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# Optimum Design of 48-Pulse Rectifier Using Unconventional Interphase Reactor

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**ABSTRACT** In order to simultaneously reduce the harmonics of input line current and ripple of load voltage in multipulse rectifier, this paper proposes a 48-pulse rectifier using the unconventional interphase reactor (IPR) with an auxiliary single-phase diode-bridge rectifier at the dc link. The primary winding of the unconventional IPR is triple-tapped, and the secondary winding is connected with a single-phase diode-bridge rectifier. The operation mode of the unconventional IPR is analyzed, and the optimal tap ratio and turn ratio are designed. With the optimal parameters of the IPR and the optimal conduction time sequence of power devices, the proposed rectifier extends the conventional 36-pulse rectifier operation to a 48-pulse operation and draws near sinusoidal input line currents, the total harmonic distortion (THD) of which is about 3.81%. The proposed 48-pulse rectifier is easy and simple to implement, and it is more suitable for high-voltage and large-current application. Some simulation and experiments are provided to validate the theoretical analysis.

**INDEX TERMS** Multipulse rectifier (MPR), interphase reactor (IPR), single-phase diode-bridge rectifier, harmonic reduction.

## I. INTRODUCTION

Because of its simple configuration and high reliability, multipulse rectifier (MPR) is one of the most popular rectifiers in high power rectification system, such as electro-chemical processes, aircraft converter system, ship propulsion system, long-range rocket launcher power supply system [1]–[3]. In these applications, MPR is the important interface between the load and generator, and the performance of the MPR affects the load and generator. Therefore, the total harmonic distortion (THD) of the input line current and ripple coefficient of the load voltage are critical problems in MPR. Modern MPRs are expected to draw sinusoidal input current form the generator.

According to lots of efforts have been made to improve the power quality in MPR [4]–[16], increasing the pulse number of MPR is the common and effective way which can be divided into three types of method. The first method is to increase the pulse number of phase-shift transformer to improve the harmonic reduction ability [4]–[6]. Using this method, the step number of input line current and the pulse number of the load voltage increase correspondingly to improve the power quality both in the input and output sides.

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However, with the increase of the output phase number, the structure of phase-shifting transformer is more and more complicated and the utilization ratio of turn coil is depressed, causing the difficulty in design and manufacture.

The second method is using a multi-tapped interphase reactor (IPR) to increase the pulse number [8], [9]. As to the basic parallel 12-pulse diode rectifier, if the double-tapped IPR with the optimal parameter is used, the step number of input line current and the pulse number of the load voltage change to be 24 pulses, and the theoretical THD of the input line current is about 7.6% under ideal condition. If the tap number is 3, the MPR needs control circuits and behaves as 36-pulse rectifier. Though increasing the tap number can improve the pulse number, the additional diodes or thyristors linked with the taps are in series with the load and the total currents through the additional diodes or thyristors are equal to the load current. The conduction losses of the diodes or thyristors are serious.

The third method is installing auxiliary circuit with the active or passive devices at dc or ac side of MPR [10]–[16]. Actually, the active auxiliary circuit controls the currents through the active devices to be a particular waveform and modulates the output currents of the three-phase diode-bridge rectifiers to meet some conditions. Although the active auxiliary circuit is the effective method of harmonic reduction,

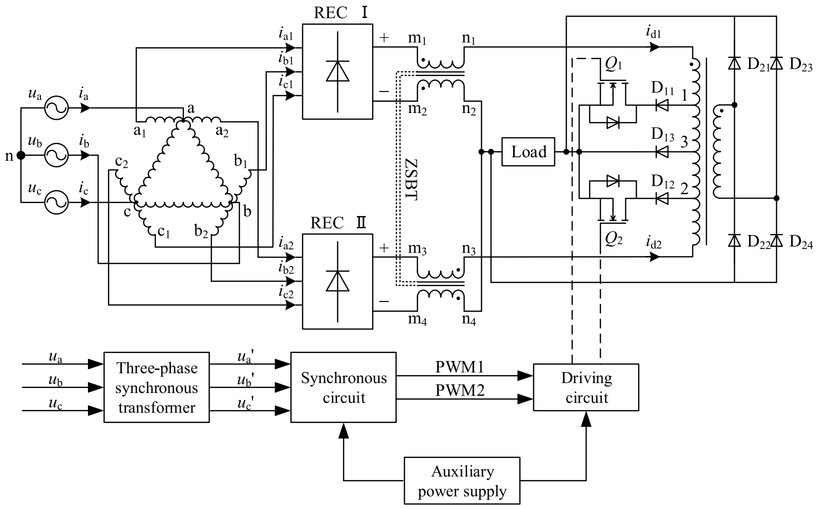



FIGURE 1. Circuit configuration of the proposed 48-pulse rectifier.

