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Multi-Phase Shifting Autotransformer Based Rectifier

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ABSTRACT In this paper, a thorough analysis is carried out in order to achieve an optimal design of a forty-four pulse rectifier. In this study, a novel Multi-phase Shifting Autotransformer (MPSA) is introduced, discussed, simulated and implemented to forty-four pulse rectifier with acceptable power rates. Accordingly, the main purpose of the paper is focused on the power kVA rating reduction for power quality applications. It provides a more economical solution to achieve harmonic mitigation in electric power systems as compared with other rectifiers. The simulation and experimental results show that the input current THD is less than 3% using the proposed topology. The results indicate a significant reduction in the total cost and volume of the proposed forty-four pulse configuration in comparison with similar configurations. Also, it is shown that the proposed converter rating is about 42% of the DC load power.

INDEX TERMS Forty-four pulse rectifier, multi-phase shifting autotransformer (MPSA), total harmonic distortion (THD).

I. INTRODUCTION

In recent years, different structures of multi-pulse rectifiers have been designed and employed in order to improve the power quality at the common point of connection in industrial applications such as power systems, ship propulsion, and aircraft electrical systems as well as high voltage DC transmission lines. MPRs have been widely used in industry due to their low harmonic distortion, simple configuration, robustness and also power factor correction [1]–[3]. Although, various structures of 12-, 18-pulse and 20-pulse rectifiers have been introduced, developed and utilized to reduce the harmonic content of the line current [4]–[6], [11], [12]; but still these structures cannot satisfy and meet the standards requirement [7], [8]. Increasing the number of pulses in MPRs using multiple output phases of the phase shift transformers is considered as one of the main solutions to improve power quality factors. The transformer's plurality will significantly increase the number of components, complexity of the design, and thus the cost of MPR [9], [10]. Subsequently, the 12-pulse rectifier is more preferable to be utilized in industrial applications mainly due to their lightweight, simplicity of the transformer, low power rate and consumption.

The input current THD of the conventional 12-pulse rectifier is theoretically around 15%, and it cannot meet IEEE and IEC standards' requirement [7], [8] once it is employed without filter. To address this issue, different studies [13], [14] recommend several active or passive auxiliary circuits on the dc or ac side of the rectifier. In [14] and [15], several active auxiliary circuits are recommended and installed at the dc side of the rectifier in order to mitigate the harmonic content. In [16], an active inter-phase transformer circuit (IPTC) with an auxiliary circuit containing an energy storage element is recommended, in [17], current injection into the dc side and in [18] and [19] using an active IPT systems are recommended to reduce the harmonic content. However, the entire valuable recommended methods cannot increase the number of voltage pulses. In [20], [21], active IPT technique has been recommended to require additional secondary winding connected with a PWM converter; however, this again potentially results in increasing complexity, losses, and total fabrication cost. Studies by [22] and [23] recommend using active power filter [22], and the Vienna rectifier [23] to increase the power quality of MPRs. However, recommended methods have also limitations on control strategies, and will increase computational complexity, and need to tackle accuracy challenges in measuring control variables. In [24], a transformer-based 24-pulse AC-DC converter has been proposed to improve power quality at the PCC. But, the THD of the supply current is more than 5% when operating at light load. Also, the high rating of magnetic parts (more than 100% of the DC load power) is the major disadvantage of the transformer-based MPRs. In contrast, the autotransformer-based MPRs reduce the rating of the magnetic parts.

Many researchers have used different configurations based on 36 and 40-pulse rectifications for improved power quality have been described by Abdollahi [25]–[30], however, the THD of ac mains current with these topologies is more than 3% when operating at light load. The United States Military has imposed Military Standard 1399 upon its electrical designers and contractors. The MIL-STD 1399 sets power supply voltage harmonics at 5% with current harmonics being 3% of the fundamental for loads of 1 kVA or more, therefore, it would be essential to apply the converters with higher number of pulses [32].

It is known that increasing the number of pulses further results in a reduction of current harmonics, which is not only accompanied by an increase in cost but also more complicated topology will be deduced. In order to increase the number of pulses without a substantial increase in the cost and complexity, normally dc ripple reinjection technique was used [29]–[31]. To overcome this problem for the THD of the input currents, in [33], a 72-pulse AC-DC converter has been proposed with transformer configurations. High rating of magnetic parts (more than 100% of the DC load power) is the major disadvantage of the previous works. In contrast, the autotransformer-based configurations reduce the rating of the magnetic parts. This is feasible because only a part of the induction motor power should be conducted by the magnetic parts in this topology. Therefore, autotransformer-based configurations could significantly reduce the size, and proportionally, the weight of the transformer. Autotransformer-based configurations is reduced the ratings of magnetic parts.

