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MULTI-PULSE AC-DC CONVERTERS FOR POWER QUALITY IMPROVEMENT

Vivek Chandra, Department of Electrical Engineering, College of Technology, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar-263145, Uttarakhand.
Harendra Singh Rawat, Associate Professor**,** Department of Electrical Engineering, College of Technology, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar-263145, Uttarakhand.
Rajiv Singh, Associate Professor**,** Department of Electrical Engineering, College of Technology, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar-263145, Uttarakhand.
Geeta Pathak, Associate Professor**,** Department of Electrical Engineering, College of Technology, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar-263145, Uttarakhand.
Shobhit Gupta, Associate Professor**,** Department of Electrical Engineering, College of Technology, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar-263145, Uttarakhand.

ABSTRACT:

The power electronics revolution has ushered in a new era of power converters with varying power ratings, from just a few watts to several megawatts. AC-DC converters are one of the most widely used forms of power converters. Significant harmonic voltages and currents are produced by semiconductor switching devices, which are frequently utilized in converter circuits. Diode bridge rectifiers are a significant source of harmonics. Mutli-pulse AC-DC Converters can be utilized to reduce the harmonics in order to meet the strict harmonic requirements imposed by IEEE Standard 519-1992. In this research work, Multi-pulse AC-DC Converters with pulse numbers 6, 12 and 24 are simulated and analysed using the MATLAB/Simulink environment. Two 12-pulse converter topologies are examined in this research work: one is supplied from a Delta/star/delta transformer, while the other is supplied from a Fork Autotransformer. Then a 24-pulse circuit is created using a pulse doubler arrangement in the existing Fork Autotransformer-based 12-pulse circuit. Total Harmonic Distortion (THD) of the input line current and Voltage Ripple Factor (VRF) of the output voltage for these configurations is also compared. It is observed that the increase in pulse number of the converter results in a significant reduction in THD and VRF. Autotransformer-based topologies in multi-pulse converters are found to be more cost-effective due to lower magnetics.

1. INTRODUCTION

With technological advancements in semiconductor devices, power electronic converters are being increasingly utilized in industries such as petrochemicals, metals, steel, mining, transportation, and more. The growing adoption of solid-state controllers across various equipment has brought benefits like enhanced efficiency and lower production costs. However, this increased usage is significantly degrading the power quality in distribution networks, which leads to increased losses, poor utilization of distribution systems, mal-operation of sensitive equipment, disturbance to nearby consumers, protective devices, and communication systems. This paper deals with multi-pulse AC-DC converters that can be used for improving power quality to reduce harmonics in ac mains and ripples in dc output.

A power quality problem refers to any issue with electrical power, such as variations in voltage, current, or frequency, that can cause equipment to malfunction or operate improperly. Voltage-related issues at the point of common coupling (PCC) typically include problems like harmonics, sags, swells, and fluctuations, often arising from non-linear loads. Similarly, power quality issues related to the current drawn from the AC mains include low power factor, harmonic currents, unbalanced currents etc. Since solid-state controllers are being used so widely, these power quality issues have become much worse. Despite their limitations, these controllers are essential because they offer benefits such as reduced cost and size, improved energy efficiency, straightforward control, minimal wear and tear, and lower maintenance requirements in modern electrical devices. Numerous organizations have created a variety of standards and benchmarks, such as the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE). In order to lessen or completely eradicate problems with power quality, these are placed on consumers, utilities, and manufacturers. Recommendations and specifications for harmonic control in electrical power systems are found in IEEE Standard 519-1992.

Harmonics and their Mitigation

Harmonic is a sinusoidal component of a periodic wave having a frequency that is an integral multiple of the fundamental frequency. Harmonics make up the non-sinusoidal current waveform. Hundreds of sinusoidal components are needed to fully characterize certain real-world waveforms. Harmonic currents lead to increased losses in various electrical equipment and distribution systems, resulting in energy wastage and inefficient use of utility assets like transformers and feeders. They can also cause vibrations and noise in electrical machines. Additionally, harmonics can impact protection systems, causing malfunctioning of protective devices. Many studies have been conducted in the last few years aiming at reducing total harmonic distortion using various techniques. Harmonic mitigation can be performed by two methods:

a. Filtering
b. Harmonics cancellation

Usually, filters are employed in already existing installations. Filters used may be active, passive or hybrid types depending upon rating and economic considerations. In some instances, these filters' ratings are nearly equal to the converter's rating, which raises the cost and increases component count and losses, which lowers system reliability. Passive filters have been employed in some cases, but these filters are bulky and lossy (**Singh and Gairola, 2006**). Sometimes the use of passive filters causes resonance problems. Although active filters appear to be an intriguing alternative and have been employed in numerous studies, this method has also drawbacks, including complexity and high cost. The alternative technique reduces the harmonic content by cancelling out harmonics using multi-pulse converters. The multi-pulse converter theory focuses on reducing harmonics on the source side. The primary benefit of the multi-pulse rectifier is its ability to reduce line current harmonic distortion. This is achieved using a phase-shifting transformer that cancels out certain low-order harmonic currents generated by the six-pulse rectifiers. Typically, increasing the number of rectifier pulses leads to a reduction in line current distortion. The basic part of this system is a six-pulse diode bridge rectifier.

The rectifiers are driven by a phase-shifting transformer with several secondary windings and can be set up as 12, 18, or 24 pulse rectifiers. A six-pulse diode rectifier is powered by each secondary winding. These six-pulse rectifiers' DC output is subsequently linked to a voltage source inverter. This paper focuses on the application of multi-pulse AC-DC converters to significantly reduce the harmonics on the source side and enhance power quality. In multi-pulse converters, increasing the number of pulses results in a reduction in harmonic content in the line current. A lot of previous research has typically achieved this by employing multiple six-pulse diode bridge rectifier circuits, each requiring a phase-shifted supply for operation. In this work, we examine the parallel operation of two six-pulse converter circuits with phase shifting achieved through an auto-transformer to create a 12-pulse circuit. Subsequently, we enhance this 12-pulse circuit by incorporating a pulse doubler circuit, which increases the pulse number to twenty-four and results in a reduced THD value. This approach allows us to achieve the performance of a 24-pulse circuit with the existing 12-pulse system while avoiding additional complexity in the topology.

2. REVIEW OF LITERATURE

This section includes a general review of the literature available. Books, conference papers, and journal articles have greatly aided the work. Harmonic currents are introduced into the utility system by power electronic loads. The study by **Rastogi *et al.* (1994)** provides a comparative analysis of harmonic reduction methods that yield a regulated dc output voltage while meeting the current harmonic restrictions outlined in IEEE Standard 519. For a three-phase utility interface, a variety of current wave shaping methods as well as active and hybrid filters are taken into consideration. The complexity (number of switches) and component ratings of these methods are compared. The book by **Paice (1996)** covers multi-pulse methods thoroughly as they offer a simple way to reduce harmonic currents at the source. Paice has reported on several isolated and non-isolated AC-DC converters designed to enhance power quality. The paper by **Choi *et al.* (1997)** presents two novel 24-pulse diode rectifier systems for high-power motor drives. It has been demonstrated in the suggested scheme 1 that a tapped interphase transformer can be used to convert a traditional 12-pulse system into a 24-pulse system. Additionally, scheme 2 uses a decreased voltampere autotransformer to demonstrate a passive 24-pulse rectifier system. With the fifth, seventh, eleventh, thirteenth, seventeenth, and nineteenth harmonics in the input line currents eliminated, the resultant systems are low cost and show clean power characteristics. In the paper written by **Singh and Gairola (2006)** a 24-pulse AC-DC converter is designed, modelled and simulated to feed non-isolated industrial loads. The proposed configuration consists of an autotransformer based on fork connection to overcome current harmonic problems in AC mains. **Bhide and Kulkarni (2006)** modelled and examined two three-pulse controlled converters operating in parallel with an interphase transformer (IPT). In order to ensure independent functioning without any circulating current, the IPT absorbs the voltage difference between the DC voltages of the two converters at any given time. This configuration also produces a six-pulse output voltage, resulting in reduced harmonic distortions. **Chaturvedi *et al.* (2006)** examined the possibility of multi-pulse converters as a power quality solution in their research. In MATLAB Simulink environment, six, twelve, eighteen, and twenty-four pulse converters have been modelled and simulated. The various multi-pulse converters modelled and simulated in this study are examples of isolated three-phase multi-pulse AC-DC converters. The simulation yields the various performance characteristics of several multi-pulse converters. Harmonics are significantly reduced as the number of pulses increases. **Singh *et al.* (2008)** gave a broad perspective on multi-pulse converter technology to academics, engineers, and designers. The multi-pulse AC-DC converter designs, their performance, aspects of power quality, considerations in component selection, current trends, upcoming advances, and possible applications are all covered in this study. An extensive analysis of multi-pulse converters has been provided in order to investigate a broad range of alternative multi-pulse AC-DC converter topologies. Due to their inherent integrated converter, smaller magnetic component size, and increased reliability from fewer components than other power quality improvement methods, these multi-pulse converters can be thought of as superior options for improving power quality. The power quality is enhanced by these converters at both ends, that is, at the dc output load and the input ac mains.

Swamy *et al.* (2010) introduced a novel 18-pulse configuration utilizing three six-pulse rectifiers, where two six-pulse rectifiers receive power through a phase-shifting isolation transformer. In contrast, the third six-pulse rectifier is directly connected to the AC source using a matching inductor. In order to reduce overall harmonics, the proposed concept uses a harmonic current cancellation technique. The suggested topology performs better, is simpler to produce, and is easier to understand. **Meng *et al.* (2016)** analysed the 12-pulse rectifier, commonly employed in high-power rectification, with the most prevalent phase-shift transformers being the delta-connected and wye-connected autotransformers. This paper compares the 12-pulse rectifiers employing the two transformers. Regarding the DC side and AC mains power quality, the two 12-pulse rectifiers are identical. The IPRs in the two 12-pulse rectifiers have the same kVA rating. However, under the same load conditions, the kVA rating of the delta-connected autotransformer was found to be lower than that of the wye-connected autotransformer. In the work by **Kant and Singh (2018)** a variable frequency induction motor drive (VFIMD) is introduced. A fifty-four pulse AC-DC converter is implemented on the grid side of the proposed VFIMD, while a 27-level cascaded multi-level inverter (MLI) is employed on the motor side. The 54-pulse converter enhances grid current quality by making it nearly sinusoidal, resulting in significantly low total harmonic distortion (THD). The proposed VFIMD demonstrates superior power quality performance at both the grid and motor ends, along with improved induction motor drive performance.