it cannot increase the pulse number of load voltage [11]. Passive auxiliary circuit is installed at dc link by substituting of unconventional IPR for traditional IPR in MPR. The primary winding of the unconventional IPR is tapped in different number and the secondary winding is connected with passive auxiliary circuit. Essentially, the passive auxiliary circuit can superimpose a voltage on the load voltage in order to increase the pulse number of load voltage and generate circulating current to increase the step number of the input line current so as to reduce the harmonics. In general, the passive auxiliary circuit is either single-phase full-wave rectifier or single-phase diode-bridge rectifier [12], [13]. For example, in a parallel 12-pulse diode rectifier, if the traditional IPR is replaced by a double-tapped IPR or an unconventional IPR with one central tap in primary winding, both modified rectifiers are 24-pulse rectifiers with the same pulse number of the load voltage and step number of the input line current under optimal condition [15].

From the above analysis, except for the method of active auxiliary circuit, other methods can simultaneously increase the pulse number of load voltage and the step number of the input line current. Therefore, in order to reduce harmonics of the input line current, use of one method or mixed method depends on the actual application.

In this paper, a novel 48-pulse rectifier using unconventional IPR with an auxiliary single-phase diode-bridge rectifier at dc link is proposed. The primary winding of the IPR is similar with triple-tapped IPR and the secondary winding connects single-phase diode-bridge to realize further harmonic reduction. The operation modes are analyzed and the unconventional IPR is designed optimally from the prospective of minimizing the THD of input line current and ripple coefficient of the load voltage. With the optimal parameters, the proposed 48-pulse rectifier operates normally, and the THD of input current is about 3.81% theoretically. In application, the experimental THD is smaller due to the leakage inductance of autotransformer and inductance of the unconventional IPR. The proposed 48-pulse rectifier is easy and simple to implement, and draws near sinusoidal input line currents to improve the power quality performance. It is more suitable for high-voltage and large-current application, such as electric traction systems, automobile control equipment, electro-chemical processes, high-voltage transmission, induction heating, plasma power supplies, and uninterruptible power supplies.

## II. PROPOSED RECTIFIER WITH UNCONVENTIONAL IPR AND ITS OPERATION MODE

### A. CIRCUIT CONFIGURATION

Fig. 1 shows the circuit configuration of the proposed 48-pulse rectifier. It consists of a delta-connected autotransformer, two three-phase diode-bridge rectifiers, a zero sequence blocking transformer (ZSBT), an unconventional IPR, and a single-phase diode-bridge rectifier. Fig. 2(a) and Fig. 2(b) show the winding configuration and the phasor diagram of the delta-connected autotransformer.

For proposed 48-pulse rectifier, there is $\pi/6$ phase difference of two groups of three-phase voltage from autotransformer. According to this requirement, the angle $\alpha$ is equal to $\pi/12$. Thus, the winding turns of autotransformer in Fig. 2 (a) should satisfy

$$\frac{N_1}{N_2} = \frac{3}{2\sqrt{3}-3} \quad (1)$$

ZSBT can generate high impedance for three frequency multiplication current to ensure that three-phase diode-bridge rectifier operates independently with $2\pi/3$ conduction of each diode. Because of the delta-connected autotransformer is not isolated, the ZSBT is necessary. The primary winding of the unconventional IPR can absorb the instantaneous difference of the output voltage of the two three-phase diode-bridge rectifiers. The secondary winding connects the input of the single-phase diode-bridge rectifier. The output of the single-phase diode-bridge rectifier connects the load.