This is true because only a portion of the power rating is used by the magnetic coupling parts.

Therefore, autotransformer-based configurations can significantly reduce the size and consequently the weight of the transformer which are the main advantages of the present study. In [34], a 72-pulse converter has been presented based on a tapped delta autotransformer platform. The total magnetics rating of this rectifier is about 62.2% of the load rating. In [34], a 72-pulse converter has been presented based on a tapped delta autotransformer platform. The total magnetics rating of this rectifier is about 62.2% of the load rating. This paper presents a forty-four pulse rectifier with similar performance but lower kVA rating.

Moreover, we should highlight that the majority of MPRs' weight and cost comes through the transformer magnetic part. To address this case in MPRs, transformers are replaced with autotransformers. Since autotransformers of the same rating utilize less magnetic material. This will reduce the entire setup weight to at least 80% of its original weight, save energy and decreases the loss and dimensions yet again [36]. In this study, I introduce and design a forty-four pulse rectifier based on MPSA with a very desirable power rate, less complexity, and low cost.

In continuation, some advantages of the proposed forty-four phase rectifier are summarized

1) The proposed forty-four pulse rectifier employs an optimized structure and lower kVA rating.
2) Compared to the other rectifiers with a higher number of pulses, the kVA rating of the proposed rectifier is approximately 42% of the load power.
3) The main advantage of the proposed forty-four pulse rectifier is a reduction in the THD. In this novel structure, the value of the THD is less than 3%. In other words, the IEEE-519 and MIL-STD 1399 requirements are satisfied.

II. THE PROPOSED FORTY-FOUR PULSE RECTIFIER

Fig. 1 shows a forty-four pulse rectifier including an MPSA as well as an IPTC. The proposed forty-four pulse rectifier consists of an MPSA to create two series of eleven-phase voltage with a 32.727-degree phase shift, two twenty-two pulse diode bridge rectifier, and an IPTC. It is worth noting that once we utilize an MPR structure for isolation phase shift transformers; then the IPTC is not required to be employed in the circuit. However since we have used the MPSA technique in this research work, it was required to employ IPTC in the circuit to ensure the independent operation of two eleven-phase autotransformer output voltages. The MPSA diagram for the forty-four pulse rectifier is shown in Fig. 2. For harmonic elimination, the required minimum phase shift can be calculated as follows [3]:

$$\text{Phase Shift} = \frac{360^\circ}{\text{Number of Converters} \times \text{Number of Pulse}} \tag{1}$$

The minimum phase displacement required for proper removal of the harmonics in a forty-four pulse rectifier (two converters with 22-pulse) is 8.18°. MPSA autotransformer produce 2 sets of eleven phases with a phase shift of 8.18° for each bridge. 2 The rectifier of the eleven diode bridge base is connected to the two eleven phase bridge of the MPSA output.

The same voltages of the two groups, i.e., V_{a1} and V_{b1}, are phase displaced of 8.18 degrees. V_{a1} and V_{b1} has a phase shift of +4.09 and −4.09 degrees from the input voltage of phase A, respectively. The number of winding turns is determined by a function of the phase voltage V_S. ($V_S = V_A$) The voltage of the windings shown in Fig. 2 is expressed by the following formula.

$$V_A = V_S\angle 0^\circ, V_B - V_S\angle -120^\circ, V_C = V_S\angle 120^\circ \tag{2}$$

We assume (V_{a1}, V_{a2}, V_{a3}, V_{a4}, V_{a5}, V_{a6}, V_{a7}, V_{a8}, V_{a9}, V_{a10}, V_{a11}) for the first rectifier and (V_{b1}, V_{b2}, V_{b3}, V_{b4}, V_{b5}, V_{b6}, V_{b7}, V_{b8}, V_{b9}, V_{b10}, V_{b11}) for the second rectifier, we also assume that the voltage of the eleven phases applied to the windings is as follows:

$$V_{a1} = V_s\angle +4.09^\circ, V_{a2} = V_s\angle -28.637^\circ,$$
$$V_{a3} = V_s\angle -61.364^\circ,$$