3. PROBLEM STATEMENT AND OBJECTIVES

The primary challenges in electricity distribution include harmonics, short-term voltage variations (such as sags, swells, and interruptions), voltage transients, unbalance, and frequency variations. Clean power is defined by a pure sinusoidal waveform, devoid of noise, and maintained within acceptable voltage and frequency limits. Multi-pulse AC-DC converters are a practical substitute for reducing harmonic distortion and enhancing power quality. The main goal of this research work is to use multi-pulse converter theory to significantly reduce harmonics on the source side, with the total harmonic distortion decreasing as the number of pulses grows. Multi-pulse converters include both isolated and non-isolated topologies. This work, however, primarily examines the non-isolated topology, which provides the benefits of reducing the total transformer magnetic rating of the phase-shifting transformer and achieving greater copper savings compared to isolated topologies. The objectives of the research work are as follows:

A. To reduce the harmonic content in the ac current mains.
B. To reduce the ripple in the dc output voltage.

4. MATERIALS AND METHODS

The leading high-power drive manufacturers worldwide are gradually implementing multi-pulse diode rectifiers in order to meet the strict harmonic criteria established by standards like IEEE Standard 519-1992. The rectifiers are fed by a phase shifting transformer with several secondary windings, and they can be set up as 12, 18, or 24 pulse rectifiers. A six-pulse bridge rectifier is powered by each secondary winding. A voltage source inverter (VSI) is linked to the six-pulse bridge rectifier's dc output. A major advantage of the multi-pulse converter is its ability to minimize harmonic distortion in the line current. This is accomplished by the phase-shifting transformer, which cancels out some of the low-order harmonic currents produced by the six-pulse rectifiers. In general, increasing the number of rectifier pulses leads to reduced line current distortion. T.H.D decreases as the number of pulses increase. However, rectifiers with more than 30 pulses are seldom utilized in practice because the additional transformer costs outweigh the marginal performance improvements.

Multi-pulse AC-DC converters can be constructed using either diode bridges or various types of thyristor bridges, with power provided by transformers such as conventional, phase-shifted, or autotransformers. Utilizing autotransformers can help reduce the overall cost of these converters. The various topologies presented in this work have been simulated in the MATLAB environment along with Simulink. This work aims to improve power quality parameters in multi-pulse converters. This is done by using phase-shifting transformers and increasing the number of pulses. A six-pulse diode bridge rectifier circuit serves as the fundamental component of all the topologies discussed in the paper. To increase the number of pulses, several six-pulse converter circuits can be paralleled. These paralleled converters are supplied from a phase-shifting transformer. An interphase transformer is also utilized in some of the topologies. FFT analysis of the input side line current and output voltage is performed using the MATLAB Simulink package to obtain the input side line current THD and output voltage's VRF, respectively.

4.1 Multi-pulse AC-DC Converters

The multi-pulse methods employ multiple converters connected in a way that the harmonics produced by one converter cancel out the harmonics generated by other converters. To illustrate the fundamental operation of multi-pulse converters, it is assumed that the DC circuit is filtered to ensure that any ripple brought on by the DC load has minimal effect on the DC current. This assumption is valid for passive loads and most converters that supply DC power to voltage source inverters (VSI). Multi-pulse systems offer two major advantages, both of which are achieved simultaneously. These benefits include:

1. Reduction of harmonics in the ac input line current.
2. Reduction of ripple in the dc output voltage.

4.1.1 Phase shifting Transformer

In the multi-pulse techniques several converters are used with a common DC load. An essential component that allows the cancellation of harmonic current pairs is a phase-shifting transformer. One of the converter bridges is supplied by a delta/star transformer, producing a three-phase set of secondary voltages that are shifted by 30° relative to the primary voltage. The other converter bridge is powered by a delta/delta transformer, which provides secondary voltages without any phase shift. As a result of the phase relationships, certain currents in one bridge are in opposite phase to those in the other. Consequently, some of the harmonic currents required by one converter are supplied by the other, resulting in the system experiencing the equivalent of a 12-pulse load. With ‘m’ number of 6-pulse converters connected properly, the characteristic current harmonics in the three-phase power source will have frequencies of $(6km \pm 1)$ with amplitudes of $1/(6km \pm 1)$ (**Paice, 1996**).

4.1.2 Cancellation of Harmonics

For a three-phase input, the phase shift can be conveniently accomplished by adding appropriate segments of voltage in a transformer. The phase shift achieved must be suitable for the number of converters involved. Typically, the minimum phase shift needed to cancel current harmonics in converters with 6-pulse waveforms is given by (**Paice, 1996**):

$$(\text{Minimum Phase Shift})^\circ = \frac{60^\circ}{\text{number of converters}}$$

The individual harmonic currents of each bridge converter stay the same in numerous multi-pulse circuits. The transformer(s) allow one bridge to supply the harmonic currents that another needs.

4.1.3 Delta/ Wye

This configuration is widely utilized. The relationship between line-to-line and line-to-neutral voltages is responsible for the 30° phase shift in voltage.

4.1.4 Delta Zigzag/ Fork

The term "zigzag" refers to the creation of output voltages from different segments of voltage vectors. In the fork configuration, the ends of the windings or vectors are left open, resembling a fork. A phase shift of 30° is produced by the fork configuration when two voltage vectors with identical amplitudes are used. Electrically balanced supplies for 12-pulse converters can be obtained by utilizing two of these fork secondary winding configurations with a ±15° phase shift. After that, these two converters can be connected in series or parallel.

4.1.5 Interphase Transformer

Multi-pulse converter circuits are often developed by connecting converters with lower pulse counts in parallel. Even if the converters have identical ripple voltage patterns, they will, in the case of multi-pulse connections, have instantaneous differences because of the phase shift in each source. If these voltage differences are not supported in some way, the device conduction patterns will be changed and each converter will interfere with the operation of the other. To prevent this interfering effect, an interphase transformer (IPT) is interposed between the two converters. To allow the converters to function independently interphase transformers are essential. The instantaneous voltage difference between the two converters is absorbed by the interphase transformer. An interphase transformer ensures that the current conduction of each individual device is maintained at 120° (**Paice, 1996**).

The interphase transformer helps manage AC voltage differences between the outputs of converters, allowing them to operate as if they were independent. Any voltage difference $(V_1 - V_2)$ will be dropped across the interphase transformer. Consequently, the load voltage will be the average of the two source voltages, or $(V_1+V_2)/2$ (**Paice, 1996**). Interphase transformers are also utilized in converter circuits where the AC voltage sources are not isolated from each other. In this setup, interphase transformers not only help manage AC voltage differences between the outputs of converters but also prevent undesired conduction paths.

4.1.6 Paralleling when the phase shift is by means of an Autotransformer

Two six-pulse converters are connected in parallel to supply power to a DC load. However, the presence of circulating currents between the converters again results in six-pulse operation rather than achieving the desired 12-pulse operation. To achieve 12-pulse results, two interphase transformers are crucial. One is connected to the positive output, and the other to the negative output. These interphase transformers isolate unwanted conduction paths, enabling the converters to function almost independently (**Paice, 1996**). The device conduction angle is 120°, and the total AC line input current is similar to a standard 12-pulse converter. The phase-shifting transformer's small size contributes to the efficiency of this setup.

4.2 Topologies

Following are the topologies discussed:

4.2.1 Six-pulse Uncontrolled Converter (Topology-I)

It is a basic six-pulse uncontrolled converter driving a constant current load.

4.2.2 Six-pulse Uncontrolled Converter powered by Delta/star transformer (Topology-II)

In this topology the six-pulse uncontrolled converter is powered by a Delta/star transformer. The supply mains are linked to the Delta connected primary of the transformer and the Star connected secondary of the transformer powers a constant current load.

4.2.3 Delta/Star/Delta transformer based 12-pulse circuit supplying a constant current load (Topology-III)

The supply mains are connected to the delta-connected primary of the transformer along with one of the two paralleled converters supplied from the star-connected secondary of the transformer and the other supplied from the delta-connected secondary of the transformer. This whole setup drives a constant current load. Block diagram representing this topology is shown in the Figure 4.1.

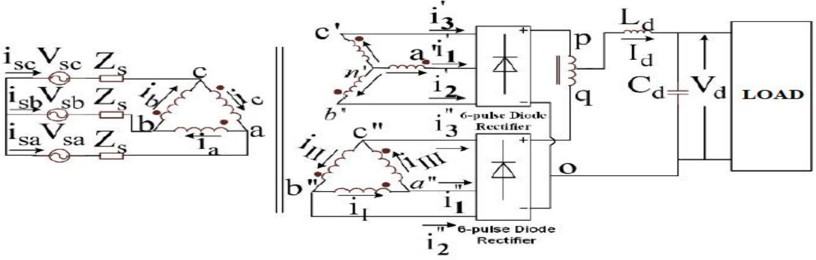

Figure 4.1 Block diagram of a D/y/d transformer supplying a constant current load with a 12-pulse, uncontrolled converter.