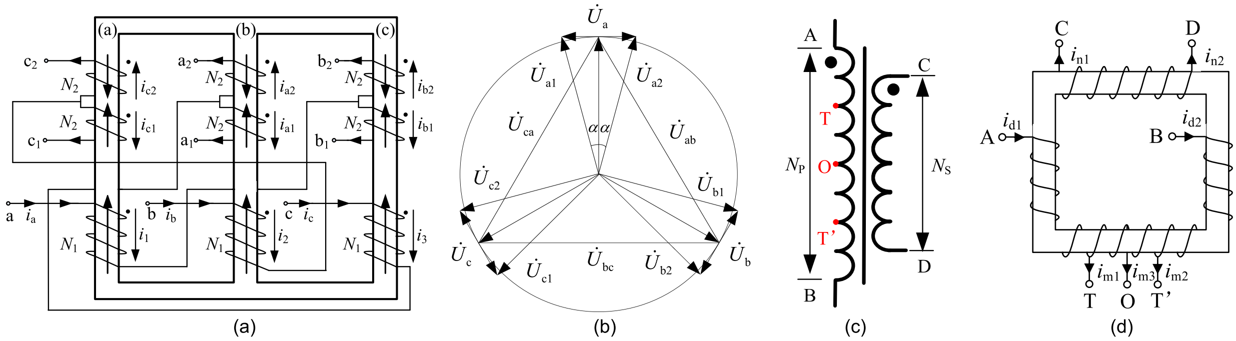


**FIGURE 2.** **(a) Winding configuration of the delta-connected autotransformer. (b) Phasor diagram of the delta-connected autotransformer. (c) Tap structure of the unconventional IPR. (d) Winding configuration of the unconventional IPR.**

Fig. 2(c) and Fig. 2(d) shows the tap structure and the winding configuration of the unconventional IPR. The tap ratio $\alpha$ is defined as

$$\alpha = \frac{N_{OT}}{N_P} = \frac{N_{OT'}}{N_P} \tag{2}$$

turns ratio of the unconventional IPR is defined as

$$m = \frac{N_S}{N_P} \tag{3}$$

where $N_P$ and $N_S$ are the numbers of turn of the primary and secondary windings of the unconventional IPR, respectively.

Because the tap number of primary winding is greater than two, the MOSFETs and control circuit are used.

### B. OPERATION MODE

In order to demonstrate the operation mode of the unconventional IPR, the following assumptions are given below.

1) The load of proposed rectifier is a large inductance loading and the load current $i_d$ can be view as a constant $I_d$.

2) The leakage inductances and resistances of autotransformer and unconventional IPR are neglected.

3) Assume that the input voltage of the proposed 48-pulse rectifier as

$$\begin{cases} u_a = U\sin(\omega t) \\ u_b = U\sin(\omega t - 2\pi/3) \\ u_c = U\sin(\omega t + 2\pi/3) \end{cases} \tag{4}$$

where $U$ is the peak value of the input phase voltage.

4) Assume that the voltage across the secondary winding of the unconventional IPR is $u_2$, and the load voltage is $u_d$. The output voltages of the two three-phase diode-bridge rectifiers are $u_{d1}$ and $u_{d2}$ respectively.

The operation mode of the unconventional IPR is determined by the relation of $u_2$ and $u_d$, working state of the MOSFETs, and the relation of $u_{d1}$ and $u_{d2}$. Therefore, there are five operation modes, as shown in Fig. 3.

*1) Mode I*: When $|u_2| < u_d$ and the MOSFETs turn OFF, the IPR operates under mode I, as shown in Fig. 3 (a). In this mode, the diodes of the single-phase diode-bridge are reverse-biased and OFF, the current $i_n$ is equal to zero, and the single-phase diode-bridge does not work. Diode $D_{13}$ of the primary winding is forward-biased and ON. The proposed rectifier operates as conventional parallel 12-pulse diode rectifier. The output currents $i_{d1}$ and $i_{d2}$ of the two three-phase diode-bridge rectifiers are

$$i_{d1} = i_{d2} = 0.5I_d \tag{5}$$

The load voltage is expressed as

$$u_d = 0.5\,(u_{d1} + u_{d2}) \tag{6}$$

*2) Mode II*: When $|u_2| < u_d$ and $u_{d1} < u_{d2}$, MOSFET $Q_1$ turns OFF and MOSFET $Q_2$ turns ON, the IPR operates under mode II, as shown in Fig. 3 (b). In this mode, the single-phase diode-bridge also does not work. Diode $D_{12}$ of the primary winding is forward-biased and ON, and diodes $D_{13}$ and $D_{11}$ are reverse-biased and OFF. The proposed rectifier operates as conventional 24-pulse diode rectifier with double-tapped IPR. According to the ampere-turn principle and Kirchhoff's voltage law (KVL), the currents $i_{d1}$ and $i_{d2}$ are calculated as

$$\begin{cases} i_{d1} = (0.5 - \alpha)I_d \\ i_{d2} = (0.5 + \alpha)I_d \end{cases} \tag{7}$$