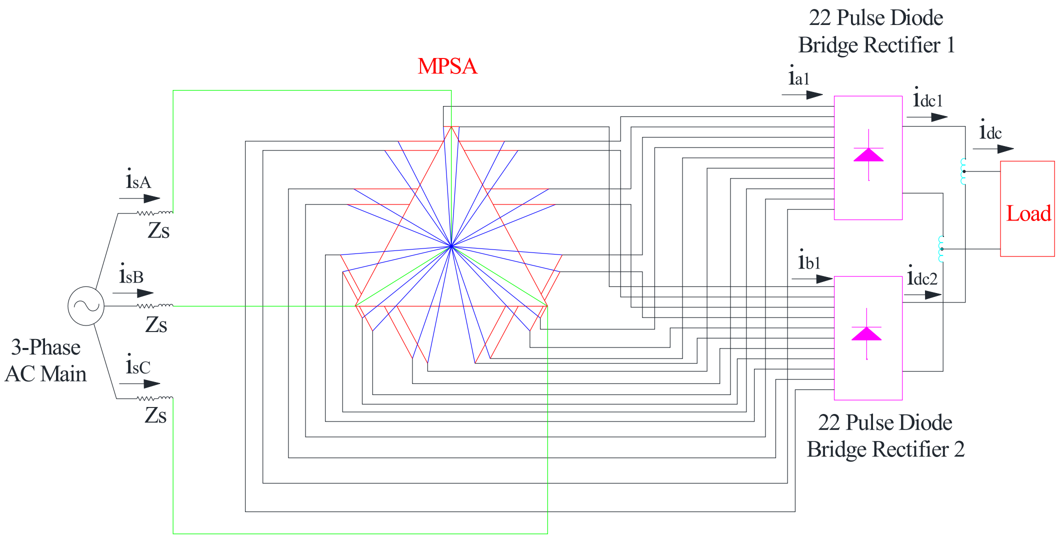

FIGURE 1. Structure of proposed polygon autotransformer according to the forty-four pulse rectifier.

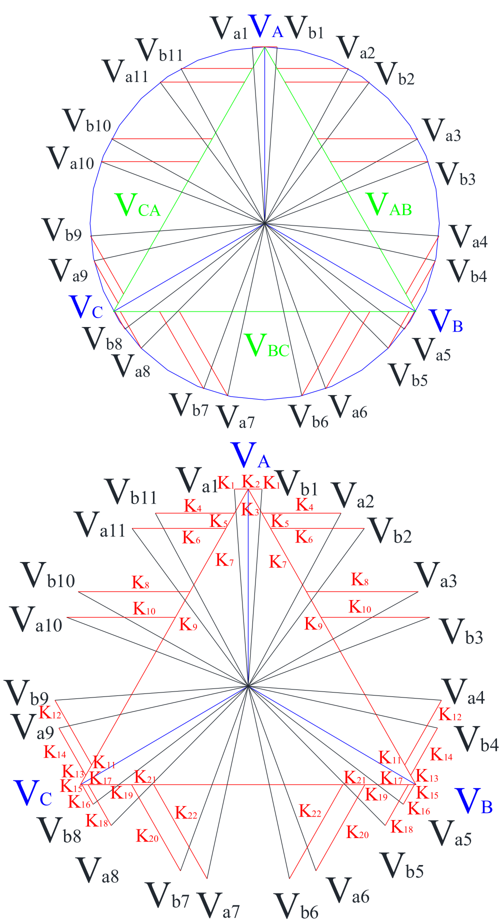

FIGURE 2. Winding arrangement and phasor diagram of MPSA.

$$V_{a4} = V_s\angle -94.091^{\circ}, V_{a5} = V_s\angle -126.818^{\circ},$$
$$V_{a6} = V_s\angle -159.545^{\circ},$$
$$V_{a7} = V_s\angle -192.272^{\circ}, V_{a8} = V_s\angle -224.999^{\circ},$$
$$V_{a9} = V_s\angle -257.726^{\circ},$$
$$V_{a10} = V_s\angle -290.453^{\circ}, V_{11} = V_s\angle -323.18^{\circ}. \quad (3)$$
$$V_{b1} = V_s\angle -4.09^{\circ}, V_{b2} = V_s\angle -36.817^{\circ},$$
$$V_{b3} = V_s\angle -69.544^{\circ},$$
$$V_{b4} = V_s\angle -102.271^{\circ}, V_{b5} = V_s\angle -134.998^{\circ},$$
$$V_{b6} = V_s\angle -167.725^{\circ},$$
$$V_{b7} = V_s\angle -200.452^{\circ}, V_{b8} = V_s\angle -233.179^{\circ},$$
$$V_{b9} = V_s\angle -265.906^{\circ},$$
$$V_{b7} = V_s\angle -298.633^{\circ}, V_{b8} = V_s\angle -331.36^{\circ}. \quad (4)$$

