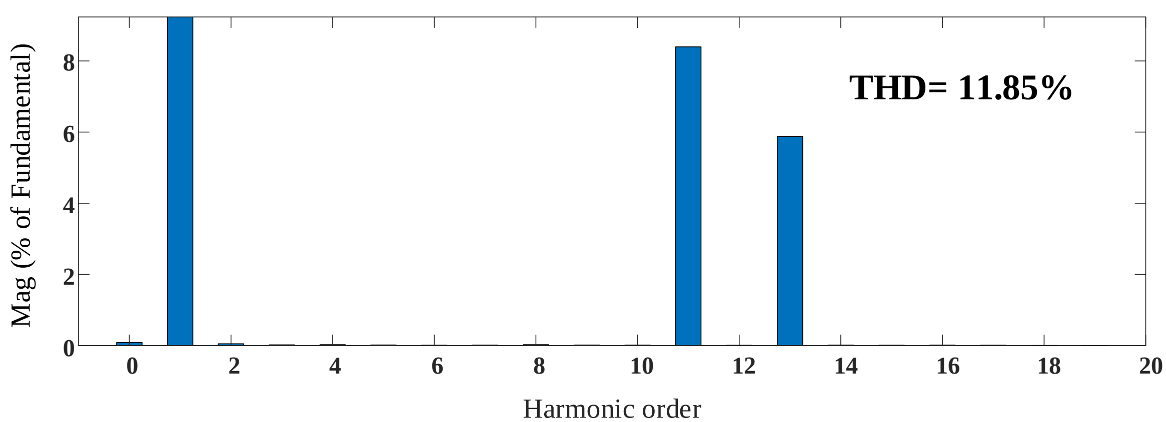

Figure 5.3: Total harmonic distortion of input line current.

5.1.2 Response of the Designed Rectifier Using PCIC-DAT

In figure 5.4, it is seen that the input line current of 24-pulse rectifier is quite good and that is the advantage of utilizing passive current injection circuit with dual auxiliary transformer.

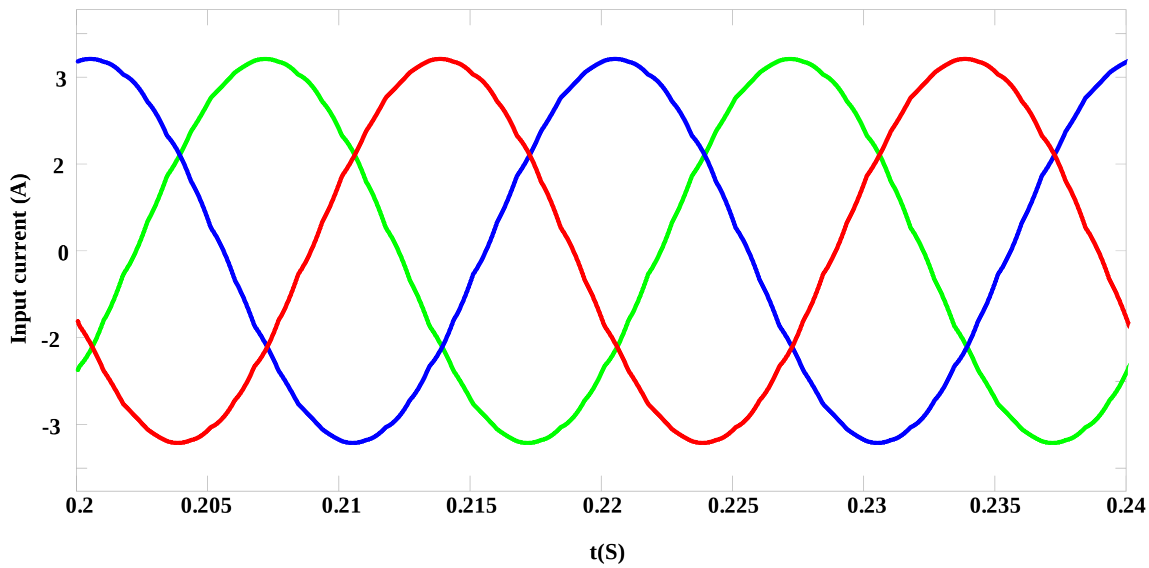

Figure 5.4: Input line current of 24-pulse operation of designed rectifier using PCIC-DAT.