The load voltage is

$$u_d = \frac{(u_{d1} + u_{d2})}{2} - \alpha_m(u_{d1} - u_{d2}) \tag{8}$$

*3) Mode III:* When $|u_2| < u_d$ and $u_{d1} > u_{d2}$, MOSFET $Q_1$ turns ON and MOSFET $Q_2$ turns OFF, the IPR operates under mode III, as shown in Fig. 3 (c). In this mode, the single-phase diode-bridge still does not work. Diode $D_{11}$ of the primary winding is forward-biased and ON, and diodes $D_{13}$ and $D_{12}$ are reverse-biased and OFF. Similar to Mode II, the currents $i_{d1}$ and $i_{d2}$ are calculated as

$$\begin{cases} i_{d1} = (0.5 + \alpha)I_d \\ i_{d2} = (0.5 - \alpha)I_d \end{cases} \tag{9}$$

The load voltage is

$$u_d = \frac{(u_{d1} + u_{d2})}{2} + \alpha_m(u_{d1} - u_{d2}) \tag{10}$$

*4) Mode IV*: When $-u_2 > u_d$ and $u_{d1} < u_{d2}$, MOSFET $Q_1$ turns OFF and MOSFET $Q_2$ turns ON, the IPR operates under

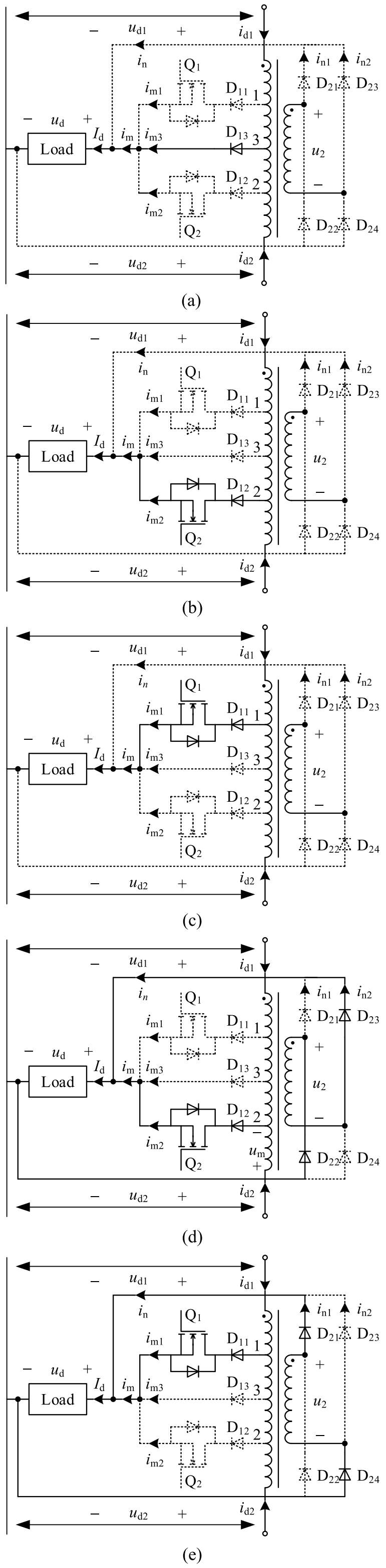



**FIGURE 3.** **Operation modes of the unconventional IPR. (a) Operation mode I. (b) Operation mode II. (c) Operation mode III. (d) Operation mode IV. (e) Operation V.**

mode I, as shown in Fig. 3 (d). In this mode, the diode $D_{22}$ and $D_{23}$ of the single-phase diode-bridge are forward-biased and ON, and diodes $D_{21}$ and $D_{24}$ are reverse-biased and OFF. Diode $D_{12}$ of the primary winding is forward-biased and ON, and diodes $D_{13}$ and $D_{11}$ are reverse-biased and OFF.

During this time interval, because the load voltage $u_d$ is greater than the voltage $u_{d1}$, the current $i_{d1}$ is equal to zero. Therefore, the current $i_{d2}$ is equal to the current $i_{m2}$.The MMF relationship of the unconventional IPR for this mode is

$$i_{d2} \cdot (0.5 - \alpha) \cdot N_1 = i_{n2} \cdot N_2 \tag{11}$$

According to Kirchhoff's current law (KCL), the relation among $i_m$, $i_n$, $i_{m2}$, $i_{n2}$ and $i_d$ is

$$i_m + i_n = i_{m2} + i_{n2} = i_d \tag{12}$$

Substituting (2), (3) and (11) into (12), (12) is transformed to

$$\frac{(0.5+\alpha)(0.5-\alpha)}{m} \cdot i_m + i_m = i_d \tag{13}$$

From (11), (12) and (13), the currents $i_{d2}$ and $i_n$ are obtained as

$$\begin{cases} i_{d2} = \dfrac{2m}{1-2\alpha+2m} i_d \\ i_n = \dfrac{1-2\alpha}{1-2\alpha+2m} i_d \end{cases} \tag{14}$$