Input voltages for 22 pulse diode bridge rectifier 1 are:

$$V_{a1} = V_A + K_1V_{CA} + K_2V_{BC}$$
$$V_{a2} = V_A - K_3V_{AB} + K_4V_{BC}$$
$$V_{a3} = V_A - K_7V_{AB} + K_8V_{BC}$$
$$V_{a4} = V_B + K_{11}V_{AB} - K_{12}V_{CA}$$
$$V_{a5} = V_B - K_{15}V_{BC} - K_{16}V_{CA}$$
$$V_{a6} = V_B - K_{19}V_{BC} + K_{20}V_{CA}$$
$$V_{a7} = V_C + K_{21}V_{BC} - K_{22}V_{AB}$$
$$V_{a8} = V_C + K_{17}V_{BC} - K_{18}V_{AB}$$
$$V_{a9} = V_C - K_{13}V_{CA} + K_{14}V_{AB}$$
$$V_{a10} = V_A + K_9V_{CA} - K_{10}V_{BC}$$
$$V_{a11} = V_A + K_5V_{CA} - K_6V_{BC} \quad (5)$$

Input voltages for 22 pulse diode bridge rectifier 1 are:

$$V_{b1} = V_A + K_1V_{AB} + K_2V_{BC}$$
$$V_{b2} = V_A - K_5V_{AB} + K_6V_{BC}$$

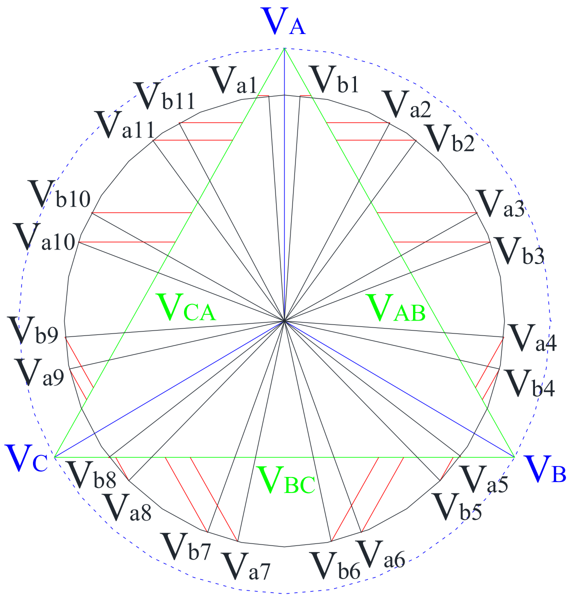

FIGURE 3. Phasor diagram of voltages in the proposed retrofit MPSA.

$$
\begin{aligned}
V_{b3} &= V_A - K_9 V_{AB} + K_{10} V_{BC}\\
V_{b4} &= V_B + K_{13} V_{AB} + K_{14} V_{CA}\\
V_{b5} &= V_B - K_{17} V_{BC} + K_{18} V_{CA}\\
V_{b6} &= V_B - K_{121} V_{BC} + K_{22} V_{CA}\\
V_{b7} &= V_C + K_{19} V_{BC} - K_{20} V_{AB}\\
V_{b8} &= V_C + K_{15} V_{BC} + K_{16} V_{AB}\\
V_{b9} &= V_C - K_{11} V_{CA} + K_{12} V_{AB}\\
V_{b10} &= V_A + K_7 V_{CA} - K_8 V_{BC}\\
V_{b11} &= V_A + K_3 V_{CA} - K_4 V_{BC}\\
V_{a9} &= V_C - K_{13} V_{CA} + K_{14} V_{AB}\\
V_{a10} &= V_A + K_9 V_{CA} - K_{10} V_{BC}\\
V_{a11} &= V_A + K_5 V_{CA} - K_6 V_{BC}
\end{aligned} \tag{6}
$$

$$
V_{AB} = \sqrt{3} V_A \angle 30^\circ,\ V_{BC} = \sqrt{3} V_B \angle 30^\circ,\ V_{CA} = \sqrt{3} V_C \angle 30^\circ \tag{7}
$$

The output voltage in the MPR is always higher than the output voltage of a conventional six-pulse rectifier. As a result, the forty-four pulse rectifier is not suitable for retrofit applications. The proposed rectifier output voltage is 20% higher than the output voltage of a conventional six-pulse rectifier. Therefore, in order to use the proposed rectifier in alternative applications, the autotransformer design and the number of windings are calculated based on the reduction of the Autotransformer output voltage by 20% Give it. This will be accomplished via modifications in the tapping positions on the windings as shown in Fig. 3. The values of constants K_1 and K_{22} are changed for retrofit applications as:

$$
\begin{aligned}
&K_1 = 0.11607, K_2 = 0.092128, K_3 = 0.18219, K_4 = 0.13801,\\
&K_5 = 0.22476, K_6 = 0.17409, K_7 = 0.40212, K_8 = 0.21852,\\
&K_9 = 0.47375, K_{10} = 0.21103,\\
&K_{11} = 0.17013, K_{12} = 0.12381,\\
&K_{13} = 0.14087, K_{14} = 0.07514,\\
&K_{15} = 0.11856, K_{16} = 0.00254,\\
&K_{17} = 0.13346, K_{18} = 0.056973,\\
&K_{19} = 0.24100, K_{20} = 0.18386,\\
&K_{21} = 0.29534, K_{22} = 0.20604.
\end{aligned} \tag{8}
$$

