



Advanced Strategies For Harmonic Mitigation In Multipulse Ac-Dc Converters

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Abstract: This paper investigates the reduction of Total Harmonic Distortion (THD) in power conversion systems using multipulse AC to DC converters. Recognized for their capability to cancel specific harmonic orders, multipulse converters are essential in improving power quality in high-power industrial applications. A comprehensive analysis is conducted on controlled (thyristor-based) and uncontrolled (diode-based) configurations under RL load conditions, focusing on pulse configurations up to 8 pulses. Simulations and empirical validation assess the effectiveness of these systems in minimizing THD and ripple current. Despite significant advancements, research gaps persist in the comparative analysis of controlled and uncontrolled converters across various pulse configurations. This study addresses these gaps by providing a detailed evaluation of THD reduction and ripple performance across multiple configurations, offering insights for optimizing power conversion systems in real-world applications.

Index Terms - THD, Multipulse AC to DC converters, HVDC, Controlled and uncontrolled converters

I. INTRODUCTION

In recent years, extensive research has focused on mitigating Total Harmonic Distortion (THD) in power conversion systems, leading to the development of sophisticated strategies that enhance power quality. Multipulse AC to DC converters have emerged as an effective solution for reducing harmonic distortion, particularly in industrial applications where power quality is critical [1], [2]. These systems are essential in modern power electronics, especially in scenarios where high-power conversion is required with minimal interference to the grid. The importance of THD reduction cannot be overstated. High levels of harmonic distortion can lead to several undesirable effects, including overheating of equipment, overloading of neutral conductors, increased losses in transformers, and malfunction of sensitive electronic devices. The IEEE Standard 519-2014 specifies the acceptable levels of harmonics in electrical systems to ensure the reliability and efficiency of the power grid [3]. This paper investigates the reduction of THD using multipulse AC to DC conversion schemes, offering a comprehensive analysis of both uncontrolled and controlled converter configurations under RL load conditions.

One of the earliest methods involves the use of passive filters to eliminate specific harmonic frequencies. While effective, this approach often requires large filter components, which can be costly and cumbersome [4]. Active filters, introduced in later years, offer more flexibility and can dynamically adjust to varying load conditions, but they come at a higher cost and complexity [5]. Multipulse converters have become a preferred method for harmonic reduction due to their inherent ability to cancel out certain harmonic orders by phase-shifting the input waveform. Zhang et al. [6] discussed the basic operation of 6-pulse and 12-pulse rectifiers, highlighting the significant reduction in THD achievable through these configurations. However, these studies often focus on specific configurations, such as 12-pulse systems, without exploring higher-pulse configurations that could offer even greater harmonic reduction.

Recent advancements have seen the integration of wide-bandgap semiconductor devices, such as SiC and GaN, into multipulse converter designs. These materials allow for higher switching frequencies and improved efficiency, making them suitable for high-power applications [7]. However, the literature on the practical implementation of these devices in multipulse converters is still limited, with most studies focusing on theoretical models or simulations. Control strategies have also been a focus of recent research. Alavi et al. [8] explored Model Predictive Control (MPC) as a method for optimizing the performance of multipulse converters, showing promising results in reducing THD. Similarly, Space Vector Modulation (SVM) has been proposed as an effective technique for harmonic reduction, although its implementation in multipulse converters is still an emerging area of study [9]. Despite the extensive research, a gap remains in the literature regarding the comparative analysis of controlled and uncontrolled multipulse converter systems across various pulse configurations. Additionally, the impact of advanced semiconductor materials and control strategies on the overall performance of these systems has not been thoroughly explored in a real-world context.

While multipulse converters are well-documented for their effectiveness in reducing THD, most studies focus on specific pulse configurations, such as 6-pulse or 12-pulse systems, without fully exploring the potential of higher pulse configurations (e.g., 18, 24, 36, 48 pulses). Furthermore, the literature often lacks a detailed comparative analysis between controlled (thyristor-based) and uncontrolled (diode-based) converters across these various configurations. Another significant gap is the limited exploration of wide-bandgap semiconductor materials in practical multipulse converter applications. While theoretical studies suggest that materials like SiC and GaN can enhance converter performance, there is a need for empirical studies that validate these claims and explore their impact on harmonic distortion and overall system efficiency. Finally, advanced control techniques like MPC and SVM have shown potential in reducing THD, but their application in multipulse converters is still in its infancy. There is a need for research that not only applies these techniques to multipulse systems but also compares their effectiveness against traditional control methods. In light of the identified research gaps, this study aims to achieve the following objectives:

In addressing the identified research gaps, this study aims to achieve the following objectives:

1. **Comparative Analysis of Pulse Configurations:** Conduct a detailed analysis of THD reduction and ripple current across various multipulse configurations, specifically focusing on configurations up to 8 pulses. This involves comparing both controlled and uncontrolled converter systems to determine the most effective setup for minimizing harmonic distortion and ripple.
2. **Simulation and Empirical Validation:** Execute comprehensive simulations and empirical studies to validate the effectiveness of different multipulse configurations in reducing THD and ripple current. This objective aims to ensure that the results are practical and applicable to real-world industrial scenarios.

II. SYSTEM ARCHITECTURE AND CONVERTER DESIGN

The architecture of a three-phase multipulse AC to DC conversion system is pivotal to its performance in reducing harmonic distortion. The system employs a phase-shifting transformer coupled with a series of three-phase converters positioned between the power supply and the load. Each converter inherently generates a 6-pulse AC to DC conversion. The 6-pulse rectifier is the basic building block, and it produces significant harmonic distortion, particularly the 5th and 7th harmonics in the input current. However, by combining multiple 6-pulse rectifiers with appropriate phase shifts, it is possible to cancel out these lower-order harmonics, significantly reducing the overall THD [10]. To extend this configuration to higher pulse counts—such as 12, 18, 24, 36 or more—a uniform phase shift is introduced. This phase shift is critical, as it cancels specific harmonic orders, thereby significantly diminishing the overall THD in the output current and voltage [11]. For instance, a 12-pulse rectifier configuration, which is formed by combining two 6-pulse rectifiers with a 30-degree phase shift, cancels the 5th and 7th harmonics, while an 18-pulse rectifier further reduces harmonics by introducing additional phase shifts [12].

In uncontrolled conversion systems, diodes are preferred due to their simplicity and reliability. Diode rectifiers are robust and do not require complex control circuits, making them suitable for applications where cost and reliability are primary concerns. However, controlled rectifiers, utilizing thyristors, offer enhanced control over the conversion process, enabling dynamic response to varying load conditions and further reducing harmonic content [13]. Thyristors can be gated on and off to control the output voltage, providing flexibility in the operation of the converter, which is particularly useful in applications requiring precise voltage control or when integrating renewable energy sources with varying outputs. The integration of these devices into multipulse converters has been extensively analyzed, revealing significant

improvements in harmonic performance [14]. For example, controlled rectifiers allow for the adjustment of the firing angle, which can be used to modulate the output voltage and improve power factor. The ability to control the output voltage also allows for better matching of the converter to the load, reducing losses and improving efficiency.