From Fig.3 (d), the load voltage $u_d$ can be expressed as

$$u_{d2} - u_m = u_d \tag{15}$$

According to the definition of the unconventional IPR, it is obtained that

$$\frac{u_m}{-u_2} = \frac{(0.5-\alpha)\,N_1}{N_2} = \frac{0.5-\alpha}{m} \tag{16}$$

Furthermore, from the KVL, the relation among $u_d$, $u_{d1}$ and $u_{d2}$ can be expressed as

$$\begin{cases} u_d = \dfrac{m}{0.5-\alpha+m} u_{d2} \\ u_{d1} = \dfrac{m-\alpha-0.5}{0.5-\alpha+m} u_{d2} \end{cases} \tag{17}$$

5) *Mode V*: When $u_2 > u_d$ and $u_{d1} > u_{d2}$, MOSFET $Q_1$ turns ON and MOSFET $Q_2$ turns OFF, the IPR operates under mode V, as shown in Fig.3 (e). In this mode, the diode $D_{21}$ and $D_{24}$ of the single-phase diode-bridge are forward-biased and ON, and diodes $D_{22}$ and $D_{23}$ are reverse-biased and OFF. Diode $D_{11}$ of the primary winding is forward-biased and ON, and diodes $D_{13}$ and $D_{12}$ are reverse-biased and OFF.

During this time interval, because the load voltage $u_d$ is greater than the voltage $u_{d2}$, the current $i_{d2}$ is equal to zero. Therefore, the current $i_{d1}$ is equal to the current $i_{m1}$.The MMF relationship of the unconventional IPR for this mode is

$$i_{d1} \cdot (0.5 - \alpha) \cdot N_1 = i_{n1} \cdot N_2 \tag{18}$$

The analysis is similar as the mode IV, the currents $i_{d1}$, $i_m$ and $i_n$ are obtained as

$$\begin{cases} i_{d1} = \dfrac{2m}{1-2\alpha+2m} i_d \\ i_n = \dfrac{1-2\alpha}{1-2\alpha+2m} i_d \end{cases} \tag{19}$$

The relation among $u_d$, $u_{d1}$ and $u_{d2}$ can be expressed as

$$\begin{cases} u_d = \dfrac{m}{0.5-\alpha+m}u_{d1} \\ u_{d2} = \dfrac{m-\alpha-0.5}{0.5-\alpha+m}u_{d1} \end{cases} \tag{20}$$

From the above analysis, it is noted that the output currents $i_{d1}$ and $i_{d2}$ of the two three-phase diode-bridge rectifiers under operation mode IV and V are different from that of under operation mode I, II and III because of the output current of single-phase diode-bridge. When the parameters $\alpha$ and $m$ of the unconventional IPR meet some condition, the proposed MPR operates as 48-pulse rectifier and reduces the harmonic in the input line current effectively.

## III. OPTIMAL DESIGN OF UNCONVENTIONAL IPR

### A. NECESSARY CONDITION

According to the operation mode, if the maximum value of the voltage $u_2$ is less than the minimum value of load voltage $u_d$, the unconventional IPR operates as triple-tapped IPR and the MPR operates as 36-pulse rectifier. In order to make the single-phase diode-bridge operates normally, the following necessary condition should be satisfied

$$|u_2|_{\max} < u_{d\min} \tag{21}$$

From Fig. 2 (a) and Fig. 2 (b), the output voltages of the delta-connected autotransformer can be expressed as

$$\begin{cases} u_{a1}=KU\sin(\omega t+\pi/12) \\ u_{b1}=KU\sin(\omega t-7\pi/12) \\ u_{c1}=KU\sin(\omega t+3\pi/4) \end{cases} \quad \begin{cases} u_{a2}=KU\sin(\omega t-\pi/12) \\ u_{b2}=KU\sin(\omega t-3\pi/4) \\ u_{c2}=KU\sin(\omega t+7\pi/12) \end{cases} \tag{22}$$

where $K$ is equal to $(\sqrt{6}-\sqrt{2})$.