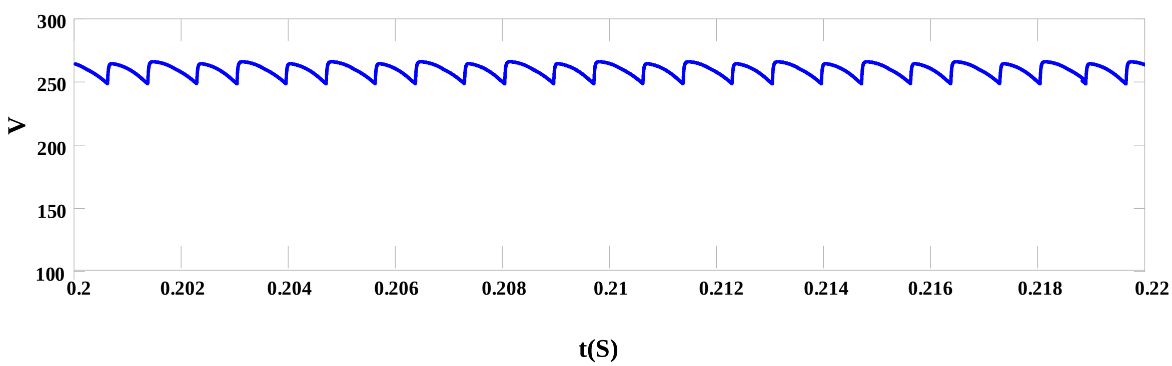

Figure 5.5: Output voltage of 24-pulse rectifier using PCIC-DAT.

In figure 5.5, it is seen that output voltage of 24-pulse rectifier having 250 volts and it carries 24-pulse.

In figure 5.6, the THD of input line current is obtained 3.33% which follows IEEE-509 standards and also less than the existing model.

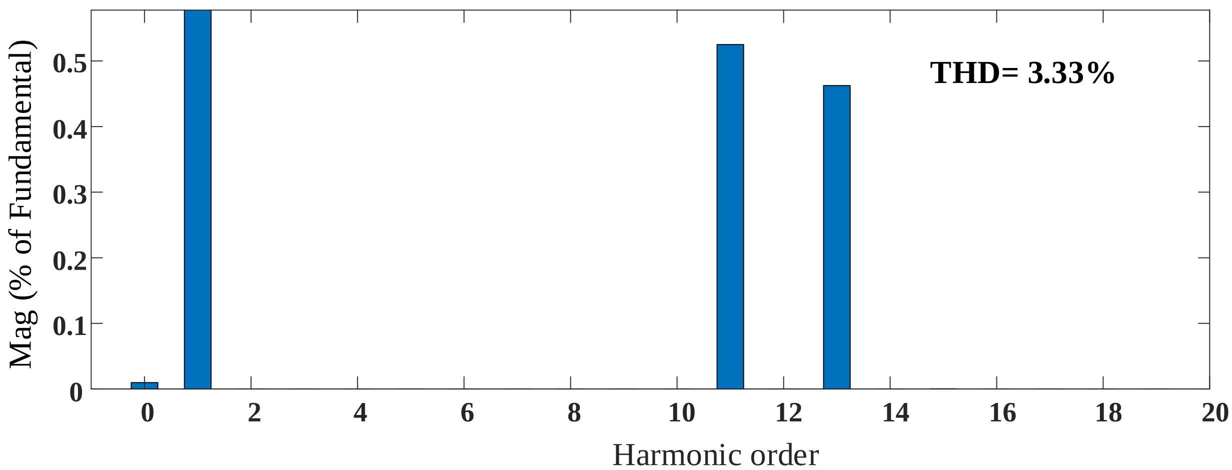

Figure 5.6: THD and harmonic order of 24-pulse rectifier input current.

5.2 Chapter Summary

In this important chapter, the performance study of a precisely built 24-pulse rectifier utilizing passive current injection via twin auxiliary transformers is analyzed. The purpose was to optimize the rectifier's performance in terms of output DC voltage quality, especially targeting a Total Harmonic Distortion (THD) of 3.33%. Leveraging MATLAB Simulink for simulation, the model attained a noteworthy output DC voltage of 250 volts, substantiating the usefulness of the suggested approach. Moreover, the performance study goes beyond harmonics to examine the transient response of the rectifier under load fluctuations. The rectifier's ability to maintain consistent output characteristics under dynamic load variations is evaluated, revealing insights into its appropriateness for real-world applications with changing loads. The efficiency and dependability of the proposed rectifier design are emphasized via comparisons with current models and standards, proving its proficiency in producing both a high-quality output voltage and compliance with industry norms.