III. MULTI-PULSE METHODS FOR HARMONIC REDUCTION IN AC TO DC CONVERTERS

In modern power electronics, maintaining high power quality is paramount, especially in systems where converters are extensively used. Multi-pulse methods are advanced techniques designed to address harmonic distortion issues in AC to DC converters. These methods leverage the interaction between multiple converters to cancel out harmonics generated by each unit, leading to improved power quality and system efficiency [1], [2]. Multi-pulse methods involve the use of multiple rectifier circuits or converters, each contributing to the reduction of harmonic distortion through strategic phase shifts. By aligning converters in a manner that harmonics from one unit are countered by those from another, significant reductions in Total Harmonic Distortion (THD) can be achieved. This approach is particularly effective in targeting specific harmonic orders, thus minimizing their impact on the overall power system [3], [4]. For example, a typical 12-pulse converter system uses two 6-pulse rectifiers that are phase-shifted by 30 degrees. This configuration effectively cancels out the 5th and 7th harmonics, which are prominent contributors to harmonic distortion in power systems. As the number of pulses increases, such as in 18-pulse or 24-pulse systems, higher-order harmonics are addressed, leading to further improvements in harmonic suppression and ripple reduction [5]. Reducing harmonic distortion is crucial for several reasons:

- **System Efficiency:** High harmonic levels can lead to increased power losses, reduced efficiency, and additional stress on electrical components. By minimizing harmonics, the overall efficiency of the power system is enhanced, contributing to lower operational costs and prolonged equipment life [6].
- **Regulatory Compliance:** Compliance with standards such as IEEE 519-2014 is essential for ensuring power quality and preventing adverse effects on the electrical grid. Multi-pulse methods are effective in meeting these regulatory requirements by achieving significant reductions in harmonic distortion [7].
- **Operational Stability:** Harmonics can cause operational issues such as resonance in electrical systems, leading to potential equipment failures or operational disruptions. Multi-pulse techniques help in stabilizing the system by reducing harmonic interference [8].

Various multi-pulse techniques are employed to achieve effective harmonic reduction:

- **6-Pulse Rectifiers:** The basic configuration involving six diodes or thyristors in a rectifier circuit. While effective for reducing some harmonics, it often requires additional techniques for comprehensive harmonic control [9].
- **12-Pulse Rectifiers:** Achieved by combining two 6-pulse rectifiers with a phase shift of 30 degrees. This configuration is widely used in industrial applications for its ability to significantly reduce 5th and 7th harmonics [10].
- **18-Pulse and 24-Pulse Rectifiers:** These setups involve additional phase-shifted rectifiers to address higher-order harmonics. The increased complexity of these configurations results in improved harmonic suppression and reduced ripple content [11].
- **Higher Pulse Configurations:** For more stringent harmonic control, configurations with 36-pulse or 48-pulse rectifiers can be used. These setups offer enhanced harmonic mitigation but come with increased complexity and cost [12].

IV. RECENT ADVANCES AND PRACTICAL CONSIDERATIONS

Recent advancements in multi-pulse converter technology focus on enhancing performance and reducing costs. Innovations include improved phase-shifting techniques, the use of advanced semiconductor materials, and the integration of sophisticated control algorithms. These developments aim to further optimize harmonic reduction and system efficiency while addressing practical challenges such as size, cost, and complexity [13], [14].

V. SIMULATION AND PERFORMANCE ANALYSIS

To assess the performance of multipulse converters, this study focuses on key parameters such as THD in the supply current, DC voltage ripple, and form factor. Simulations are conducted under consistent RL load conditions across various multipulse converter configurations to ensure a rigorous and fair comparison between controlled and uncontrolled systems. The simulation results indicate that higher pulse configurations (e.g., 24-pulse or 30-pulse systems) exhibit a substantial reduction in THD, aligning with the stringent requirements set by IEEE Standard 519-2014 for harmonic control in electrical power systems [15]. The results demonstrate that the use of phase-shifting transformers in combination with multiple converters effectively cancels out lower-order harmonics, leading to cleaner power output and improved efficiency. In a 24-pulse system, for example, four 6-pulse rectifiers are used, each with a phase shift of 15 degrees between them. This configuration effectively cancels the 5th, 7th, 11th, and 13th harmonics, resulting in a significant reduction in THD. The DC voltage ripple is also minimized, which is critical for applications requiring a stable DC output, such as in HVDC transmission systems or in the integration of renewable energy sources like solar PV and wind turbines [16].

5.1 Uncontrolled Multi-Pulse Converters

A. Six-Pulse Converter: The basic converter unit in HVDC transmission systems is the six-pulse converter bridge, as seen in Fig. 1. This diagram illustrates the fundamental setup of a 6-pulse rectifier, highlighting the arrangement of components and the resultant harmonic profile. It works in two different ways: inversion, when power moves from the DC side to the AC side, and rectification, when power moves from the AC side to the DC side. If the converter's thyristor valves are forward biased, they function as switches that are activated by a gate pulse and conduct current. A six-pulse converter produces recognizable AC side current harmonics of the pattern $6n \pm 1$. In a similar vein, a six-pulse converter's distinctive DC side voltage harmonics similarly follow the pattern $6n \pm 1$. Fig.2 shows THD for input current uncontrolled Six-Pulse Converter.

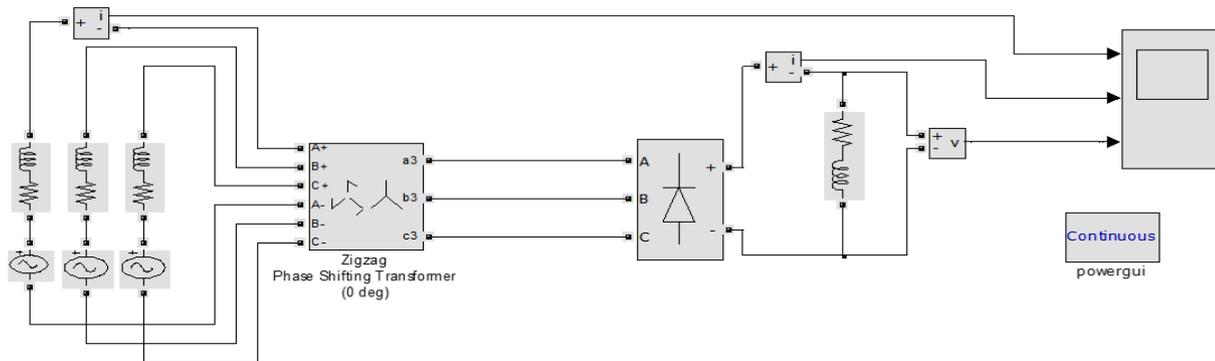


Fig. 1. Uncontrolled Six-Pulse Converter

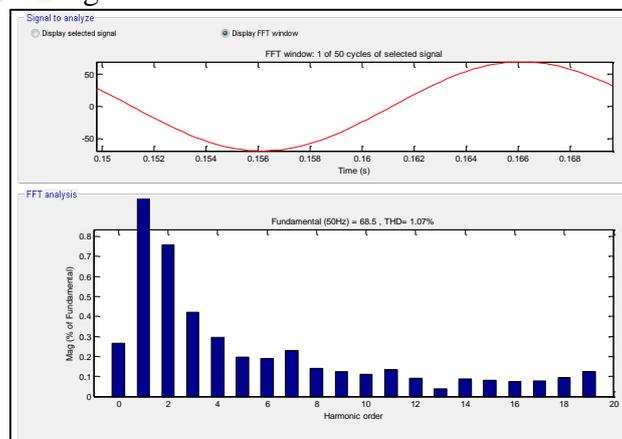


Fig. 2. THD for input current Uncontrolled Six-Pulse Converter

B. Twelve Pulse Converter: Two completely controlled six-pulse converter bridges coupled in sequence make up a twelve-pulse converter. Two 3-phase systems that are separated by 30 electrical degrees are needed for this setup. On both the AC and DC sides, the 6-pulse harmonics are essentially cancelled out by the phase difference between the two systems. Twelve-pulse converter bridge, as seen in Fig. 3 and THD for input current is shown in Fig. 4.