4.2.4 Fork Auto-transformer based 12-pulse circuit supplying a constant current load (Topology-IV)

In this topology, a Fork Auto-transformer is employed to supply the two six-pulse diode bridge rectifiers. The output from the uncontrolled converter is directed to the inputs of two interphase transformers, which are then connected to a constant current load. The main winding of the fork autotransformer is connected to the supply mains. Copper can be saved by employing the Fork Auto-transformer configuration rather than the D/y/d transformer configuration (**Kaur *et al.*, 2019**). This topology is depicted in the Figure 4.2.

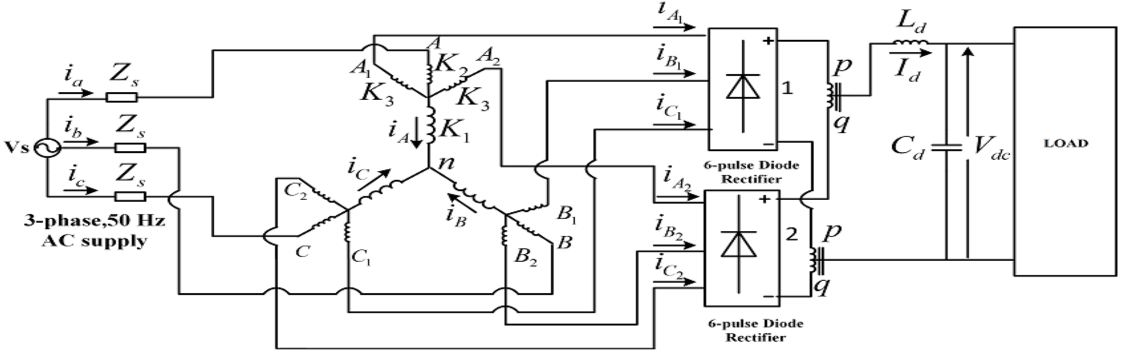

Figure 4.2 Block Diagram of Fork connected auto-transformer supplying a constant current load with a 12-pulse, uncontrolled converter.

4.2.5 A 12-pulse circuit using a Pulse Doubler to create 24-pulse circuit (Topology-V)

A standard 12-pulse system can be converted into a 24-pulse system by using a tapped interphase transformer. The schematic diagram for this topology is shown in Figure 4.3. By eliminating the 5th, 7th, 11th, 13th and so forth harmonics from the input line currents, the resultant system exhibits clean power characteristics and is cost-effective (**Choi *et al.*, 1997**).

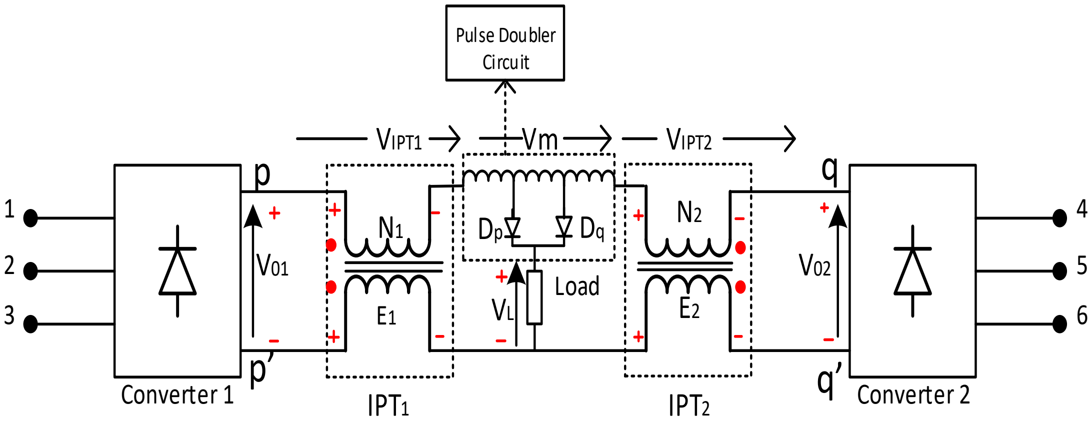

Figure 4.3 Circuit Diagram for 24-pulse circuit using a pulse doubler in the existing 12-pulse circuit.

Fourier series of the rectifier input current is analysed by **(Choi *et al.*, 1997)**. It is found that when “k” is set to 0.2457, the fifth, seventh, eleventh, thirteenth, seventeenth, and nineteenth harmonics in the input line current I_a are eliminated, resulting in 24-pulse characteristics from the input current's perspective.

5. RESULTS AND DISCUSSIONS

The Multi-pulse AC-DC Converter topologies presented in this thesis have been simulated in MATLAB Simulink program. Five simulation models have been constructed using the MATLAB Simulink package. The phase voltages are indicated by V_{an}, V_{bn}, and V_{cn}, and the line voltages are shown by V_{ab}, V_{ba}, V_{bc}, V_{cb}, V_{ca}, and V_{ac}. The line currents drawn from the AC supply mains are indicated by i_a, i_b and i_c. A constant current load of 10A is driven by all the topologies studied below. To determine the Total Harmonic Distortion (THD) and Voltage Ripple Factor (VRF) as a percentage, FFT analysis was performed on the supply side line current waveforms and output voltage waveform respectively, using MATLAB Simulink package.

5.1 Six-pulse Operation of Uncontrolled Converter (Topology-I)

A six-pulse diode bridge rectifier circuit feeding a constant current load is simulated in MATLAB Simulink, the simulation circuit for which is depicted in Figure 5.1.

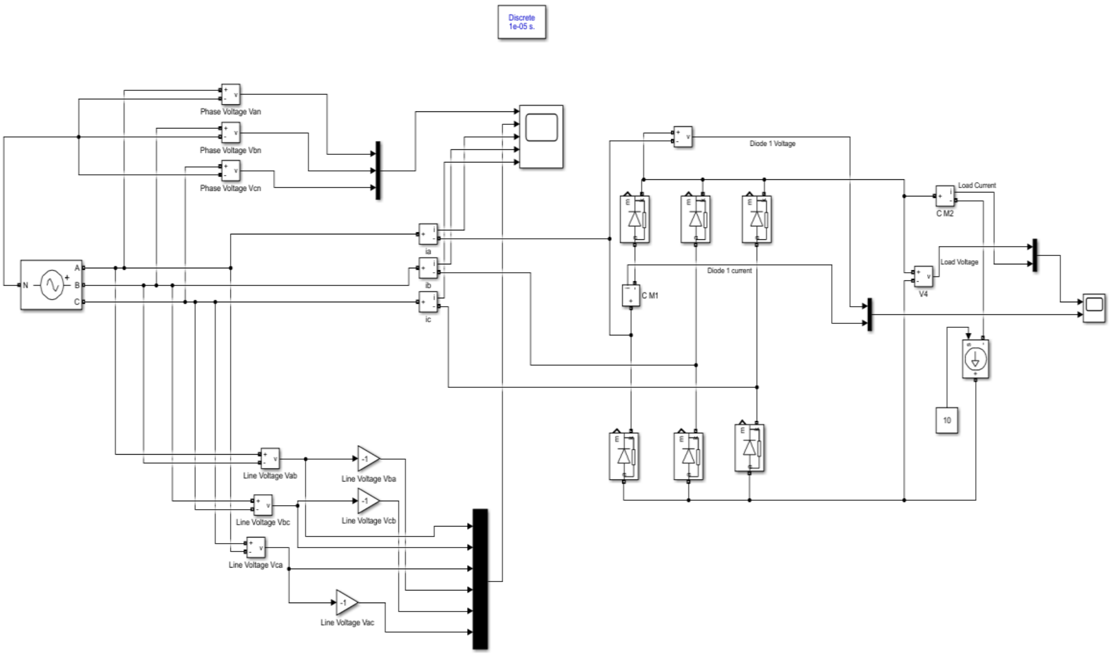

Figure 5.1 Simulation Circuit for a Six-pulse Uncontrolled Converter feeding a constant current load.

The line currents have a waveform similar to a quasi-square wave as depicted in Figure 5.2. The waveforms of the load side voltage and current as well as the voltage across and current through diode 1 are shown in Figure 5.3. The FFT window for the supply side current waveform, is shown in Figure 5.4.

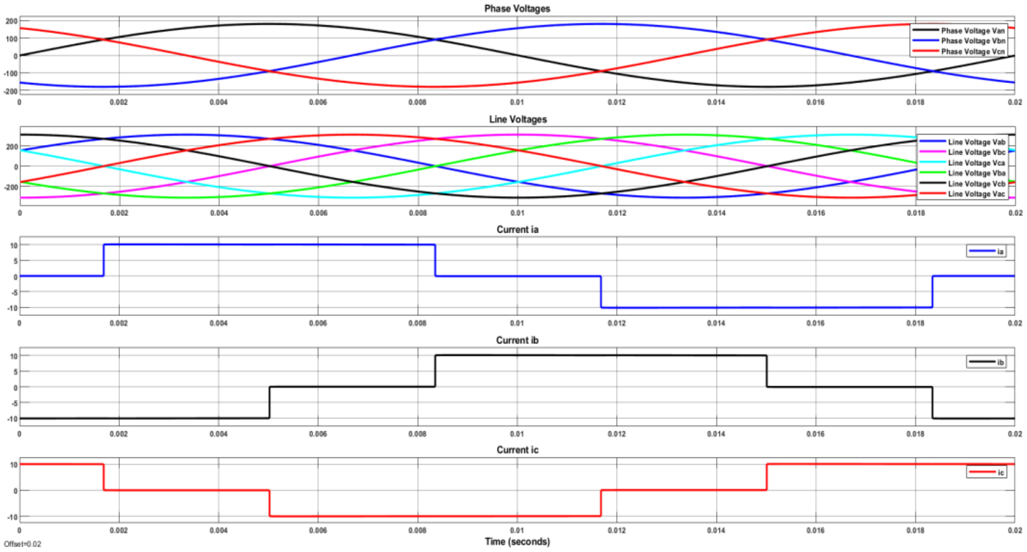

Figure 5.2 Voltage and Line current waveforms of a Six-pulse Uncontrolled Converter.