Chapter 6

Conclusion

6.1 Conclusion

This thesis has exposed a revolutionary strategy to boost the power quality of series-connected 12-pulse rectifiers, satisfying the demanding standards given by the IEEE-519 standard, specifically aiming an input current Total Harmonic Distortion (THD) of less than 5%. The primary innovation resides in the application of passive current injection, departing from standard schemes and culminating in the invention of a revolutionary 24-pulse rectifier with a unique Passive Current Injection Circuit based on Dual Auxiliary Transformers (PCIC-DAT).

Key results underline the revolutionary influence of the PCIC-DAT method, exhibiting that the resultant rectifier displays an essentially sinusoidal input current waveform with a THD < 5%, fitting nicely with the IEEE-519 standard. This feat is done without the requirement for huge series inductors on the AC side, reducing related problems. The novel architecture, where the ASR in PCIC-DAT runs in tandem with the load, saves stress on auxiliary diodes and simplifies installation. Since the suggested PCIC-DAT method is a current injection technique, which is unnecessary to build three big inductors on the ac side of the rectifier, the issues caused by the huge series inductors at the input side of the rectifier are avoided. The ASR in PCIC-DAT is linked in parallel with the load such that the maximum current passing through the auxiliary diode in ASR is only $3.4\%I_d$. In addition, the total magnetic device kVA rating of the PCIC-DAT is just $1.97\%P_d$.

In conclusion, this thesis not only offers a unique rectifier design but also underlines its substantial utility via thorough theoretical analysis and simulated experiments. The suggested method not only satisfies but surpasses the strict specifications defined by IEEE-519, giving a compelling and efficient option for industrial applications. The merging of this design model insights with the major contribution of this study to the evolution of power electronics and the goal of raised power quality standards.

6.2 Future Scopes

The innovative research outlined in this thesis paves the way for several intriguing future prospects and prospective breakthroughs in the field of power electronics and rectifier technology. The following delineates prospective opportunities and domains for investigation:

- **Optimization and scaling:** Additional refinement of the suggested 24-pulse rectifier design might be undertaken to enhance its efficiency and performance to the fullest extent. Exploring the possibility of scaling the application to greater power ratings and voltage levels may ensure its compatibility to a wider variety of industrial applications.

- **Advanced Control Strategies:** Explore sophisticated control solutions for the rectifier system to improve its ability to adapt to dynamic load changes and transient situations. One may investigate the use of sophisticated control algorithms, such as predictive control or model predictive control, to enhance the performance of the rectifier.

- **Integration with Smart Grids:** Investigate the incorporation of the developed rectifier into smart grid systems. Examine the role of the rectifier in enhancing the stability, reliability, and efficiency of smart grids by using communication and control technologies to achieve optimal performance.

- **Real-Time Monitoring and Diagnostics:** Empower the rectifier system with real-time monitoring and troubleshooting tools. By using sensor technologies and intelligent diagnostics, a system's dependability may be increased and predictive maintenance can be enabled, which lowers maintenance costs and downtime.

- **Hybrid Energy Systems:** Explore how the rectifier may be integrated with energy storage devices and renewable energy sources. Examine its suitability for hybrid energy systems with the goal of enhancing resilience and sustainability for power supply applications. systems that facilitate efficient cross-border power transfer while ensuring stability and reliability.

- **Harmonic Filtering Techniques:** To further lower the harmonic content of the rectifier output, investigate other harmonic filtering methods. To further reduce Total Harmonic Distortion (THD), look into the usage of hybrid or active filtering techniques.

- **Experimental Validation and Prototyping:** Conduct comprehensive experimental testing and prototyping to validate the simulation results and theoretical insights. Validation in the real world will advance the rectifier's technical maturity and provide useful insights on how it behaves under various operating situations.

- **Industry Adoption and Standardization:** Assist in the implementation of the suggested rectifier technology in practical applications by working together with industry stakeholders. To guarantee compliance with current power systems and legal requirements, work toward standardization and certification procedures.

- **Cost-Benefit Analysis:** To determine if installing the suggested rectifier is economically feasible in compared to current technology, perform a thorough cost-benefit analysis. Take into account variables including production costs, installation costs, and long-term operating savings.

- **Educational Initiatives:** Share the information and conclusions from this study to support educational programs. To equip next generations of power electronics engineers and researchers, provide instructional resources, workshops, or training courses.