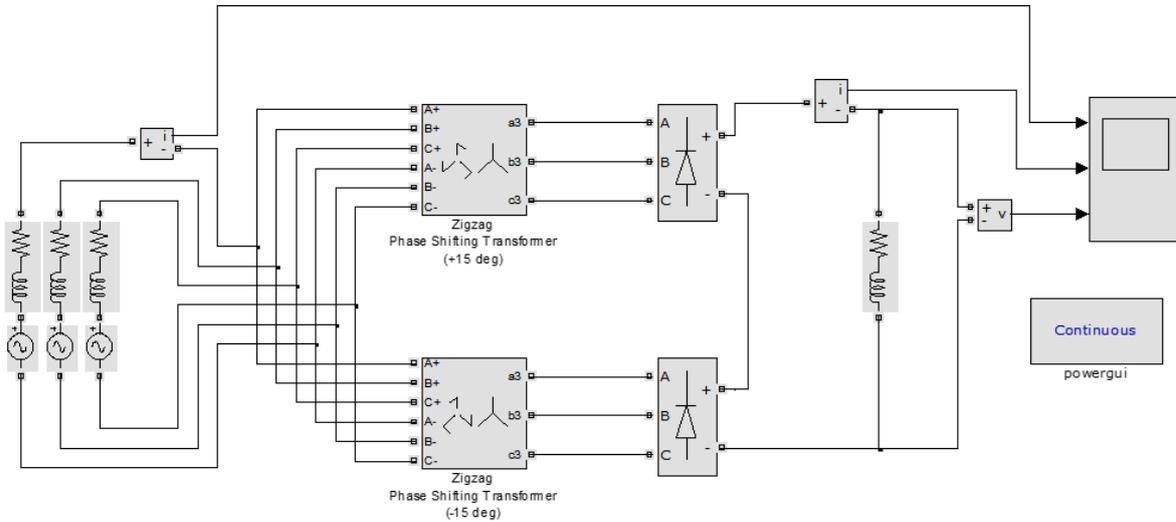


Fig. 3. Uncontrolled twelve pulse converter

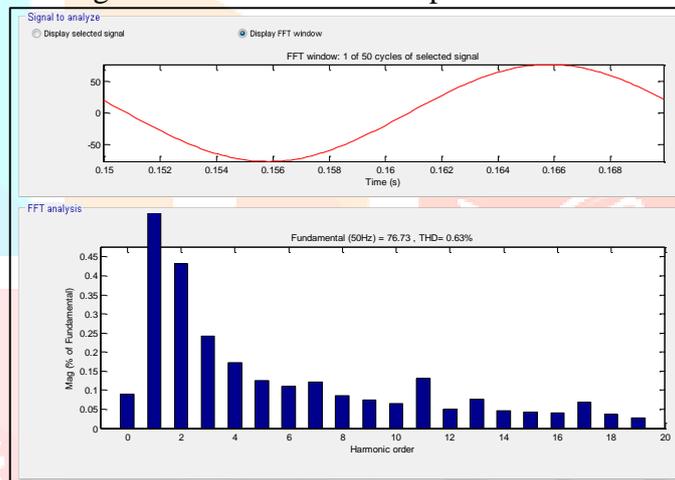


Fig. 4. THD for input current Uncontrolled twelve pulse converter

C. Eighteen Pulse Converter

The magnetic circuit used in this 18-pulse topology is identical to that of a 6-pulse converter. As a result, this topology is generally favored. The outcomes of the simulation closely match any outcome produced by an 18 pulse converter. Between each of the three phase shift transformers with star-connected secondary, a phase shift of 20° has been supplied. Figure shows the integration of two 6-pulse rectifiers with phase-shifting transformers, demonstrating how specific harmonic orders are cancelled out. Eighteen-pulse converter bridge, as seen in Fig. 5 and THD for input current is shown in Fig. 6.

D. Twenty-Four Pulse Converter

This configuration consists of four six-pulse converters that are phase-shifted 15 degrees apart from one another in order to achieve 24-pulse rectification. Both the AC and DC sides' harmonics are much reduced as a result. The phase shift will cause the AC output voltage to display harmonics of order 24n±1, which include the 23rd, 25th, 47th, 49th harmonics, with magnitudes of 1/23rd, 1/25th, 1/47th, 1/49th, ..., and so on. 24-pulse converter bridge, as seen in Fig. 7 and THD for input current is shown in Fig. 8.