The K_1 and K_{22} values represent the number of rounds of multithreaded autotransformers for proper phase displacement with the approach to adjust the output voltage required for retrofit applications. The proposed MPSA winding configuration is shown in Fig. 4. The configuration of the winding is based on the equations (4) and (5), and constants K_1-K_{22}. For example, the voltage Va1 is obtained by tapping a portion $k_1 = 0.11607$ of the voltage V_{CA} and connecting one end of an approximate $k_2 = 0.092128$ of voltage V_{BC} to this tap. Interphase transformer circuit (IPTC) to ensure the independent operation of the two 22 pulse diode bridges. In Fig. 5, the input and output voltage of the twenty-two phase polygon autotransformer is depicted. The output of autotransformer includes two series eleven phase voltage series with 8.18 degrees.

III. SIMULATION AND EXPERIMENTAL STUDY VALIDATION

The proposed forty-four pulse rectifier structure has been modeled, simulated and evaluated in Simulink/MATLAB software. The simulation conditions are as follows: (1) the linear value of the input voltage is 460 V; (2) the load power is 50 hp. The results of the simulation of the various sections of the proposed forty-four pulse rectifier, confirm the proper performance of the proposed rectifier. Fig. 6 shows the simulation model of the forty-four pulse rectifier. In Fig. 7, the output voltage of forty-four pulse rectifier is presented.

Fig. 8 (a) shows the voltage input line and its spectrum, and (b) current input line and its spectrum, respectively. As shown in Fig. 8, under full load condition, the input current and voltage THD for the proposed forty-four pulse rectifier is 1.55% and 1.06%, respectively. The currents of the input line and their spectrum under 50% and 20% of full load power are presented in Fig. 9. The THD of the input line current is about 1.93% and 2.84% under 50% of full load power and 20% of full load power, respectively. In comparison with the full load power, the THD under light load has a slight increase but still remain under 3%. Also, compared to the other MPRs with a higher number of pulses, the harmonics in the proposed forty-four pulse rectifier are reduced significantly.