Furthermore, from the modulation theory, the output voltage of the two three-phase diode-bridge rectifiers can be written as

$$\begin{cases} u_{d1} = S_{a1}u_{a1}+S_{b1}u_{b1}+S_{c1}u_{c1} \\ u_{d2} = S_{a2}u_{a2}+S_{b2}u_{b2}+S_{c2}u_{c2} \end{cases} \tag{23}$$

where $S_{a1}$, $S_{b1}$, $S_{c1}$, $S_{a2}$, $S_{b2}$, and $S_{c2}$ are the switching functions. The switching function $S_{a1}$ can be expressed as

$$S_{a1} = \begin{cases} 0 & \omega t \in \left[0, \dfrac{\pi}{12}\right], \ \omega t \in \left[\dfrac{9\pi}{12}, \dfrac{13\pi}{12}\right], \\ & \omega t \in \left[\dfrac{21\pi}{12}, \dfrac{24\pi}{12}\right] \\ 1 & \omega t \in \left[\dfrac{\pi}{12}, \dfrac{9\pi}{12}\right] \\ -1 & \omega t \in \left[\dfrac{13\pi}{12}, \dfrac{21\pi}{12}\right] \end{cases} \tag{24}$$

and the relation among the switching function is

$$\begin{cases} S_{b1} = S_{a1}\angle -2\pi/3 \\ S_{c1} = S_{a1}\angle +2\pi/3 \end{cases} \quad \begin{cases} S_{a2} = S_{a1}\angle -\pi/6 \\ S_{b2} = S_{b1}\angle -\pi/6 \\ S_{c2} = S_{c1}\angle -\pi/6 \end{cases} \tag{25}$$

therefore, the output voltages $u_{d1}$ and $u_{d2}$ can be expressed as

$$u_{d1} = \begin{cases} \sqrt{3}KU\cos(\omega t+\dfrac{\pi}{12}-\dfrac{k\pi}{3}), \ \omega t \in \left[\dfrac{k\pi}{3}, \dfrac{k\pi}{3}+\dfrac{\pi}{12}\right] \\ \sqrt{3}KU\cos(\omega t-\dfrac{\pi}{4}-\dfrac{k\pi}{3}), \ \omega t \in \left[\dfrac{k\pi}{3}+\dfrac{\pi}{12}, \dfrac{(k+1)\pi}{3}\right] \end{cases} \tag{26}$$

$$u_{d2} = \begin{cases} \sqrt{3}KU\cos(\omega t-\dfrac{\pi}{12}-\dfrac{k\pi}{3}), \ \omega t \in \left[\dfrac{k\pi}{3}, \dfrac{k\pi}{3}+\dfrac{\pi}{4}\right] \\ \sqrt{3}KU\cos(\omega t-\dfrac{5\pi}{12}-\dfrac{k\pi}{3}), \ \omega t \in \left[\dfrac{k\pi}{3}+\dfrac{\pi}{4}, \dfrac{(k+1)\pi}{3}\right] \end{cases} \tag{27}$$

From Fig. 1 and Fig. 2, the voltage across the primary winding of the unconventional IPR can be calculated as

$$u_1 = u_{d1} - u_{d2} \tag{28}$$

According to the definition of $m$, the voltage $u_2$ can be expressed as

$$u_2 = \begin{cases} (6-4\sqrt{3})mU\sin(\omega t-\dfrac{k\pi}{3}), \\ \quad \omega t \in \left[\dfrac{k\pi}{3}, \dfrac{k\pi}{3}+\dfrac{\pi}{12}\right] \\ (4\sqrt{3}-6)mU\sin(\omega t-\dfrac{\pi}{6}-\dfrac{k\pi}{3}), \\ \quad \omega t \in \left[\dfrac{k\pi}{3}+\dfrac{\pi}{12}, \dfrac{k\pi}{3}+\dfrac{\pi}{4}\right] \\ (6-4\sqrt{3})mU\sin(\omega t-\dfrac{\pi}{3}-\dfrac{k\pi}{3}), \\ \quad \omega t \in \left[\dfrac{k\pi}{3}+\dfrac{\pi}{4}, \dfrac{(k+1)\pi}{3}\right] \end{cases} \tag{29}$$