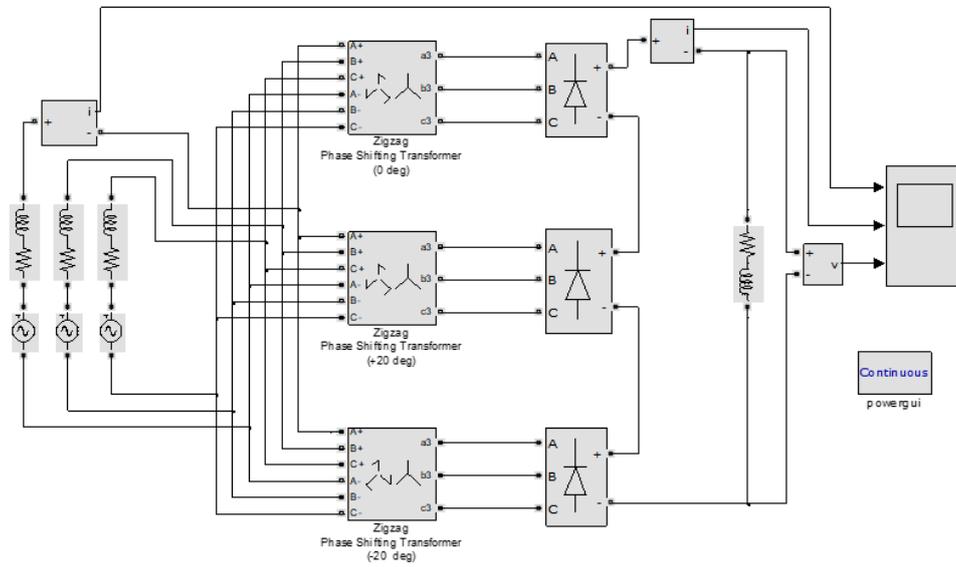


Fig. 5. Uncontrolled eighteen pulse converter

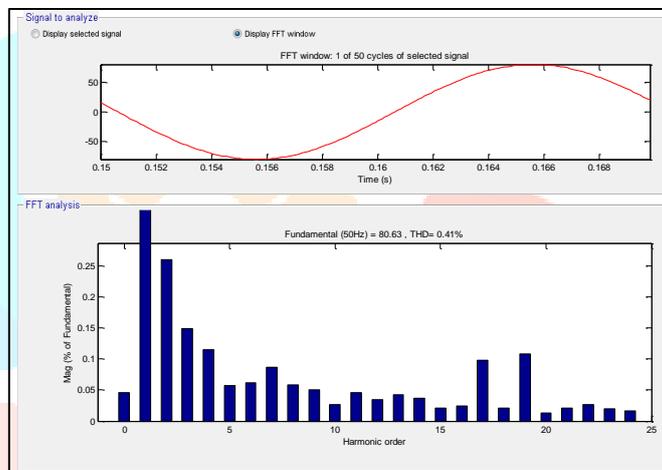


Fig. 6. THD for input current for eighteen pulse converter

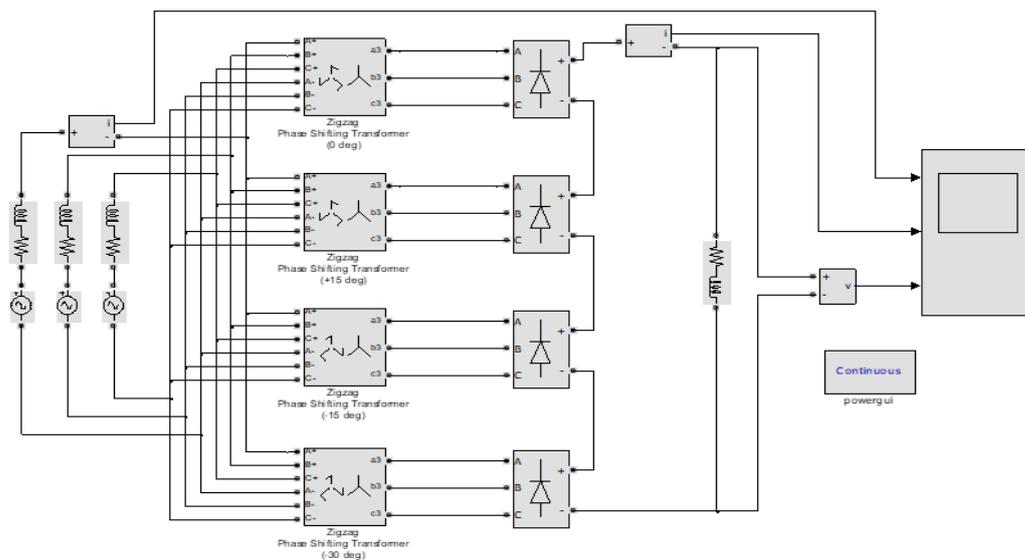


Fig. 7. Uncontrolled twenty four pulse converter

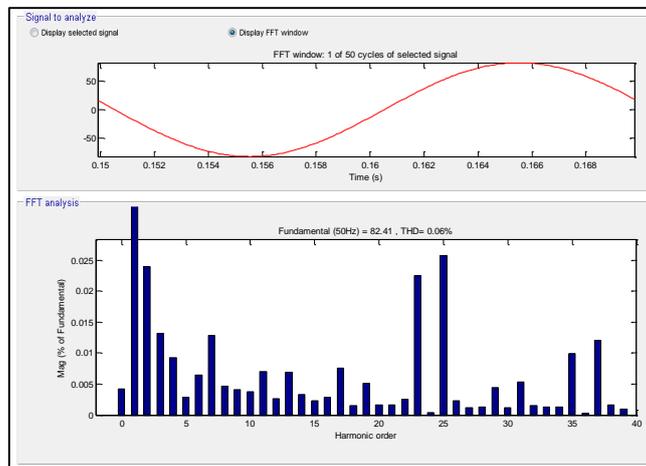


Fig. 8. THD for input current Uncontrolled twenty four pulse converter

E. Thirty-Pulse Converter

With this configuration, harmonics on the AC and DC sides are greatly reduced because to thirty-pulse conversion, which is made possible by six six-pulse converters phase-shifted by 12° from one another. In relation to the phase shift, the AC output voltage will display harmonics of order $30n \pm 1$, such as the 29th, 31st, 59th, and 61st harmonics, with magnitudes of $1/29^{\text{th}}$, $1/31^{\text{st}}$, $1/59^{\text{th}}$, $1/61^{\text{st}}$, and so on, relative to the phase shift. 30-pulse converter bridge, as seen in Fig. 9 and THD for input current is shown in Fig. 10.

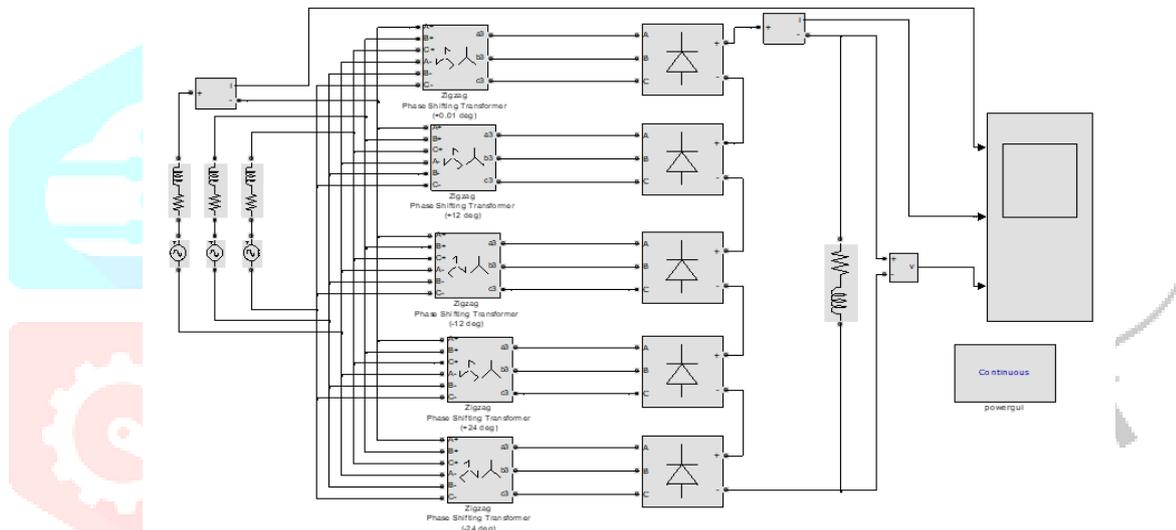


Fig. 9. Uncontrolled thirty pulse converter

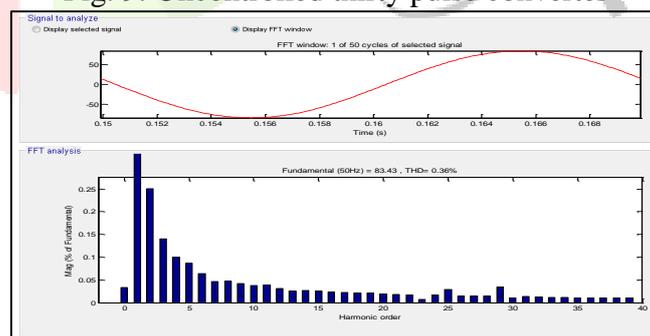


Fig. 10. THD for input current Uncontrolled thirty pulse converter

F. Thirty-Six Pulse Converter

Thirty-six pulses can be converted with this configuration, which consists of six six-pulse converters phase-shifted by 10° from one another. Both the AC and DC sides' harmonics are much reduced as a result. There will be $36n \pm 1$ harmonics in the AC output voltage. 36-pulse converter bridge, as seen in Fig. 11 and THD for input current is shown in Fig. 12.