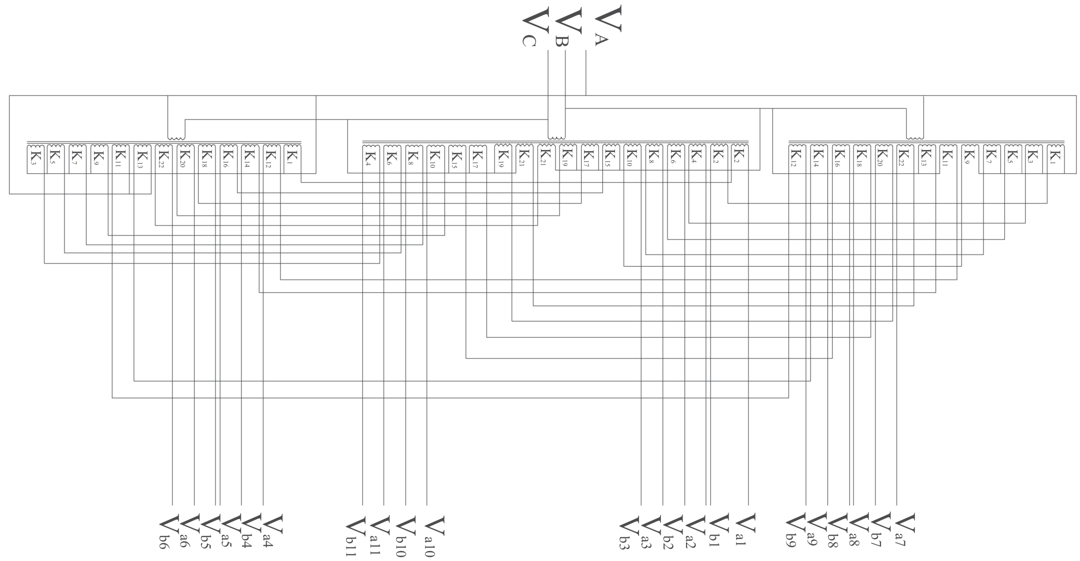

FIGURE 4. **Winding configuration of the proposed MPSA.**

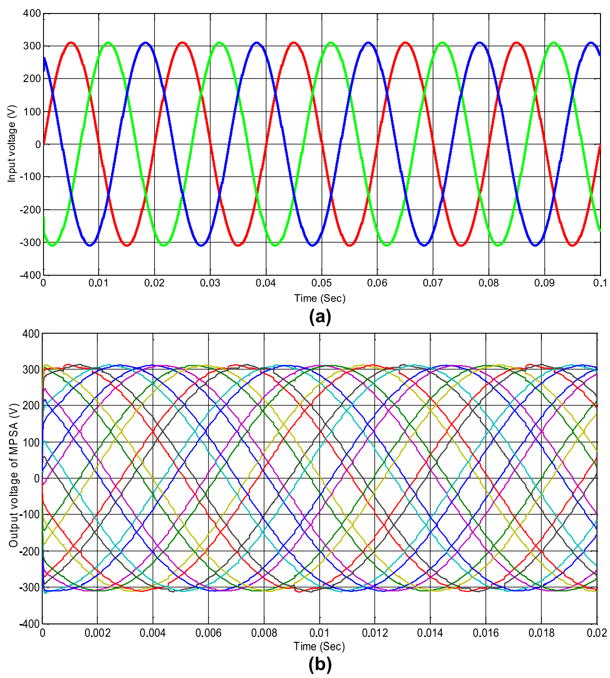

FIGURE 5. **(a) The input line voltage, and (b) the output voltage of twenty-two phase MPSA.**

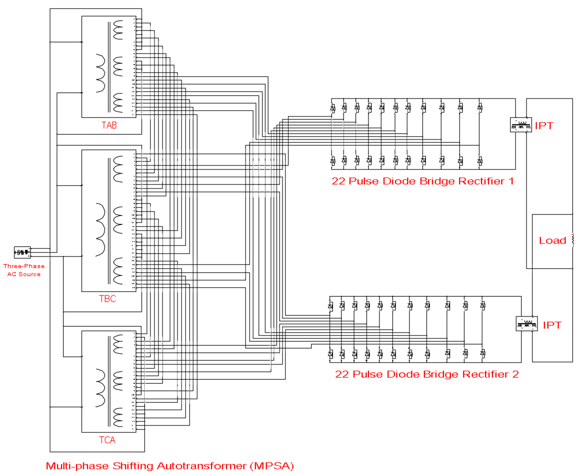

FIGURE 6. **Simulation model of the forty-four pulse rectifier.**

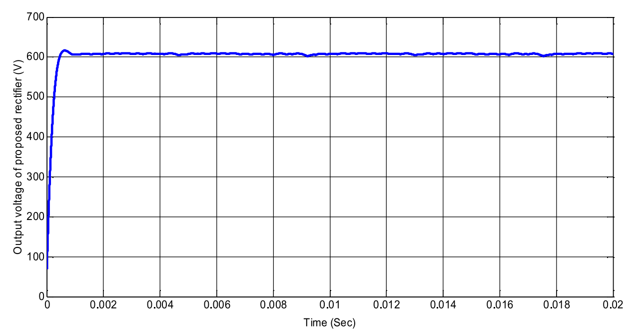

FIGURE 7. **The load voltage in the proposed rectifier.**

In Table 1, a comparative analysis is carried out between the conventional 6-pulse rectifier and the proposed forty-four pulse rectifier under various power quality indices. According to Table 1, the THD of supply current in the conventional 6-pulse rectifier is varied between 28.52% in the full load condition to 52.80% in the light load condition.

One can easily conclude from Table 1 that in the proposed forty-four pulse rectifier, the input source THD and power factor in full load condition are 1.55% and 0.999 and in light load, conditions are 2.84% and 0.998, respectively. In other words, the IEEE-519 and MIL-STD 1399 limits are satisfied.

Input current THD and power factor variations are also shown in Fig. 10, for 6-pulse, and forty-four pulse rectifiers.

TABLE 1. Comparison of Simulated Power Quality Parameters OF The Different Rectifiers

Topology	% THD of V_{ac}	AC Mains Current I_{SA} (A)		% THD of I_{SA}, at		Distortion Factor, DF		Displacement Factor, DPF		Power Factor, PF	
		Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full Load	Light Load	Full Load
6-pulse	5.63	10.25	52.56	52.80	28.52	0.884	0.959	0.985	0.988	0.872	0.948
12-pulse [37]	3.66	10.47	53.58	13.19	7.36	0.991	0.996	0.992	0.980	0.983	0.977
24-pulse [37]	3.12	10.50	52.31	5.77	4.51	0.998	0.998	0.996	0.997	0.9984	0.995
Proposed forty-four pulse	1.06	10.6	50.94	2.84	1.55	0.998	0.999	0.998	0.999	0.998	0.999

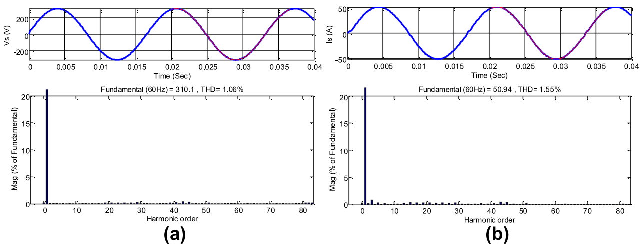

FIGURE 8. (a) input line voltage and its spectrum, (b) input line current and its spectrum under full load power.