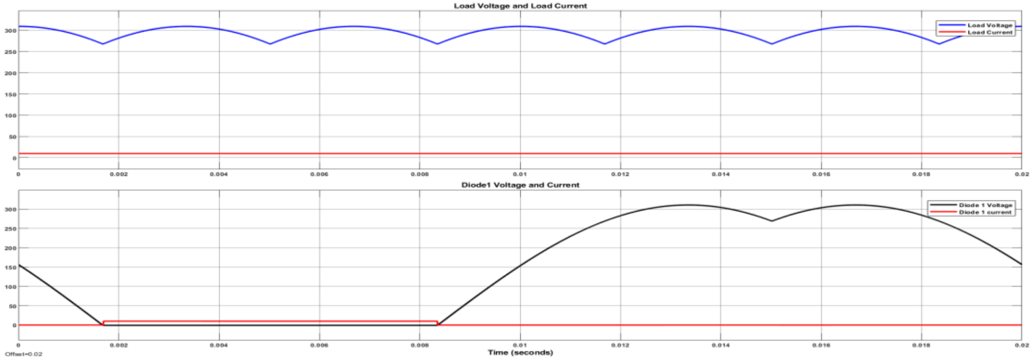

Figure 5.3 Voltage and current waveforms for load and diode-1.

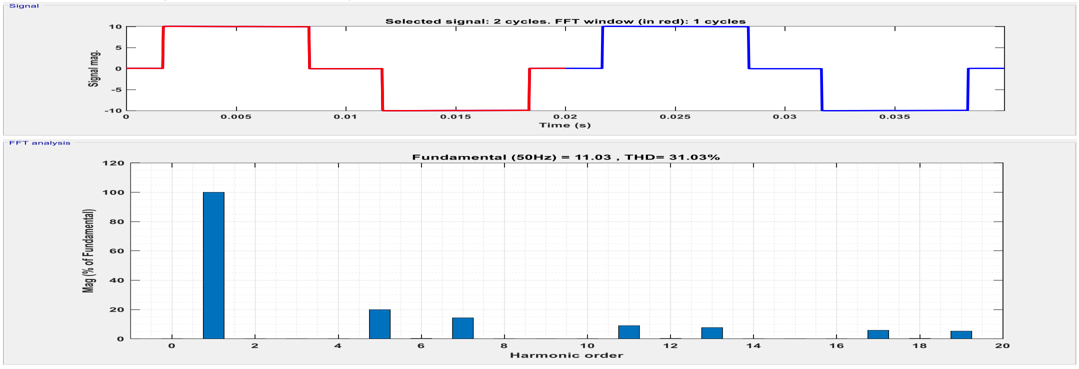

Figure 5.4 FFT window for the supply side line current waveform.

The input side line current waveform's THD value, as determined by FFT analysis, is 31.03%, a significantly high value when compared to IEEE Standard 519-1992.

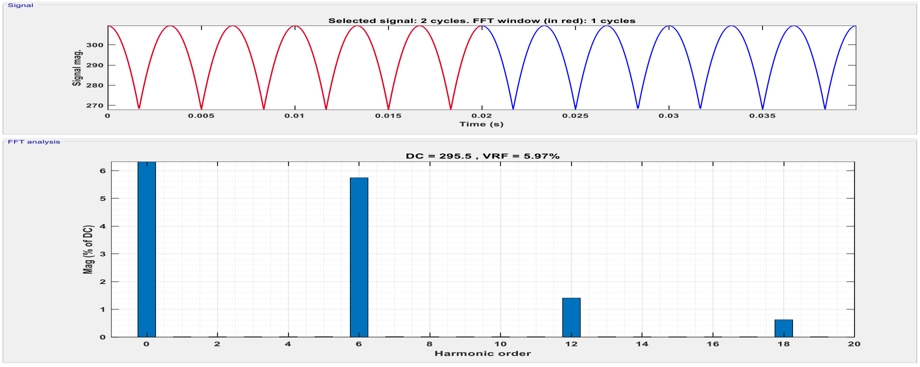

Figure 5.5 FFT window for the output voltage waveform.

The output voltage waveform's VRF, determined by FFT analysis, is 5.97% as shown in Figure 5.5.

5.2 Delta/Star Transformer fed Six-pulse Uncontrolled Converter (Topology-II)

This design uses a Delta/star transformer to power the six-pulse uncontrolled converter. Waveforms for the phase voltages, line voltages, load voltage and load current are depicted in Figure 5.6.

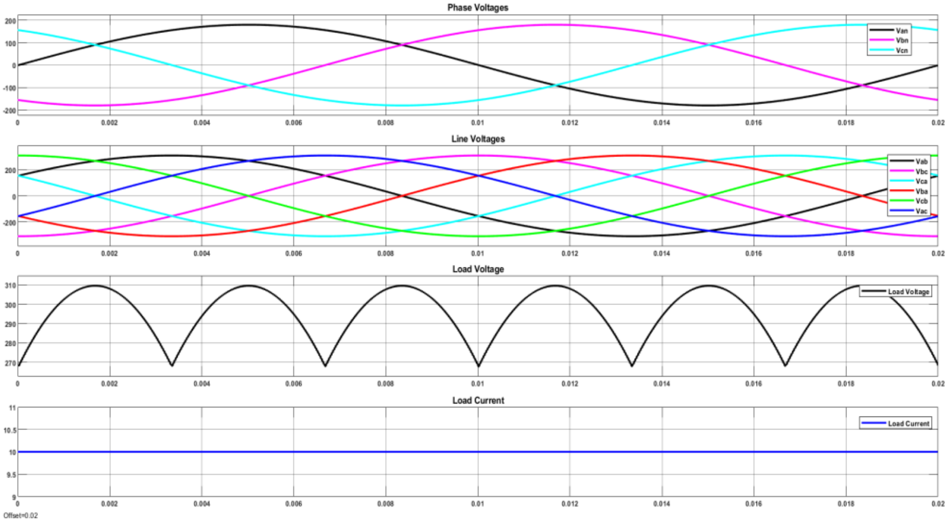

Figure 5.6 Voltage waveforms on the source side and load end, along with load current waveform.

The line currents have a waveform similar to a stepped-wave as shown in Figure 5.7.

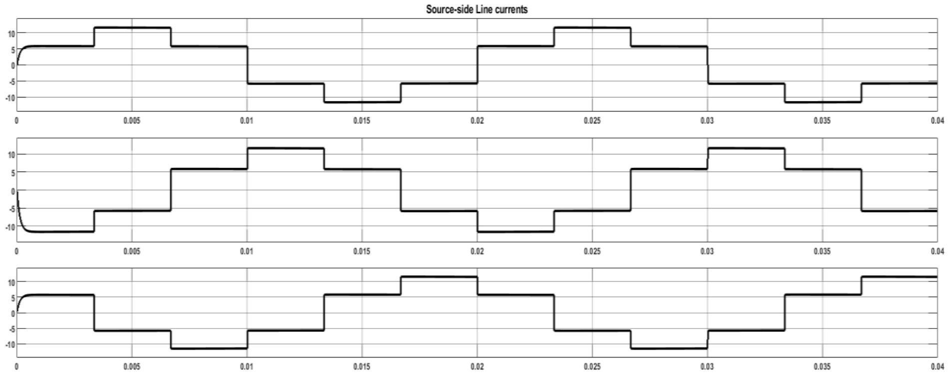

Figure 5.7 Waveforms for the line currents drawn from the AC mains.

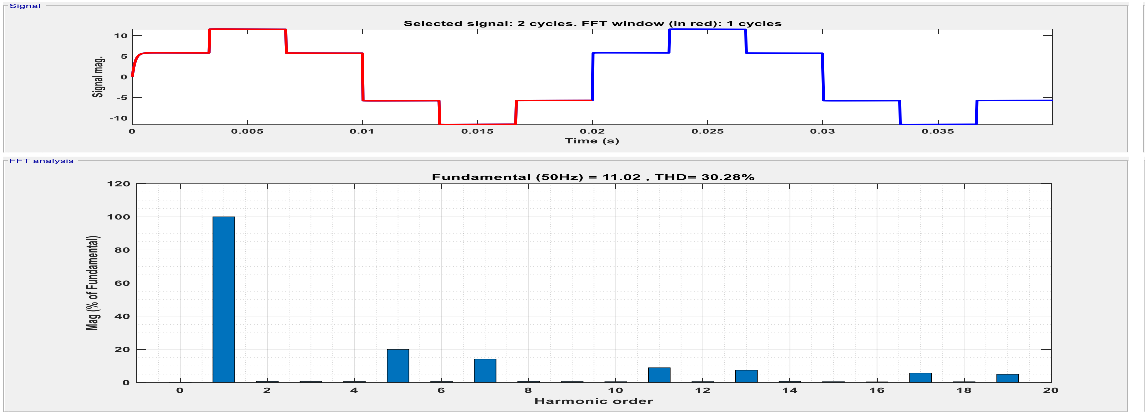

Figure 5.8 FFT window for supply side line current waveform.

As shown in Figure 5.8, the input side line current waveform's THD value, determined by FFT analysis, is 30.28%.

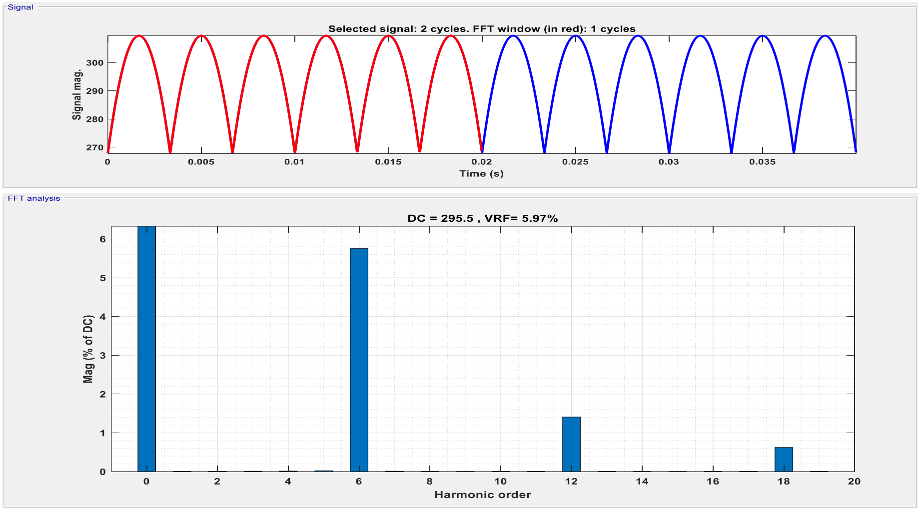

Figure 5.9 FFT window for output voltage waveform.