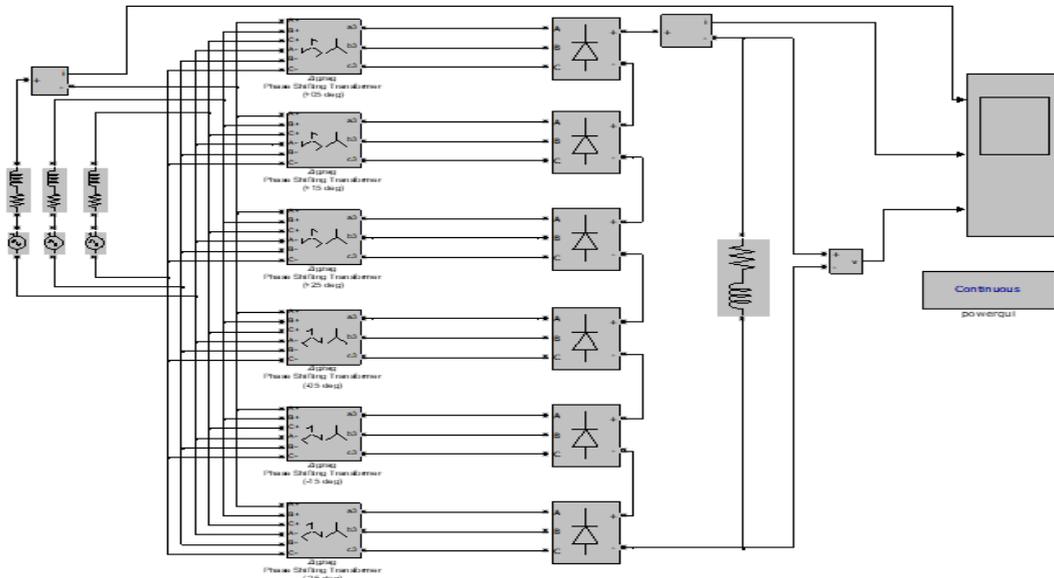


Fig. 11. Uncontrolled Thirty-Six Pulse Converter

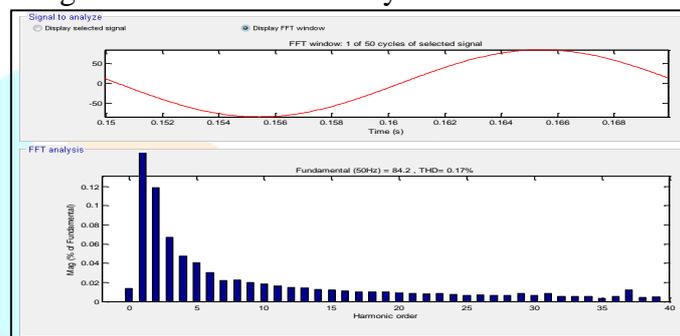


Fig. 12. THD for input current Uncontrolled Thirty-Six Pulse Converter

G. Forty-Eight Pulse Converter

Even 24-pulse, 30-pulse, or 36-pulse converters without AC filters might generate voltage harmonics for high-power FACTS controllers that might be too high for the AC systems to tolerate. An effective workaround for this problem is to employ a 48-pulse converter system. Eight six-pulse converters, each phase-shifted by 7.5° from the others, are used in this system. All eight transformer primaries are linked in series to create this setup. Through additional mitigation of harmonic distortions in both the AC and DC sides, this configuration efficiently lowers harmonics and enhances overall power quality. 48-pulse converter bridge, as seen in Fig. 13 and THD for input current is shown in Fig. 14.

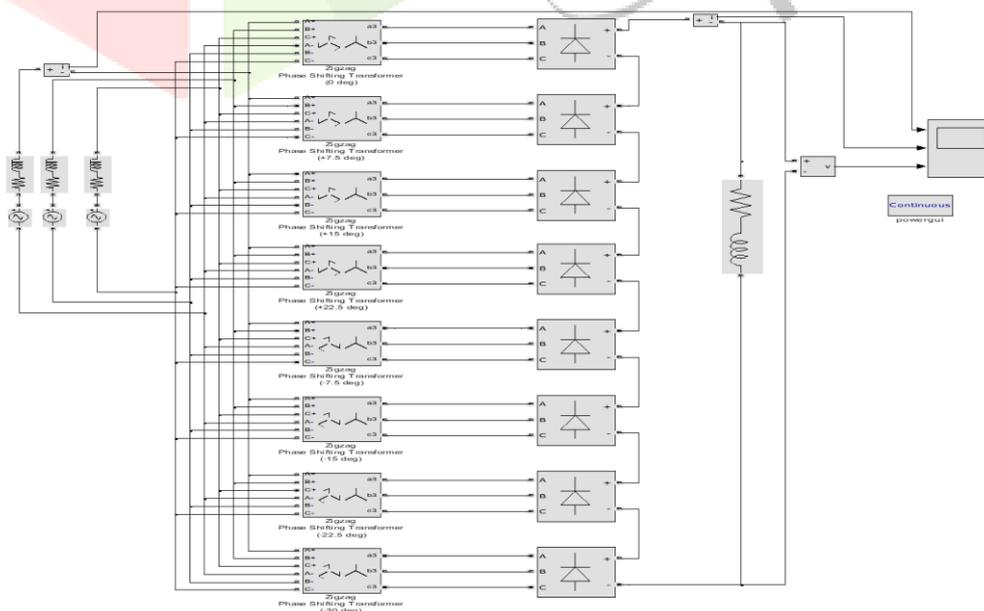


Fig. 13. Uncontrolled Forty-Eight Pulse Converter

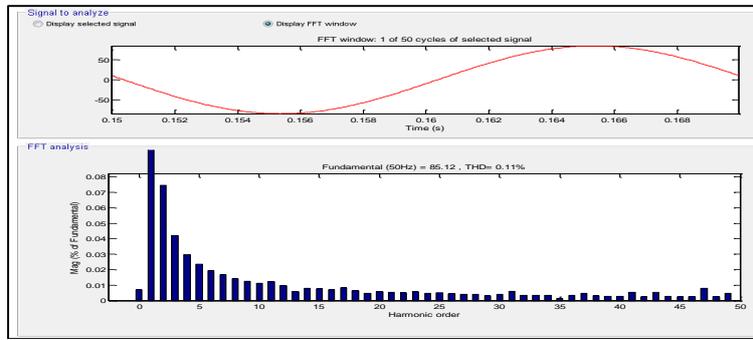


Fig. 14. THD for input current Uncontrolled Forty-Eight Pulse Converter

5.2 Simulation of Controlled Multi-Pulse Converters

For the simulation of controlled multi pulse converters instead of the diode bridge we use the Thyristor Bridge and the corresponding pulses are given.

A. Six-Pulse Converter: Key elements of power electronics are controlled six-pulse converters, which use thyristor valves to convert AC to DC. They produce harmonics at orders of $6n \pm 1$, i.e., 5th, 7th, and 11th harmonics, notwithstanding their efficiency. In order to maintain power quality and guarantee stable operation, these harmonics can distort waveforms and affect system performance. For this reason, filters and control strategies are required.