From (22), the maximum of the absolute value of $u_2$ is calculated as

$$|u_2|_{\max} = m\,|u_1|_{\max} = \frac{9\sqrt{2}-5\sqrt{6}}{2}mU \tag{30}$$

When the unconventional IPR is under the operation mode I, the MPR operates as conventional 12-pulse diode rectifier. Under the operation mode II or III, the unconventional IPR operates as double-tapped IPR, and the MPR operates as conventional 24-pulse diode rectifier. Only under the operation mode IV and V, the single-phase diode-bridge is working normally. Assume that the positive half cycle of input voltage for phase "a" starts from zero-crossing point when the radian $\omega t$ is equal to zero. The first phase angle $\theta_1$ is defined when the MOSFET $Q_2$ turns ON. Assume that the first phase angle when the absolute value of $u_2$ is equal to load voltage $u_d$ to be $\theta_2$. Since the voltage $u_2$ is symmetrical and its period is $\pi/6$, the phase angle $\theta_2$ should be in the time interval of $[0, \pi/12]$. In order to increase the pulse number, the condition $\theta_1 < \theta_2$ should be satisfied. The conduction time sequence of the power devices is shown in Fig. 4.

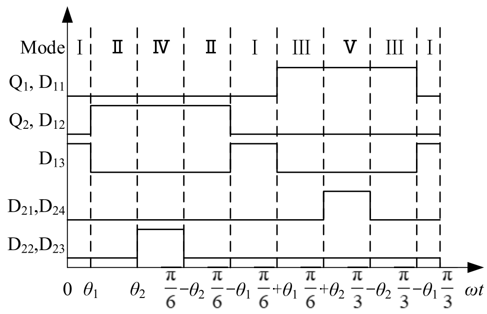



**FIGURE 4. The conduction time sequence of the power devices.**

According to the above analysis of the operation modes and the output voltage $u_{d1}$ and $u_{d2}$, the load voltage $u_d$ of the proposed rectifier can be expressed in the interval $[0, 2\pi]$ as

$$u_d = \begin{cases} \frac{\sqrt{6}+3\sqrt{2}}{4} KU\cos(\omega t - \frac{\pi}{6}k),\ \omega t \in \left[\frac{\pi}{6}k, \frac{\pi}{6}k+\theta_1\right) \\ AKU\sin(\omega t - \frac{\pi}{6}k + \varphi),\ \omega t \in \left[\frac{\pi}{6}k+\theta_1, \frac{\pi}{6}k+\theta_2\right) \\ \frac{2\sqrt{3}m}{2m+1-2\alpha} KU\cos(\omega t - \frac{\pi}{6}k - \frac{\pi}{12}), \\ \omega t \in \left[\frac{\pi}{6}k+\theta_2, \frac{\pi}{6}k+\frac{\pi}{6}-\theta_2\right) \\ AKU\sin(\varphi - \omega t + \frac{\pi}{6}k + \frac{\pi}{6}), \\ \omega t \in \left[\frac{\pi}{6}k+\frac{\pi}{6}-\theta_2, \frac{\pi}{6}k+\frac{\pi}{6}-\theta_1\right) \\ \frac{\sqrt{6}+3\sqrt{2}}{4} KU\cos(\omega t - \frac{\pi}{6}k - \frac{\pi}{6}), \\ \omega t \in \left[\frac{\pi}{6}k+\frac{\pi}{6}-\theta_1, \frac{\pi}{6}k+\frac{\pi}{6}\right] \end{cases} \tag{31}$$

where $A = \sqrt{\left(6-3\sqrt{3}\right)\alpha^2 + (6+3\sqrt{3})/4}$, $\varphi = \arctan[(2+\sqrt{3})/2\alpha]$.

From (31), the minimum load voltage can be calculated as

$$u_{dmin} = \left(\frac{\sqrt{6}+3\sqrt{2}}{4} + \frac{9\sqrt{2}-5\sqrt{6}}{2}\alpha\right) U \tag{32}$$

From (21), (30), and (32), it is obtained that

$$m - \alpha > \frac{7+4\sqrt{3}}{2} \approx 6.9641 \tag{33}$$

Therefore, when the parameters $\alpha$ and $m$ satisfy the above necessary condition, the unconventional IPR can operate normally.

### B. OPTIMAL PARAMETERS DESIGN

Actually, the above necessary condition is essential and critical, which cannot ensure the proposed MPR operating as 48-pulse rectifier and minimizing the THD of the input line current. Some parameters should be design optimally, such as the optimal tap and turn ratio of the unconventional IPR.