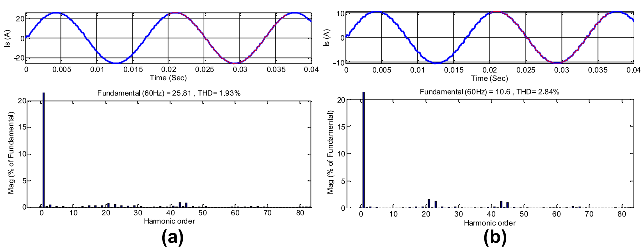

FIGURE 9. input line current and its spectrum, (a) under 50% of full load power, (b) under 20% of full load power.

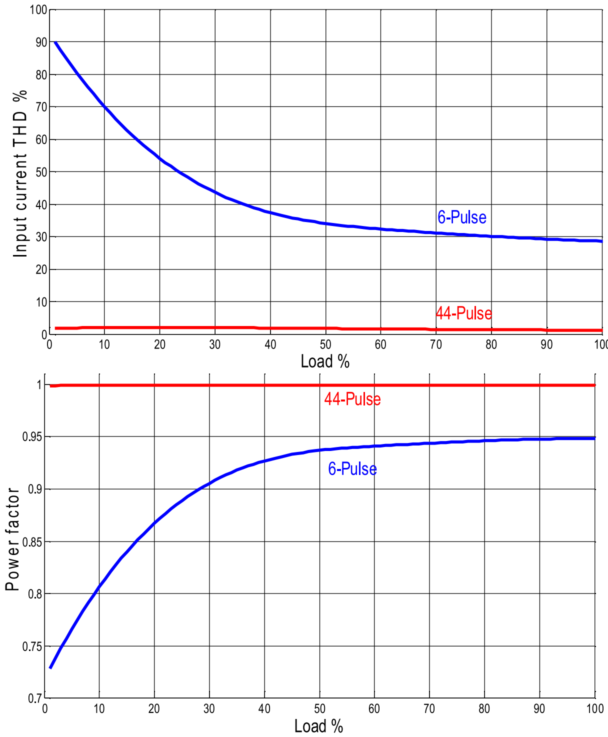

FIGURE 10. Variation of THD and power factor with load in 6-pulse and forty-four pulse rectifiers.

Results show that the input current corresponding to the proposed configuration has an almost unity power factor. Furthermore, in the worst case (light loads) the current THD has reached below 2.84% for the proposed topology.

In Fig. 11, a laboratory-scale prototype of the proposed forty-four pulse rectifier is presented. The experimental condition satisfies: (1) the input phase voltage is 380 V, (4) the resistance load power is 10 kW. As shown in Fig. 11, under light and full load conditions, the input current THD for the proposed forty-four pulse rectifier is 2.8% and 1.71%, respectively. The experimental outcomes confirm that the proposed forty-four pulse rectifier satisfies the IEEE Standard 519 limits. A high degree of agreement between the simulation and experimental results approves the efficiency of the proposed forty-four pulse rectifier configuration for various industrial applications.

IV. APPARENT POWER RATINGS

The apparent power (kVA) ratings of the forty-four pulse configuration are calculated using the following equation [2]:

$$S = 0.5 \sum V_{winding} I_{winding} \tag{9}$$

Where $V_{winding}$ is the rms voltage across each part of the MPSA, IPTC windings and $I_{winding}$ indicates the full load current of the same windings obtained from the simulation. The kVA rating for MPSA and IPTC are 4157 VA, and 45 VA, respectively. It means that the required magnetic ratings of the proposed topology are about 42% of the load rating while the current THD is less than 3%. Several rectifiers [10]–[12] have a lower kVA rating than the proposed rectifiers, but the proposed rectifier is a tradeoff among the pulse number, the complexity of the scheme, the ability to reduce THD, and the kVA rating. Fig. 12 shows the comparison of the proposed

TABLE 2. Cost and Size Comparison Of The Proposed Forty-Four Pulse Rectifier With The Existing MPRs

Part	Unit cost ($)	20-Pulse [29]	20-Pulse [30]	20-Pulse [31]	36-pulse [35]	40-pulse [29]	40-pulse [30]	40-pulse [31]	72-pulse [35]	72-pulse [34]	Proposed forty-four pulse
Total kVA rating (% of load rating)	4.5 times the kVA	63.83	47.76	56.13	44.15	63.98	48.45	57.26	44.33	62.20	42.00
Diode	2.25	20	20	20	36	42	42	42	38	38	32
Approximate total cost ($)		332.23	259.92	297.58	279.67	382.41	312.52	352.17	284.98	365.4	261