The output voltage waveform's VRF is 5.97% as shown in Figure 5.9.

5.2 Delta/Star/Delta Transformer fed 12-pulse Uncontrolled Converter (Topology-III)

The utilizes a Delta/Star/Delta configuration as a phase-shifting transformer to power the two six-pulse converters connected in parallel. Simulation model of delta/star/delta transformer is shown in Figure 5.10.

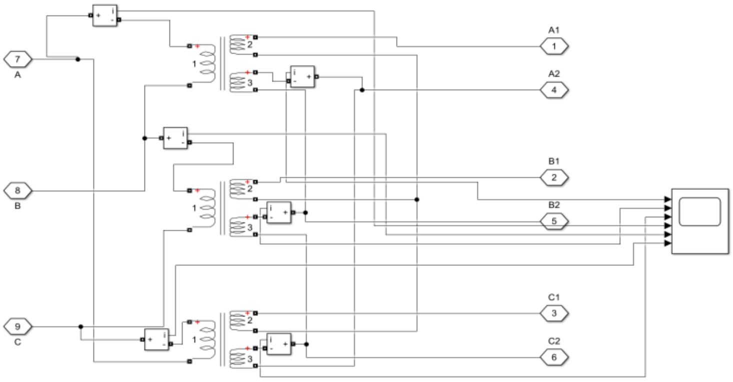

Figure 5.10 Simulation model of a Delta/Star/Delta transformer.

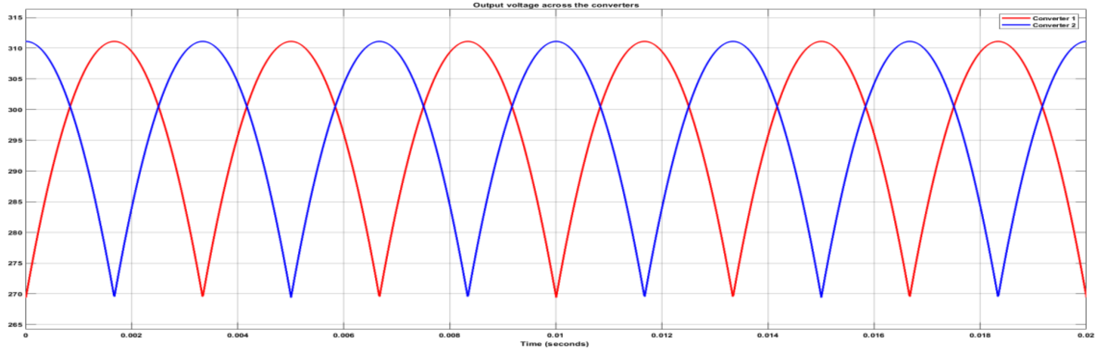

Figure 5.11 Output voltages across converter 1 and converter 2 terminals.

The output voltage across the terminals of the two six-pulse converters is shown in Figure 5.11 and voltage waveform obtained across the inter-phase transformer is displayed in Figure 5.12.

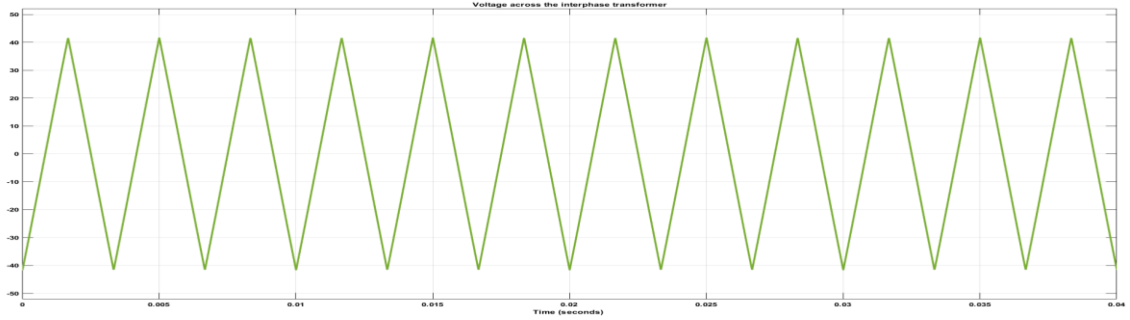

Figure 5.12 Voltage waveform across the interphase transformer.

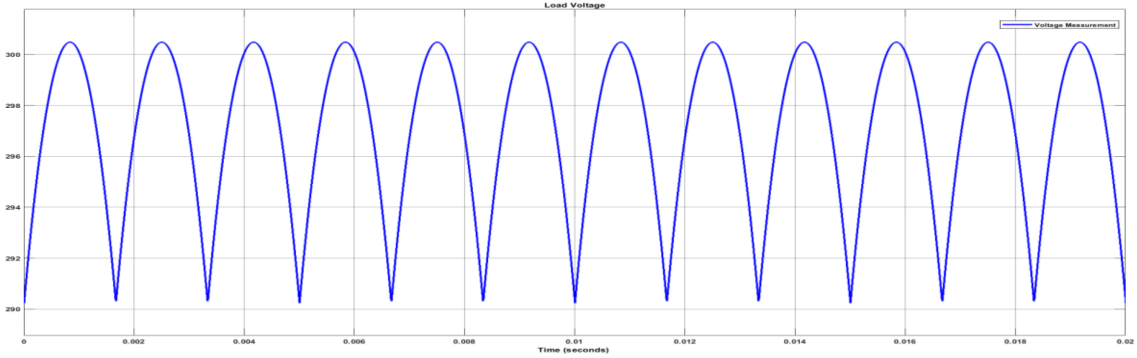

Figure 5.13 Load voltage waveform.

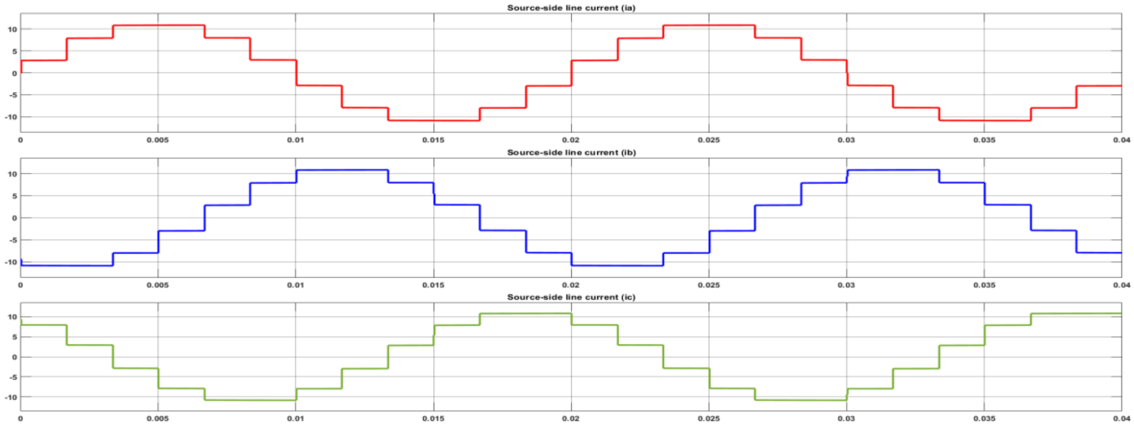

Figure 5.14 Waveforms for source-side line currents.

The waveforms for load voltage and source-side line currents are shown in Figure 5.13 and 5.14 respectively. Based on a thorough examination of the supply side current waveform's FFT window, the THD value obtained is 15.07% as shown in Figure 5.15.

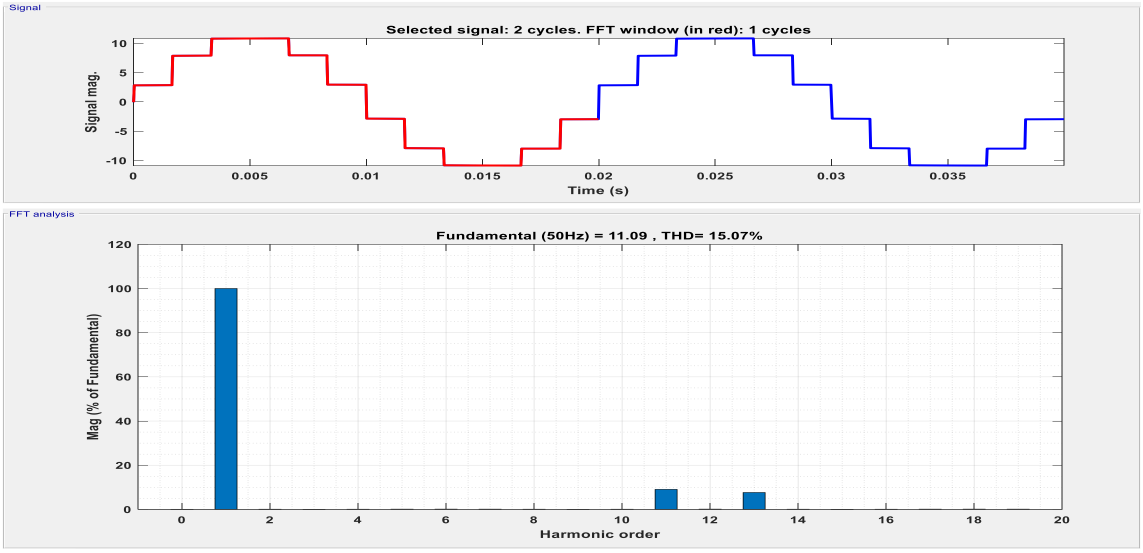

Figure 5.15 FFT window for supply side line current waveform.