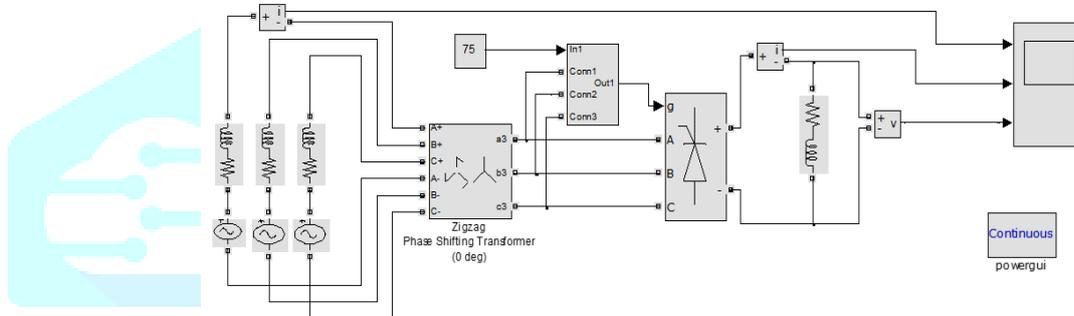


Fig. 15. Controlled six-pulse Converter

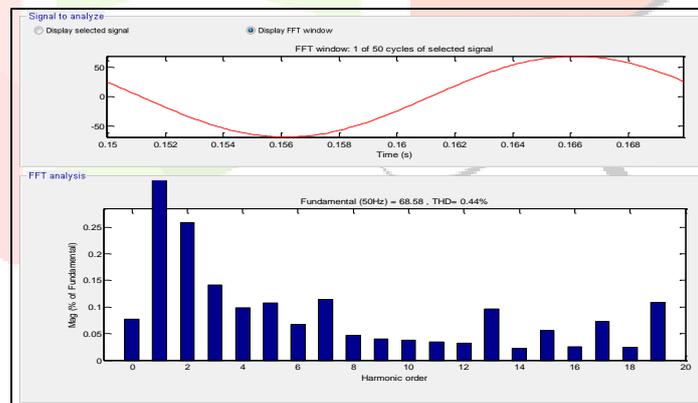


Fig. 16. THD for input current for Controlled six-pulse Converter

B. Twelve Pulse Converter: By employing two six-pulse converters, each phase-shifted by 30° , to lessen harmonic distortion, twelve-pulse converters improve power quality in HVDC systems. The overall waveform and system performance are enhanced by this design, which dramatically lowers the harmonic orders to $12n \pm 1$ (i.e., the 11th, 13th, and 23rd harmonics). Even with this decrease, certain harmonics might still exist, in which case additional mitigation strategies are needed to maximize system stability and efficiency.

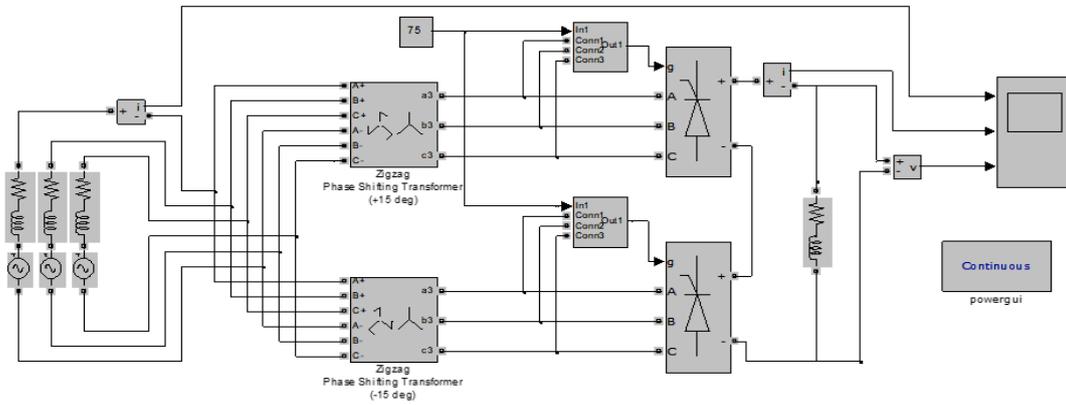


Fig. 17. Controlled Twelve Pulse Converter

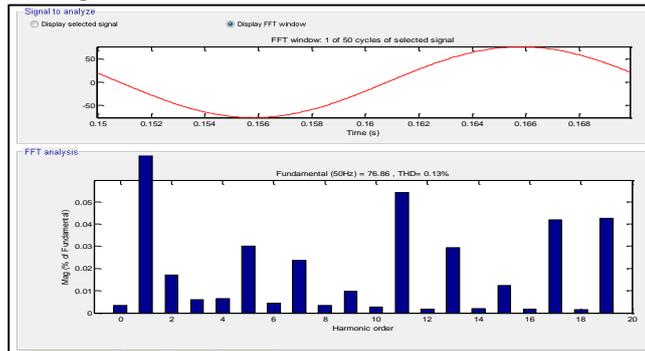


Fig. 18. THD for input current

C. Eighteen-Pulse Converter: In order to attain better power quality in HVDC systems, three six-pulse converters that are phase-shifted by 20° are used by eighteen-pulse converters to further improve harmonic control. By reducing harmonics to orders of $18n \pm 1$ (i.e., 17th, 19th, and 35th harmonics), this arrangement minimizes distortion considerably when compared to converters with lower pulse counts. Even though the waveform quality is much improved by this arrangement, extra filtering and handling of some remaining harmonics can still be necessary to preserve system efficiency.

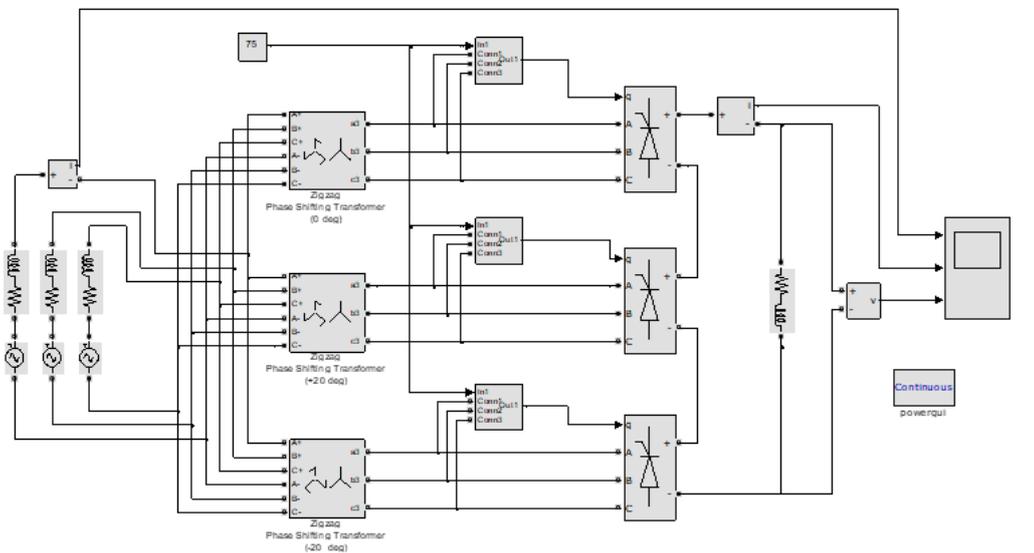


Fig. 19. Controlled eighteen pulse converter

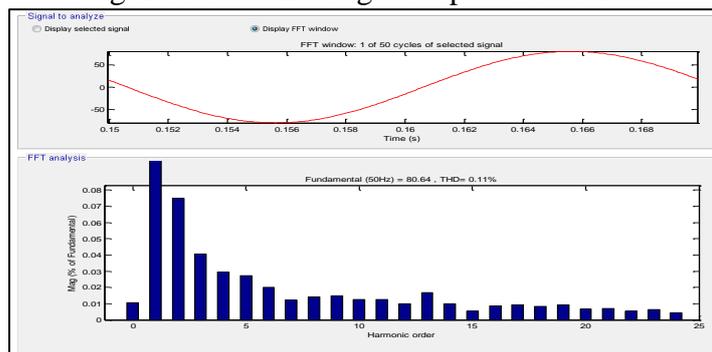


Fig. 20. THD for input current Controlled eighteen pulse converter

D. Twenty-Four Pulse Converter: To accomplish enhanced harmonic mitigation in HVDC systems, twenty-four-pulse converters use four six-pulse converters that are phase-shifted by 15° between them. When compared to lower-pulse converters, this arrangement significantly improves waveform quality and system performance by reducing harmonic orders to $24n \pm 1$ (i.e., 23rd, 25th, and 47th harmonics). Even with the great reduction of harmonics, additional filtering could be required to remove any residual distortions and guarantee excellent performance.