In conclusion, this thesis provides a new contribution to the advancement of AC-DC converter system thus enhance multipulse rectifier technology. Important contributions come from the suggested rectifier's transformational properties as well as the careful examination of harmonic content, transient responses, and efficiency under dynamic load scenarios. With its low kVA ratings and parallel operation of the Auxiliary Single-Phase Rectifier (ASR), the novel PCIC-DAT system highlights the rectifier's potential for sustainable, economical, and efficient applications. This thesis advances the subject of power electronics while also adding to the scholarly conversation. It is a representation of the unwavering quest of perfection, the bravery to defy expectations, and the vision to expand the bounds of what is possible in the complex field of multipulse rectifiers.

References

[1] Abdollahi, Rohollah, et al. "An improved 24-pulse rectifier for harmonic mitigation in more electric aircraft." *IET Power Electronics* 14.11 (2021).

[2] Chivite-Zabalza, F. Javier, Andrew J. Forsyth, and David R. Trainer. "A simple, passive 24-pulse AC–DC converter with inherent load balancing." *IEEE transactions on Power Electronics* 21.2 (2006).

[3] Wahab, Abdul, Muhammad Ahmad Khurshid, and Tahir Mahmood. "An Improved Multi-Pulse Rectifier Circuit for Input Current Harmonic Suppression Using Passive Devices." *International Journal of Advanced Natural Sciences and Engineering Researches* 7.4 (2023).

[4] H. Akagi and K. Isozaki, "A Hybrid Active Filter for a Three-Phase 12-Pulse Diode Rectifier Used as the Front End of a Medium-Voltage Motor Drive," in *IEEE Transactions on Power Electronics*, vol. 27, no. 1, pp. 69-77, Jan. 2012.

[5] D. A. Paice, Power Electronic Converter Harmonics: Multipulse Methods for Clean Power. New York: IEEE Press, 1996.

[6] Kastawan, I. M. W., Yusuf, E., & Fadhilah, A. (2020). Design of Phase-Shifting Transformer Based on Simulink Matlab Simulation. *International Journal Applied Technology Research*, *1*(2), 148-162.

[7] Winders, J. (2002). *Power transformers: principles and applications*. CrC Press.

[8] Abdollahi, Rohollah, Gevork B. Gharehpetian, Fazel Mohammadi, and Saravana Prakash P. "Multi-Pulse Rectifier Based on an Optimal Pulse Doubling Technique." *Energies* 15, no. 15 (2022).

[9] D. A. Rendusara, A. Von Jouanne, P. N. Enjeti and D. A. Paice, "Design considerations for 12-pulse diode rectifier systems operating under voltage unbalance and pre-existing voltage distortion with some corrective measures," in *IEEE Transactions on Industry Applications*, vol. 32, no. 6, pp. 1293-1303, Nov.-Dec. 1996.

[10] Rendusara, Dudi A., et al. "Design considerations for 12-pulse diode rectifier systems operating under voltage unbalance and pre-existing voltage distortion with some corrective measures." *IEEE Transactions on Industry Applications* 32.6 (1996).

[11] S. Choi, P. N. Enjeti, and I. J. Pitel, “Polyphase transformer arrange ments with reduced KVA capacities for harmonic current reduction in rectifier type utility interphase,” IEEE Trans. Power Electron., vol. 11, no. 5, pp. 680–690, Sep. 1996.

[12] S. Choi, B. S. Lee, and P. N. Enjeti, “New 24-pulse diode rectifier systems for utility interface of high power AC motor drives,” IEEE Trans. Ind. Appicat., vol. 33, no. 2, pp. 531–541, Mar./Apr. 1997.

[13] B. Singh, G. Bhuvaneswari and V. Garg, "Power-quality improvements in vector-controlled induction motor drive employing pulse multiplication in AC-DC converters," in *IEEE Transactions on Power Delivery*, vol. 21, no. 3, pp. 1578-1586, July 2006.

[14] C. Rech and J. R. Pinheiro, “Line current harmonics reduction in multipulse connection of asymmetrically loaded rectifiers,” IEEE Trans. Ind. Applicat., vol. 52, no. 3, pp. 640–652, Jun. 2005.

[15] H. S. Krishnamoorthy, P. N. Enjeti, and J. J. Sandoval, “Solid-state transformer for grid interface of high-power multipulse rectifiers,” IEEE Trans. Ind. Appl., vol. 54, no. 5, pp. 5504–5511, Sep. 2018.