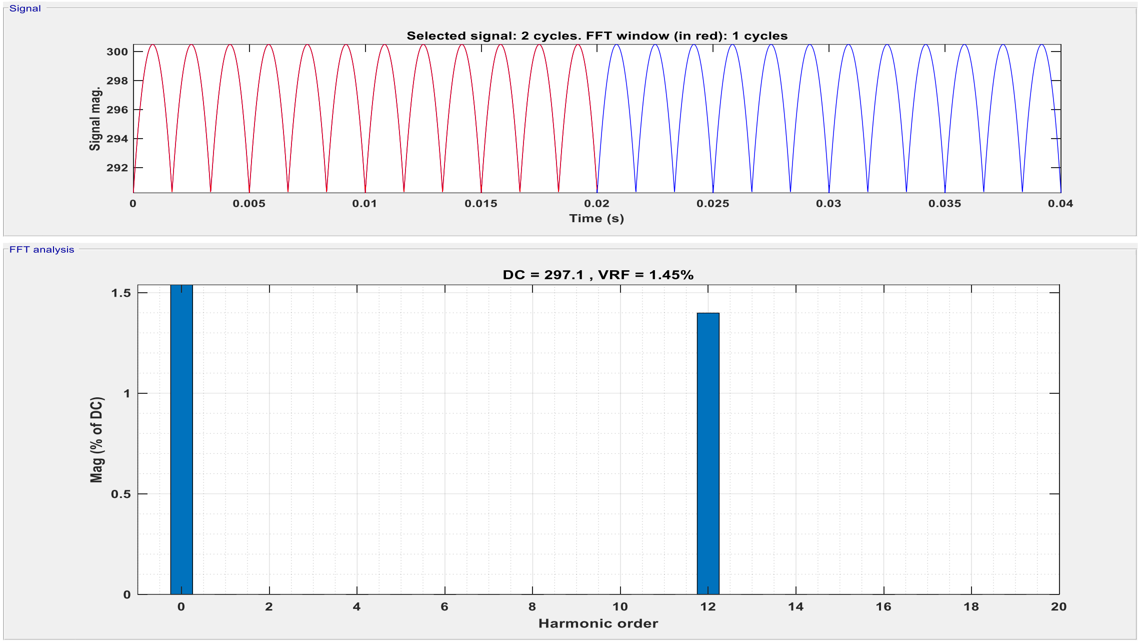

Figure 5.16 FFT window for output voltage waveform.

The output voltage waveform's VRF, determined by FFT analysis, is 1.45 % as shown in Figure 5.16.

5.4 Fork Auto-transformer fed 12-pulse Uncontrolled Converter (Topology-IV)

The simulation circuit for a fork auto-transformer that is used to power the two six-pulse converters connected in parallel is shown in Figure 5.17. Waveforms obtained for this topology are shown in Figure 5.18 and Figure 5.19.

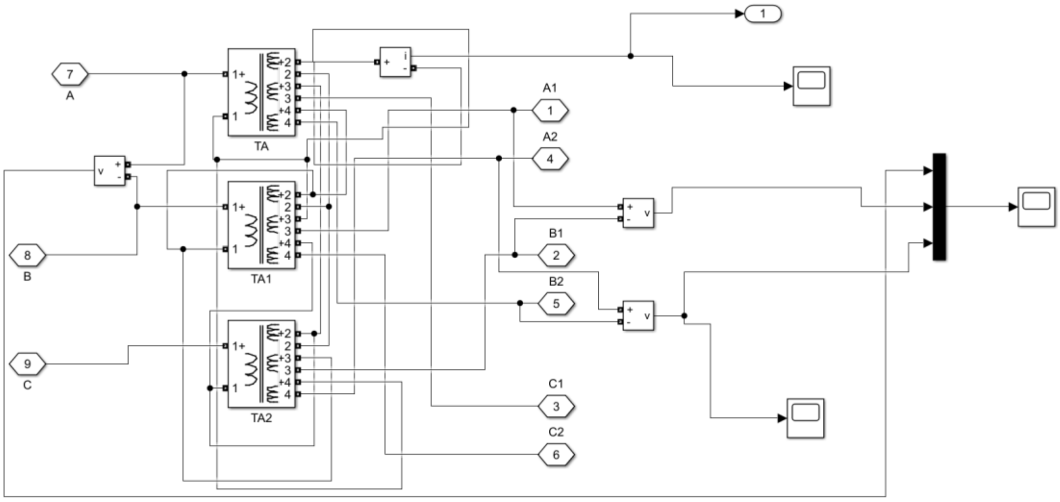

Figure 5.17 Simulation circuit for a Fork Auto-transformer.

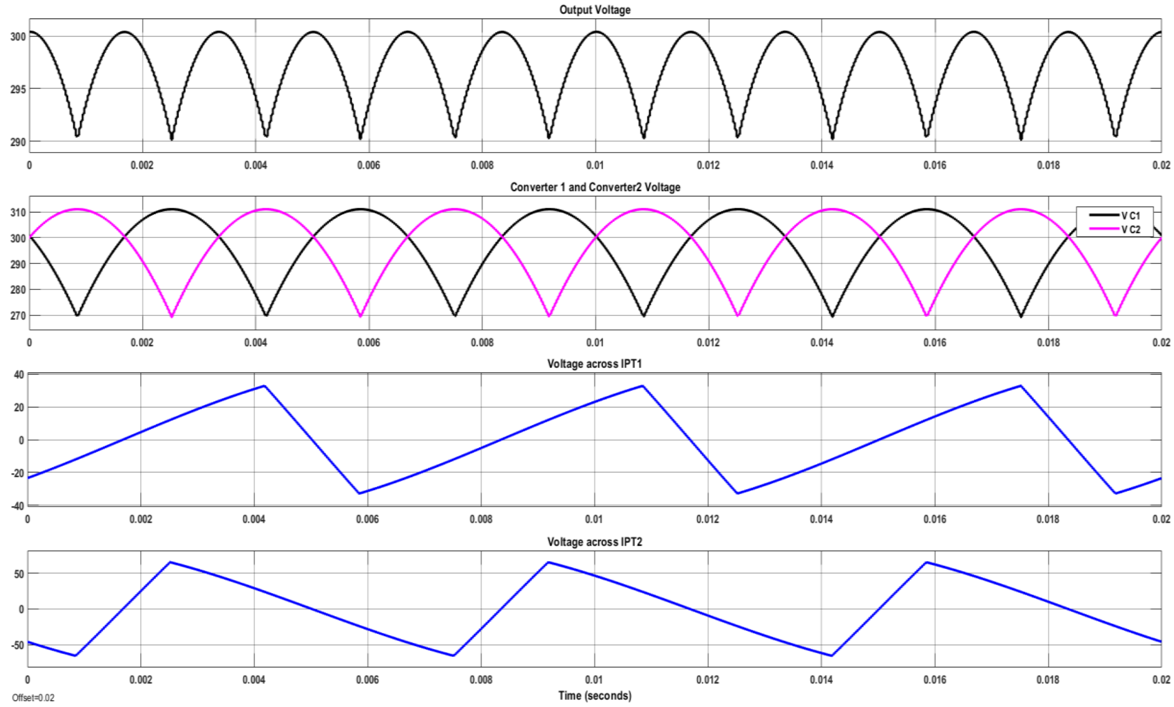

Figure 5.18 Waveforms for output voltage, converter 1 and converter 2 voltages, voltages across IPT 1 and IPT 2.

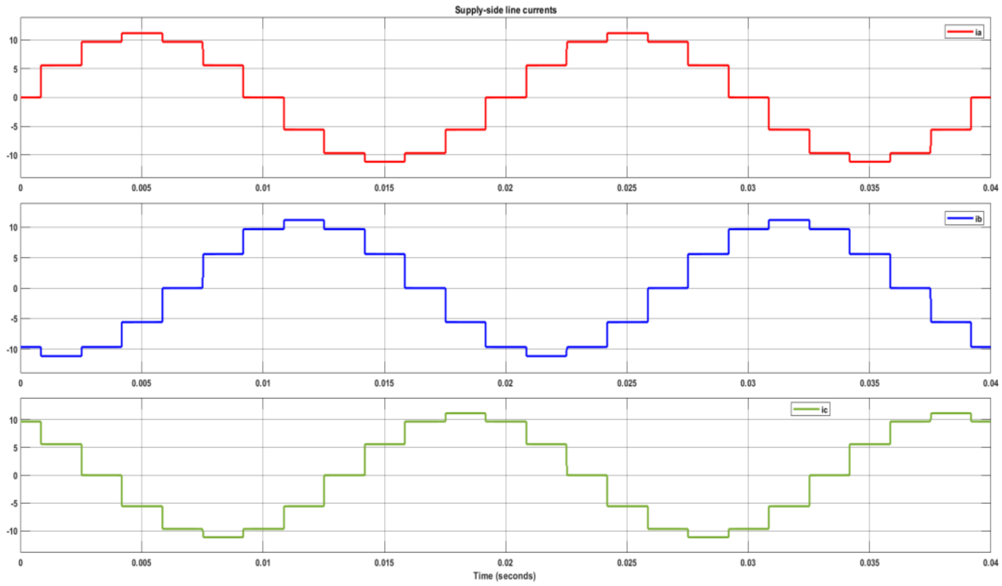

Figure 5.19 Waveforms for the supply-side line currents.