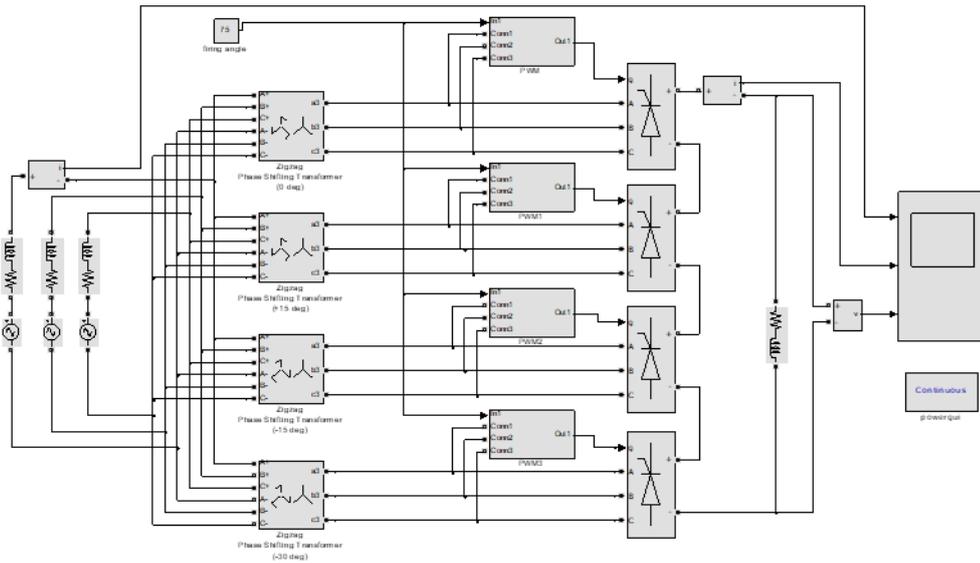


Fig. 21. Controlled twenty four pulse converter

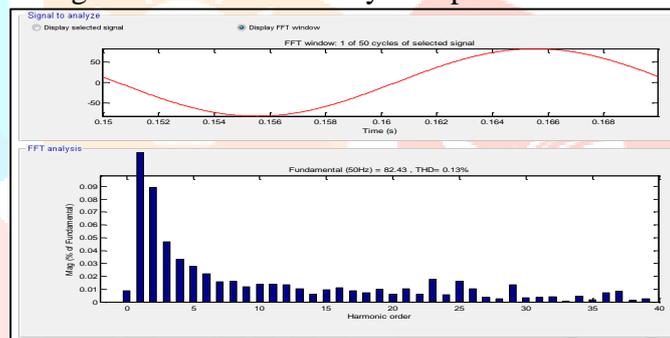


Fig. 22. THD for input current Controlled twenty four pulse converter

E. Thirty Pulse Converter: Thirty-pulse converters are intended to improve harmonic performance even more by using six phase-shifted six-pulse converters in HVDC systems. By reducing harmonic orders to $30n \pm 1$ (i.e., the 29th, 31st, and 59th harmonics), this arrangement improves system efficiency and waveform quality significantly. Even with the significant harmonic reduction, residual distortions can still exist in some form, requiring further filtering and management to ensure optimal system operation.

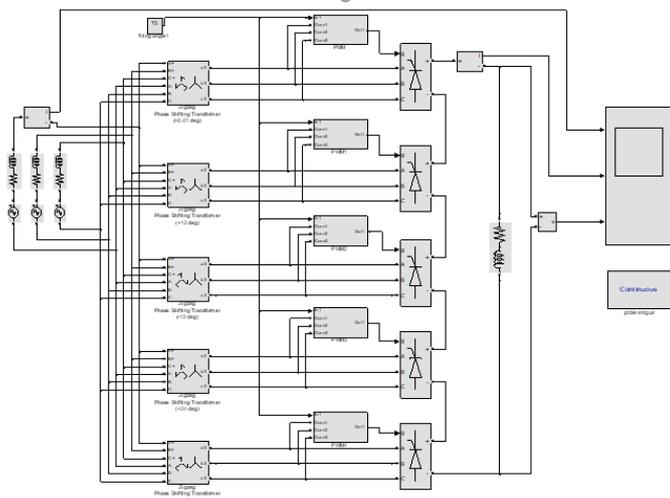


Fig. 23. Controlled Thirty Pulse Converter

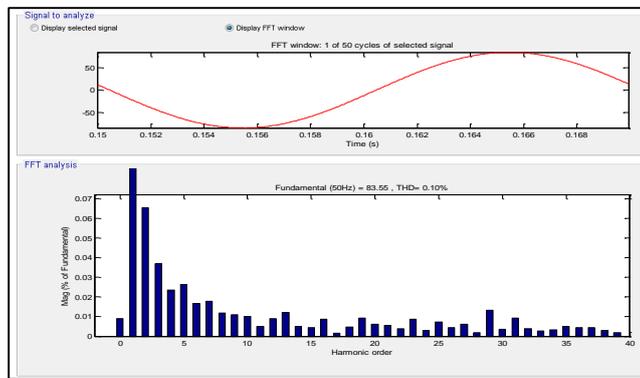


Fig. 24. THD for input current Controlled Thirty Pulse Converter

F. Thirty-Six Pulse Converter: Six six-pulse converters, each phase-shifted by 10° , are used in thirty-six-pulse converters to improve harmonic performance in HVDC systems. Compared to lower-pulse converters, this configuration significantly improves waveform quality and minimizes distortion by limiting harmonic orders to $36n \pm 1$ (i.e., 35th, 37th, and 71st harmonics). Even when harmonics are much reduced, residual harmonics could still exist and need to be filtered further to provide the best possible system performance.

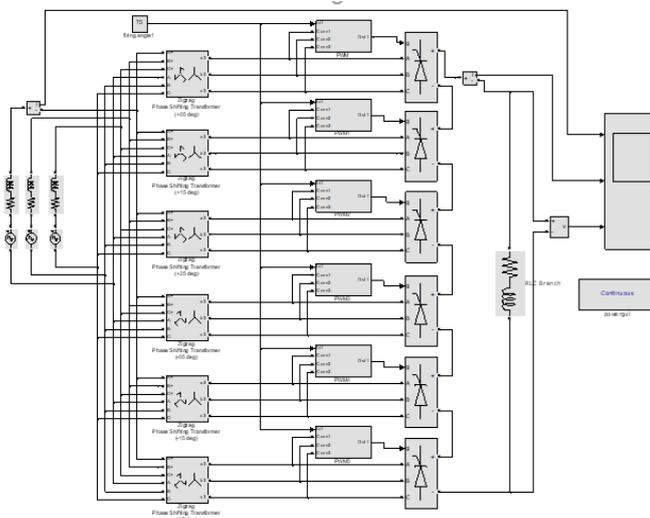


Fig. 25. Controlled Thirty-Six Pulse Converter

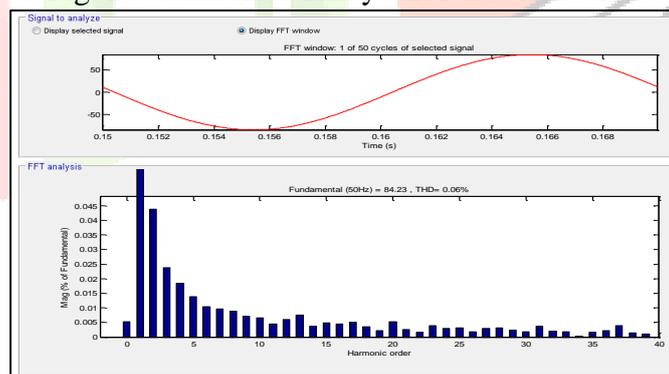


Fig. 26. THD for input current Controlled Thirty-Six Pulse Converter

G. Forty-Eight Pulse Converter: In order to obtain improved harmonic reduction in HVDC applications, forty-eight-pulse converters are sophisticated systems that employ eight six-pulse converters, each phase-shifted by 7.5° . By reducing harmonics to orders of $48n \pm 1$ (i.e., 47th, 49th, and 95th harmonics), this arrangement greatly improves system efficiency and waveform quality. Even with a significant reduction in harmonic content, residual harmonics can still exist, in which case more filtering and control techniques would be required to guarantee optimal system operation.