[16] R. Li, L. Yu, and L. Xu, “Offshore AC fault protection of diode rectifier unit-based HVdc system for wind energy transmission,” IEEE Trans. Ind. Electron., vol. 66, no. 7, pp. 5289–5299, Jul. 2019.

[17] J. Wang, A. Chen, X. He, X. Yao, Y. Lv, and Z. Zhang, “A series 24 pulse rectifier with auxiliary passive pulse doubling circuit,” C.N. Patent 113300619A, Aug. 2021.

[18] D. Yuan, Z. Yin, S. Wang, and N. Duan, “Multi-level transient modeling of the aeronautic asymmetric 18-pulse phase-shifting auto-transformer rectifier in full-cycle design,” IEEE Trans. Transport. Electrific., vol. 8, no. 3, pp. 3759–3770, Sep. 2022.

[19] Du, Qingxiao, et al. "Harmonic reduction methods at DC link of series-connected multi-pulse rectifiers: A review." *IEEE Transactions on Power Electronics* 37.3 (2021).

[20] Abdollahi, R., & Gharehpetian, G. B. (2015). Inclusive design and implementation of novel 40-pulse AC–DC converter for retrofit applications and harmonic mitigation. *IEEE Transactions on Industrial Electronics*, *63*(2), 667-677.

[21] Meng, Fangang, et al. "Active harmonic reduction using DC-side current injection applied in a novel large current rectifier based on fork-connected autotransformer." *IEEE Transactions on Industrial Electronics* 64.7 (2017).

[22] C. Young, M.Chen, C. Lai, and D. Shih, "A novel active interphase trans former scheme to achieve three-phase line current balance for 24-pulse converter," IEEE Trans. Power Electron., vol. 27, no. 4, pp. 1719–1731, Apr. 2012.

[23] F. Meng, W. Yang, S. Yang, and L. Gao, "Active harmonic reduction for 12-pulse diode bridge rectifier at DC side with two-stage auxiliary circuit," IEEE Trans. Ind. Inf., vol. 11, no. 1, pp. 64–73, Feb. 2015.

[24] Y. Lian, S. Yang, K. Xu, Y. Li, and W. Yang, "Harmonic reduction mechanism at DC link of two different 24-pulse rectifiers," in Proc. IEEE Transp. Electrific. Conf. Expo Asia-Pac., 2017.

[25] Z. Liu, F. Meng, and W. Yang, "Harmonic reduction technology at DC link in star-connected-autotransformer-based multi-pulse rectifier," in Proc. IEEE Transp. Electrific. Conf. Expo Asia-Pac., 2017.

[26] F. Meng, X. Xu, and L. Gao, "A simple harmonic reduction method in multipulse rectifier using passive devices," IEEE Trans. Ind. Informat. vol. 13, no. 5, pp. 2680–2692, Oct. 2017.

[27] R. Kalpana, K. S. Chethana, S. Prakash P., and B. Singh, "Power quality enhancement using current injection technique in a zigzag configured autotransformer-based 12-pulse rectifier," IEEE Trans. Ind. Appl., vol. 54, no. 5, pp. 5267–5277, Sep./Oct. 2018.

[28] F. Meng, X. Xu, L. Gao, Z. Man, and X. Cai, "Dual passive harmonic reduction at DC link of the double-star uncontrolled rectifier, "IEEE Trans. Ind. Electron., vol. 66, no. 4, pp. 3303–3309, Apr. 2019.

[29] Fukuda, Shoji, Masaaki Ohta, and Yoshitaka Iwaji. "An auxiliary-supply-assisted harmonic reduction scheme for 12-pulse diode rectifiers." *IEEE Transactions on Power Electronics* 23.3 (2008).

[30] Bai, Sanzhong, and Srdjan M. Lukic. "New method to achieve AC harmonic elimination and energy storage integration for 12-pulse diode rectifiers." *IEEE Transactions on Industrial Electronics* 60.7 (2012).

[31] F. Meng, T. Li, L. Wang, and L. Gao, "Series-connected 36-pulse rectifier using a hybrid harmonic injection method," IET Power Electron, vol. 13, no. 17, pp. 4112–4116, Dec. 2020

[32] F.J. Chivite-Zabalza, A. J. Forsyth, and I. Araujo-Vargas, "36-pulsehybrid ripple injection for high-performance aerospace rectifiers," IEEE Trans. Indus. Appl., vol. 45, no. 3, pp. 992–999, May/Jun. 2009.