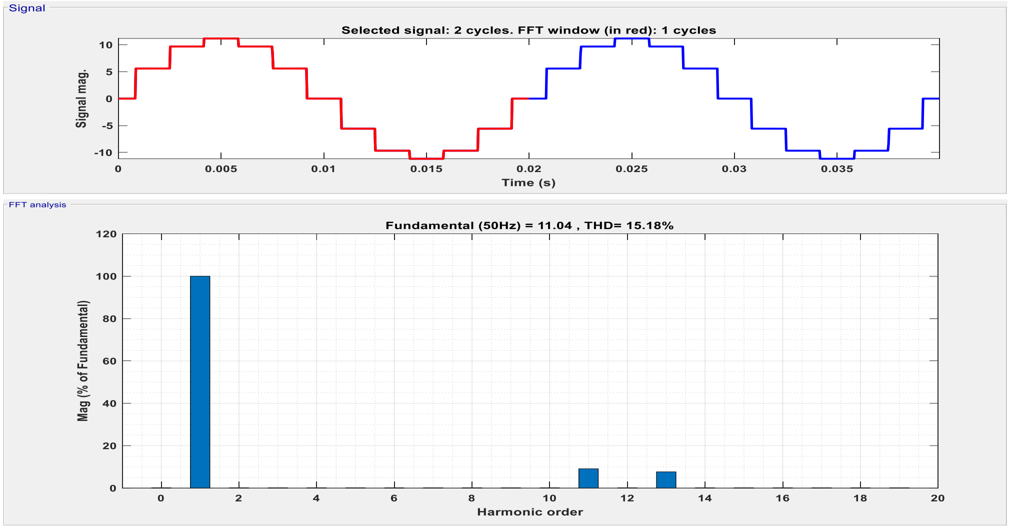

Figure 5.20 FFT window for supply side line current waveform.

The THD value obtained is 15.18 % as shown in Figure 5.20, suggesting a considerable decrease in THD with an increase in pulse count.

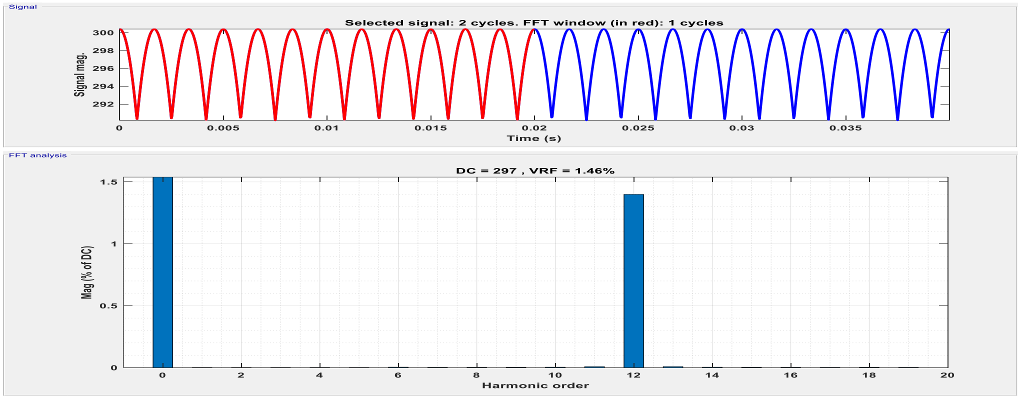

Figure 5.21 FFT window for output voltage waveform.

FFT analysis yielded a VRF of 1.46% for the output voltage waveform as shown in Figure 5.21

5.5 Fork Auto-transformer based 24-pulse Uncontrolled Converter topology by using a pulse doubler arrangement in the existing 12-pulse circuit (Topology-V)

A 24-pulse system is produced by utilizing a pulse doubler arrangement in the pre-existing Fork Auto-transformer based 12-pulse system simulated in section 5.4. The waveforms obtained for this topology are shown in Figure 5.22 and Figure 5.23.

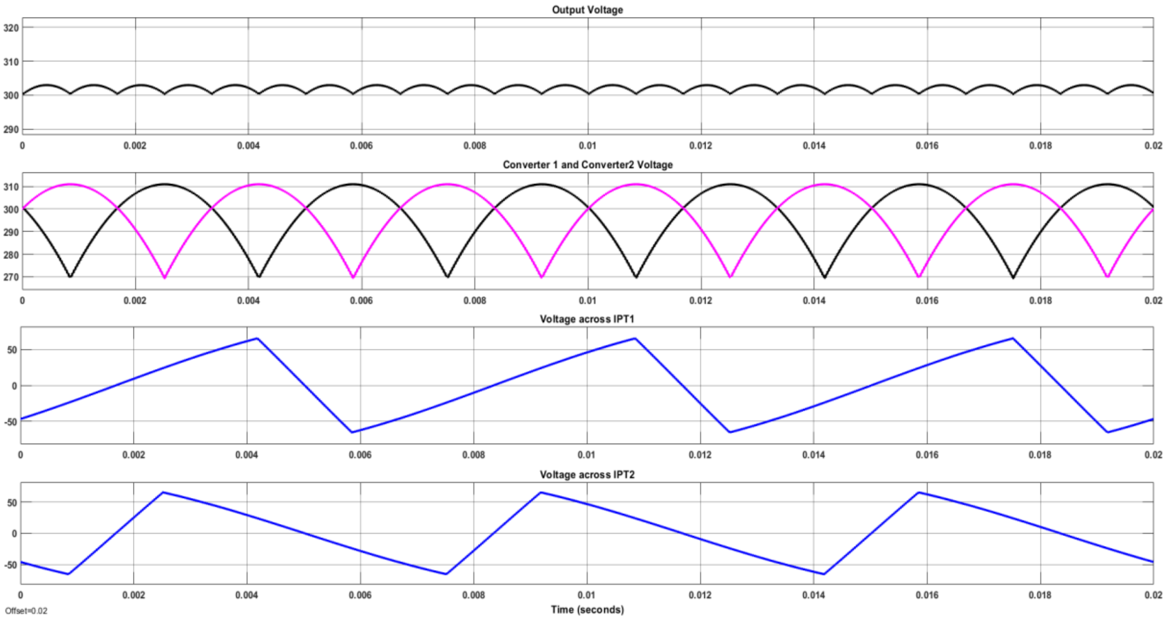

Figure 5.22 Waveforms for output voltage, converter 1 and converter 2 voltages, voltages across IPT 1 and IPT 2.

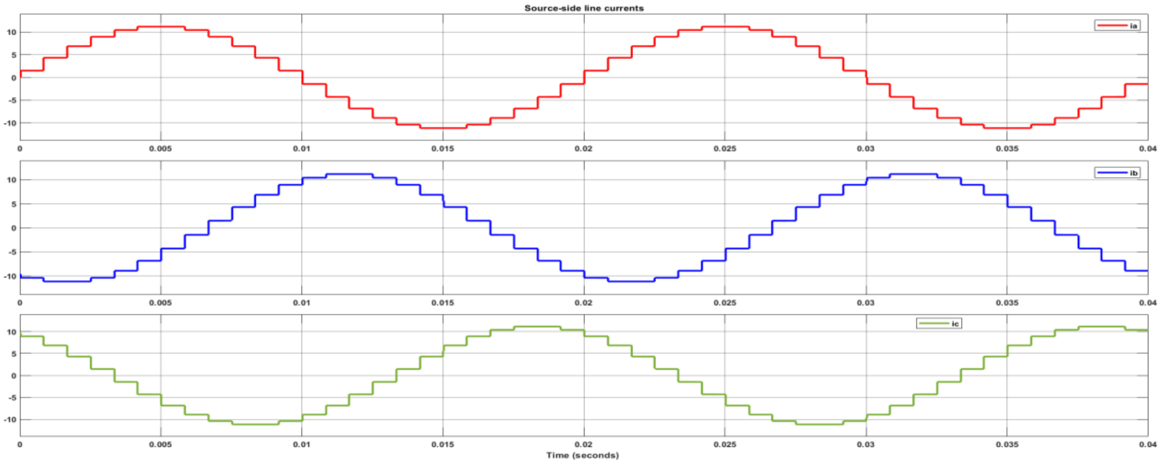

Figure 5.23 Waveforms for the supply-side line currents.

It is noteworthy that the source-side line currents appear to be closer to a sinusoidal waveform as the number of pulses increases.

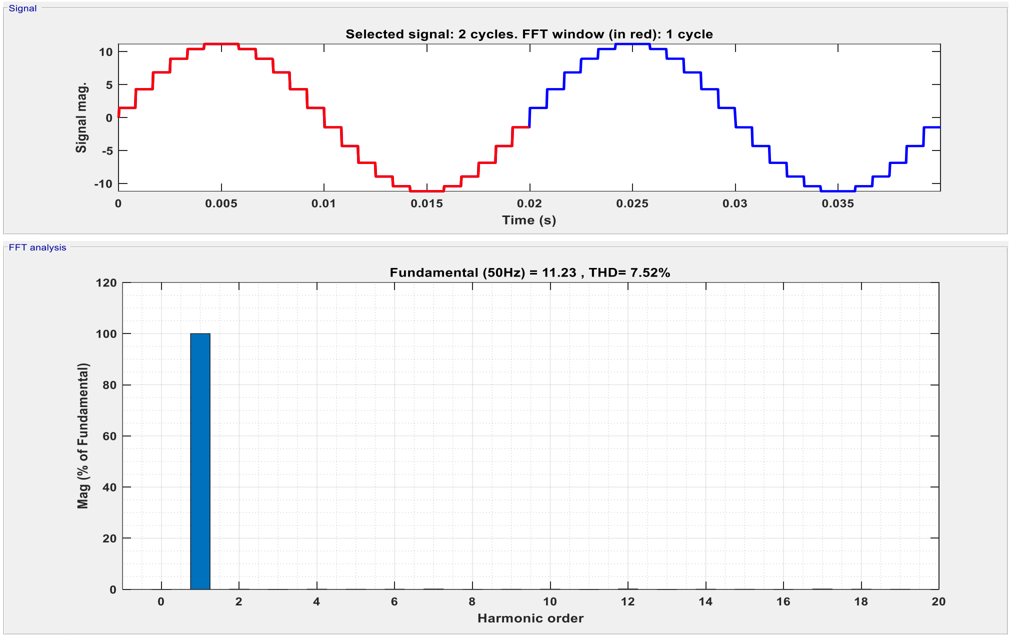

Figure 5.24 FFT window for supply side line current waveform.