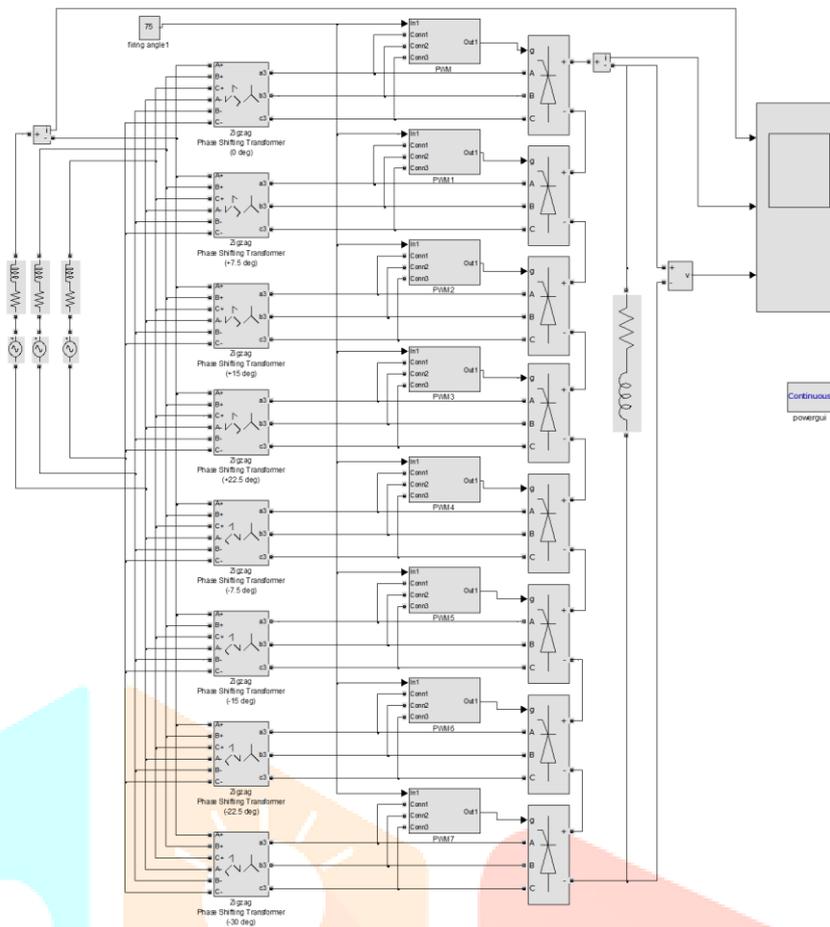


Fig. 27. Controlled Forty-Eight Pulse Converter

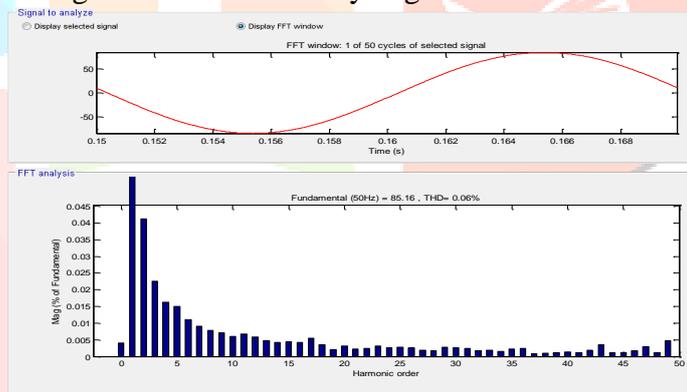


Fig. 28. THD for input current Controlled Forty-Eight Pulse Converter

VI. ANALYSIS OF SIMULATION RESULTS

The outcomes gathered from the MATLAB/SIMULINK modeling and simulation of the previously described converter models have been obtained. The study involved a comprehensive analysis of many configurations, encompassing diverse load types, to assess critical performance elements like Total Harmonic Distortion (THD), ripple content, and form factor. The main distinction between controlled and uncontrolled multi-pulse converters is the subject of this comparison. To allow for a thorough comparison, all results are listed in Tables 1 and Table 2.

Table 1: Parameters for Uncontrolled converter

Parameter	Total Harmonic Distortion			% Ripple Content			Form Factor		
	No. of Pulses	R Load	RL Load	RC Load	R Load	RL Load	RC Load	R Load	RL Load
06	0.78	1.07	1.21	4.625	4.352	4.385	1.00	1.00	1.00
12	0.51	0.63	0.65	1.412	0.9479	0.9399	1	1	1
18	0.37	0.41	0.45	1.066	0.5821	0.5848	1	1	1
24	0.24	0.06	0.38	0.7492	0.0588	0.3256	1	1	1
30	0.20	0.36	0.36	0.4954	0.313	0.3328	1	1	1
36	0.20	0.17	0.18	0.4477	0.2739	0.2198	1	1	1
48	0.14	0.11	0.28	0.5320	0.2988	0.3478	1	1	1

Table 2: Parameters for controlled converter

Parameter	Total Harmonic Distortion			% Ripple Content			Form Factor		
	No. of Pulses	R Load	RL Load	RC Load	R Load	RL Load	RC Load	R Load	RL Load
06	0.45	0.44	7.64	4.55	12.1	78.0	1.01	1.00	1.26
12	0.13	0.13	0.14	6.14	35.4	6.41	1.00	1.00	1.00
18	0.11	0.11	0.23	4.50	4.49	4.49	1.00	1.00	1.00
24	0.11	0.13	0.19	3.35	3.33	3.34	1.00	1.00	1.00
30	0.09	0.10	0.11	2.55	2.56	2.49	1	1	1
36	0.03	0.06	0.09	2.15	2.12	2.07	1	1	1
48	0.09	0.06	0.02	1.57	1.60	1.62	1	1	1

The effect of load variation on various multi-pulse converters shows that current THD reduces with RL load due to the smoothing effect of inductance. Similar effects are seen in several multi-pulse converters; that is, the harmonic spectrum is negatively impacted by the increased current discontinuities.

VII. CONCLUSION

This research highlights the essential function that multi-pulse AC to DC converters play in improving power quality and reducing Total Harmonic Distortion (THD) in contemporary electrical systems. Significant reductions in harmonic content are obtained by increasing the number of pulses in these converters, which improves efficiency and reliability, particularly in high-power settings. Higher pulse counts on controlled converters demonstrate better performance than uncontrolled ones, with less THD and ripple content that changes depending on the kind of load.

Subsequent investigations ought to focus on contrasting diverse pulse arrangements, evaluating the advantages of sophisticated semiconductors such as SiC and GaN, and investigating the amalgamation of mixed systems. Furthermore, to satisfy the increasing needs of high-voltage and high-power applications, greater pulse converter development and the implementation of advanced control strategies will be crucial.

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