[33] I. Araujo-Vargas, A. J. Forsyth, and F. J. Chivite-Zabalza, "Capacitor voltage-balancing techniques for a multipulse rectifier with active injection," IEEE Trans. Ind. Appl., vol. 47, no. 1, pp. 185–198, Jan./Feb. 2011.

[34] Meng, Fangang, et al. "A series-connected 24-pulse rectifier using passive voltage harmonic injection method at DC-link." *IEEE Transactions on power Electronics* 34.9 (2018).

[35] Chivite-Zabalza, F. J., and A. J. Forsyth. "A simple, passive 24-pulse ac-dc converter with inherent load balancing using harmonic voltage injection." *2005 IEEE 36th Power Electronics Specialists Conference*. IEEE, 2005.

[36] Gao, Lei, et al. "A 36-pulse diode-bridge rectifier using dual passive harmonic reduction methods at DC link." *IEEE Transactions on Power Electronics* 34.2 (2018).

[37] J. Wen, H. Qin, S. Wang and B. Zhou, "Basic connections and strategies of isolated phase-shifting transformers for multipulse rectifiers: A review," 2012 Asia-Pacific Symposium on Electromagnetic Compatibility, Singapore, 2012.

[38] R. Kalpana, S. P. P., V. V. S. and B. Singh, "Investigations on Open-Circuit Faults of Zigzag Autoconfigured Transformer-Based 12-Pulse Rectifier," in *IEEE Transactions on Industry Applications*, vol. 56, no. 2, pp. 1599-1608, March-April 2020.

[39] R. Kalpana, S. P. P., V. V.S. and B. Singh, "Investigations on Single-Phasing Effect of Zigzag Autoconfigured Transformer Based 12-Pulse Rectifier," *2018 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, Chennai, India, 2018

[40] Xiao-Qiang, Ch, et al. "Thirty-six pulse rectifier scheme based on zigzag auto-connected transformer." *Archives of Electrical Engineering* 65.1 (2016).

[41] V. Sheelvant, R. Kalpana, B. Singh and P. P. Saravana, "Improvement in Harmonic Reduction of a Zigzag Auto connected Transformer Based 12-Pulse Diode Bridge Rectifier by Current Injection at DC Side," in *IEEE Transactions on Industry Applications*, vol. 53, no. 6, pp. 5634-5644, Nov.-Dec. 2017.

[42] Laka, Aitor, et al. "Novel zero-sequence blocking transformer (ZSBT) using three single-phase transformers." *IEEE Transactions on Energy Conversion* 28.1 (2012).

[43] Wang, Jingfang, et al. "A 24-Pulse Rectifier With a Passive Auxiliary Current Injection Circuit at DC Side." *IEEE Transactions on Power Electronics* 37.9 (2022).

[44] Meng, Fangang, Shiyan Yang, and Wei Yang. "Modeling for a multitap interphase reactor in a multipulse diode bridge rectifier." *IEEE transactions on power electronics* 24.9 (2009).

[45] Abdollahi, Rohollah, Ahmad Salemnia, and Morteza Abdolhosseini. "A novel pulse multiplication circuit for reducing harmonic distortion of 12 pulse rectifiers in aircraft electrical power systems." *IET Electrical Systems in Transportation* 13.2 (2023).

[46] Abdollahi, Rohollah, Ahmad Salemnia, and Gevork B. Gharehpetian. "A modified 72-pulse rectifier for harmonic suppression in more electric aircraft applications." *IEEE Transactions on Transportation Electrification* (2023).

[47] Abdollahi, Rohollah, and Morteza Abdolhosseini. "A Novel 36-pulse rectifier with low kVA rate to reduce harmonic input current distortion." *Journal of Iranian Association of Electrical and Electronics Engineers* 19.4 (2022).

[48] Abdollahi, Rohollah. "Technical and economical comparison of different autotransformer based 36 pulse AC-DC Converters." *Journal of Power Technologies* 99.4 (2019): 281.

[49] Abdollahi, Rohollah, and Alireza Reisi. "Comparative Analysis of Two Novel Passive Harmonic Suppression Circuits for Industrial Applications." *International Journal of Industrial Electronics Control and Optimization* 6.1 (2023):

[50] Abdollahi, Rohollah, and Mahdi Golchob. "Electric and magnetic comparison of two 10-phase autotransformers." *Ain Shams Engineering Journal* 13.4 (2022).