The THD value obtained is 7.52%, as shown in Figure 5.24. A significant drop in THD is observed with an increase in pulse count from 12 to 24.

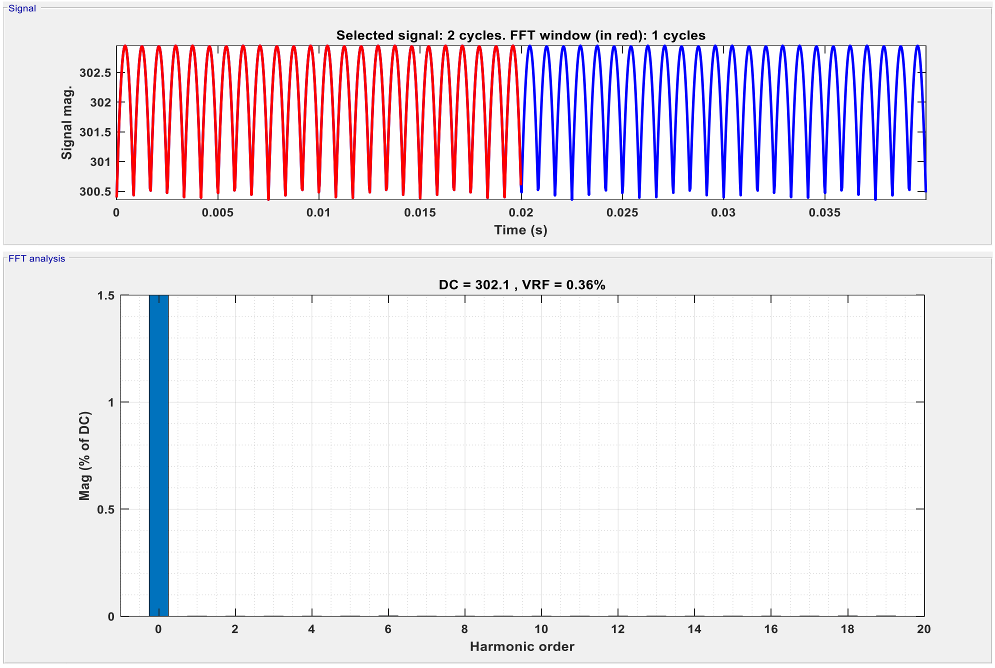

Figure 5.25 FFT window for output voltage waveform.

The output voltage waveform has a VRF of 0.36%, as shown in Figure 5.25. Thus, as the number of pulses is increased, the voltage ripple factor (VRF) decreases considerably.

5.6 An Overview of the Results Attained

The variations observed in the supply-side line current's total harmonic distortion (THD) which is one of the most important power quality parameters, are reported in Table 5.1.

Table 5.1 Supply Side Line Current T.H.D for various Converter Topologies

S. No.	Converter Topologies	Supply Current T.H.D
1.	6-pulse Uncontrolled Converter	31.03 %

2.	6-pulse Uncontrolled Converter fed from a Delta/Star transformer	30.28 %
3.	12-pulse Uncontrolled Converter fed from a Delta/star/delta transformer	15.07 %
4.	12-pulse Uncontrolled Converter fed from a Fork Auto-transformer	15.18 %
5.	24-pulse Uncontrolled Converter fed from a Fork Auto-transformer	7.52 %

Additionally, the variations observed in the output voltage ripple factor (VRF), which is another important power quality parameter, are reported in Table 5.2.

Table 5.2 Output Voltage R.F for various Converter Topologies

S. No.	Converter Topologies	Output Voltage R.F
1.	6-pulse Uncontrolled Converter	5.97 %
2.	6-pulse Uncontrolled Converter fed from a Delta/Star transformer	5.97 %
3.	12-pulse Uncontrolled Converter fed from a Delta/star/delta transformer	1.45 %
4.	12-pulse Uncontrolled Converter fed from a Fork Auto-transformer	1.46 %
5.	24-pulse Uncontrolled Converter fed from a Fork Auto-transformer	0.36%

6. CONCLUSION

The conclusions drawn from this research work are stated below:

- When the converter's pulse count rises from 6 to 12 and then to 24, a notable decrease in the total harmonic distortion (T.H.D) of the input line current is noted in relation to supply-side power quality indices. A reduction in the supply-side line current T.H.D from 31.03%, which was the case for a six-pulse uncontrolled converter, to 7.52% for a Fork Auto-transformer fed 24-pulse converter was observed.
- The output voltage ripple factor (V.R.F) for different multi-pulse converter topologies decreases considerably due to a rise in the pulse number of the multi-pulse converter. It was observed that the output voltage ripple factor decreased from 5.97%, which was the case for a six-pulse uncontrolled converter, to 0.36% for a Fork Auto-transformer fed 24-pulse converter.

LITERATURE CITED

Abdollahi, R. 2020. Multi-Phase Shifting Autotransformer Based Rectifier. *IEEE Open J. Indus. Elect. Soc.*, 1(1): 38-45.

Bhide, R. S. and Kulkarni, S. V. 2006. Analysis of Parallel Operation of Converters with Interphase Transformer. *'In: India International Conference on Power Electronics'* at Chennai, India, during. December 19-21. pp. 193-196.

Chaturvedi, P. K., Jain, S., Pradhan, K. C. and Goyal, V. 2006. Multi-pulse converters as a viable solution for power quality improvement. *'In: IEEE Power India Conference'* at New Delhi, during. April 10-12. 6 pp.

Choi, S., Lee, B. S. and Enjeti, P. N. 1997. New 24-Pulse Diode Rectifier Systems for Utility Interface of High-Power AC Motor Drives. *IEEE Trans. Indus. Appl.*, 33(2): 531-541.

Dugan, R. C., McGranaghan, M. F., Santoso, S. and Beaty, H. W. 2012. Electrical Power Systems Quality. 3rd edition. McGraw-Hill Education, New York. 880 p.

Kant, P. and Singh, B. 2018. A Multi-Pulse AC-DC Converter Fed Multi-Level Inverter for Power Quality Improvement in VCIMD. *'In: IEEE Energy Conversion Congress and Exposition (ECCE)'* at Portland, USA. during. September 23-27. pp. 4531-4536.

Kaur, A., Gupta, Y. and Choudhuri, S. G. 2019. Fork and D/y/d Connected Transformer Supplied 12-Pulse Uncontrolled Converter fed Retrofit Vector Controlled Induction Motor Drive: A Comparative Study. *'In: IEEE Region 10 Conference (TENCON)'* at Kochi, India, during. October 17-20. pp. 1643-1648.

Meng, F., Gao, L., Yang, W. and Yang, S. 2016. Comprehensive comparison of the delta- and wye-connected autotransformer applied to 12-pulse rectifier, *J. Mod. Power Syst. Clean Energy*, 4(1): 135–145.

Paice, D. A. 1996. Power Electronic Converter Harmonics: Multi-pulse Methods for Clean Power. IEEE Press, Piscataway, NJ, USA. 202 p.

Rastogi, M., Naik, R. and Mohan, N. 1994. A Comparative Evaluation of Harmonic Reduction Techniques in Three-Phase Utility Interface of Power Electronic Loads. *IEEE Transactions on Industry Applications*, 30(5): 1149-1155.

Singh, B. and Gairola, S. 2006. A Fork Connected Auto-Transformer Based 24-Pulse AC-DC Converter. *'In: India International Conference on Power Electronics'* at Chennai, India, during. December 19-21. pp. 183-187.

Singh, B., Bhuvaneswari, G. and Garg, V. 2006. Harmonic Mitigation Using 12-Pulse AC-DC Converter in Vector-Controlled Induction Motor Drives. *IEEE Transactions on Power Delivery*, 21(3): 1483-1492.

Singh, B., Bhuvaneswari, G. and Garg, V. 2006. Power-Quality Improvements in Vector-Controlled Induction Motor Drive Employing Pulse Multiplication in AC-DC Converters. *IEEE Transactions on Power Delivery*, 21(3): 1578-1586.

Singh, B., Chandra, A. and Al-Haddad, K. 2015. Power Quality Problems and Mitigation Techniques. John Wiley and Sons Ltd., West Sussex, United Kingdom. 582 p.

Singh, B., Gairola, S., Chandra, A. and Al-Haddad, K. 2007. Power Quality Improvements in Isolated Twelve-Pulse AC-DC Converters Using Delta/Double-Polygon Transformer, *'In: IEEE Power Electronics Specialists Conference'* at Orlando, FL, USA, during. June 17-21. pp. 2848-2853.

Singh, B., Gairola, S., Chandra, A. and Al-Haddad, K. 2007. Zigzag Connected Autotransformer Based Controlled AC-DC Converter for Pulse Multiplication. *'In: IEEE International Symposium on Industrial Electronics'* at Vigo, Spain, during. June 04-07. pp. 889-894.

Singh, B., Gairola, S., Singh, B. N., Chandra, A. and Al-Haddad, K. 2008. Multi-pulse AC-DC Converters for Improving Power Quality: A Review. *IEEE Trans. Power Elect.*, 23(1): 260-281.

Swamy, M., Kume, T. J. and Takada, N. 2010. A Hybrid 18-Pulse Rectification Scheme for Diode Front-End Rectifiers With Large DC-Bus Capacitor. *IEEE Transactions on Industry Applications*, 46(6): 2484-2494.

Wu, B. 2006. High-Power Converters and AC Drives. John Wiley and Sons, Inc., New Jersey. 333 p.