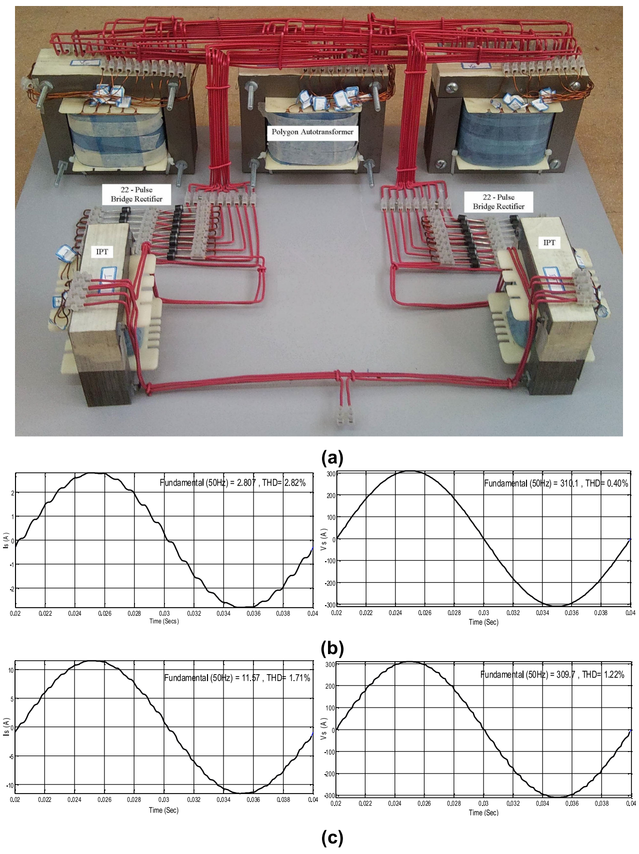

FIGURE 11. (a) Laboratory prototype, (b) input line current/voltage and its spectrum at light load, and (c) input line current/voltage and its spectrum at full load of the proposed rectifier (Experimental results).

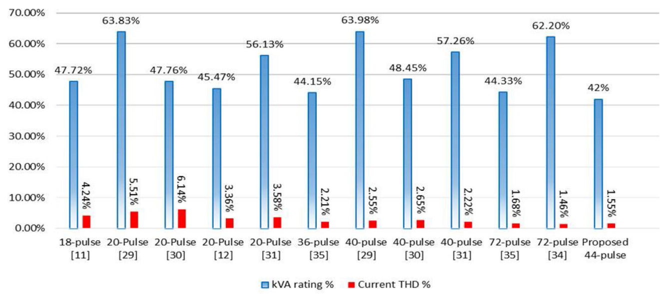

FIGURE 12. Comparison of magnetic power rating (%kVA) and %current THD in different MPRs.

forty-four pulse and other MPRs in terms of kVA rating and % current THD. It indicates that the kVA rating of the proposed forty-four rectifier is 42% while the current THD is less than 1.6%. Also, the kVA rating of the proposed rectifier is 21.98% less than the 40-pulse [29], 6.45% less than the 40-pulse [30], 15.26% less than the 40-pulse [31], 20.2% less than the 72-pulse [34], and 2.33% less than the 72-pulse [35] configurations.

Table 2 includes an analytic studies between the number of diodes, magnetic rating comparison, and cost analysis for the proposed forty-four pulse configuration with 20-pulse rectifier [29]–[31], 36-pulse rectifier [35], 40-pulse rectifier [29]–[31], and 72-pulse rectifier [34], [35]. The rule of thumb is employed to estimate the costs of the transformer.

As mentioned in Ref [35], the cost is estimated at 4.5 times the kVA rating of the transformer. It should be emphasized that the total cost and size of the system is determined by the transformer magnetic rating. From the above discussion, it can be concluded that the proposed forty-four pulse rectifier can provide effective performance. The proposed rectifier has a similar performance with higher pulse systems but the proposed rectifier have many benefits such as lower components, less complexity in term of design and finally provides an economical solution for industrial applications.

V. CONCLUSION

In this research, an efficient forty-four pulse rectifier based on a retrofit MPSA with an IPTC is suggested. With comparison to the conventional MPRs, the harmonic distortion in the input line is significantly reduced. This research presents a novel forty-four pulse rectifier with a very simple, flexible and robust structure. The kVA is 42% of the load power and the current THD is less than 3% which are in accordance with IEEE 519 and MIL-STD 1399 limits. Finally, the outcomes of this research are of immediate interest for several industrial applications such as HVDC transmission, ship propulsion and finally power converter system of aircraft.

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