In Fig. 1 and Fig. 2, According to the ampere turns balance principle and Kirchoff's current law, it is obtained that

$$\begin{cases} i_a = 2[\frac{1}{\sqrt{3}}(S_{b1}-S_{c1}) - S_{b1}]i_{d1} \\ \quad +2[\frac{1}{\sqrt{3}}(S_{c2}-S_{b2}) - S_{c2}]i_{d2} \\ i_b = 2[\frac{1}{\sqrt{3}}(S_{c1}-S_{a1}) - S_{c1}]i_{d1} \\ \quad +2[\frac{1}{\sqrt{3}}(S_{a2}-S_{c2}) - S_{a2}]i_{d2} \\ i_c = 2[\frac{1}{\sqrt{3}}(S_{a1}-S_{b1}) - S_{a1}]i_{d1} \\ \quad +2[\frac{1}{\sqrt{3}}(S_{b2}-S_{a2}) - S_{b2}]i_{d2} \end{cases} \tag{34}$$

According to the operation mode of the unconventional IPR, the output currents of the two three-phase diode-bridge rectifiers can be expressed as

$$i_{d1} = \begin{cases} \frac{1}{2}I_d \quad \omega t \in \left[\frac{\pi}{3}k, \frac{\pi}{3}k+\theta_1\right) \\ \left(\frac{1}{2}-\alpha\right)I_d \quad \omega t \in \left[\frac{\pi}{3}k+\theta_1, \frac{\pi}{3}k+\theta_2\right) \\ 0 \quad \omega t \in \left[\frac{\pi}{3}k+\theta_2, \frac{\pi}{3}k+\frac{\pi}{6}-\theta_2\right) \\ \left(\frac{1}{2}-\alpha\right)I_d \quad \omega t \in \left[\frac{\pi}{3}k+\frac{\pi}{6}-\theta_2, \frac{\pi}{3}k+\frac{\pi}{6}-\theta_1\right) \\ \frac{1}{2}I_d \quad \omega t \in \left[\frac{\pi}{3}k+\frac{\pi}{6}-\theta_1, \frac{\pi}{3}k+\frac{\pi}{6}+\theta_1\right) \\ \left(\frac{1}{2}+\alpha\right)I_d \quad \omega t \in \left[\frac{\pi}{3}k+\frac{\pi}{6}+\theta_1, \frac{\pi}{3}k+\frac{\pi}{6}+\theta_2\right) \\ \frac{2m}{1-2\alpha+2m}I_d \quad \omega t \in \left[\frac{\pi}{3}k+\frac{\pi}{6}+\theta_2, \frac{\pi}{3}k+\frac{\pi}{3}-\theta_2\right) \\ \left(\frac{1}{2}+\alpha\right)I_d \quad \omega t \in \left[\frac{\pi}{3}k+\frac{\pi}{3}-\theta_2, \frac{\pi}{3}k+\frac{\pi}{3}-\theta_1\right) \\ \frac{1}{2}I_d \quad \omega t \in \left[\frac{\pi}{3}k+\frac{\pi}{3}-\theta_1, \frac{\pi}{3}k+\frac{\pi}{3}\right] \end{cases} \tag{35}$$

$$i_{d2} = \begin{cases} \frac{1}{2}I_d \quad \omega t \in \left[\frac{\pi}{3}k, \frac{\pi}{3}k+\theta_1\right) \\ \left(\frac{1}{2}+\alpha\right)I_d \quad \omega t \in \left[\frac{\pi}{3}k+\theta_1, \frac{\pi}{3}k+\theta_2\right) \\ \frac{2m}{1-2\alpha+2m}I_d \quad \omega t \in \left[\frac{\pi}{3}k+\theta_2, \frac{\pi}{3}k+\frac{\pi}{6}-\theta_2\right) \\ \left(\frac{1}{2}+\alpha\right)I_d \quad \omega t \in \left[\frac{\pi}{3}k+\frac{\pi}{6}-\theta_2, \frac{\pi}{3}k+\frac{\pi}{6}-\theta_1\right) \\ \frac{1}{2}I_d \quad \omega t \in \left[\frac{\pi}{3}k+\frac{\pi}{6}-\theta_1, \frac{\pi}{3}k+\frac{\pi}{6}+\theta_1\right) \\ \left(\frac{1}{2}-\alpha\right)I_d \quad \omega t \in \left[\frac{\pi}{3}k+\frac{\pi}{6}+\theta_1, \frac{\pi}{3}k+\frac{\pi}{6}+\theta_2\right) \\ 0 \quad \omega t \in \left[\frac{\pi}{3}k+\frac{\pi}{6}+\theta_2, \frac{\pi}{3}k+\frac{\pi}{3}-\theta_2\right) \\ \left(\frac{1}{2}-\alpha\right)I_d \quad \omega t \in \left[\frac{\pi}{3}k+\frac{\pi}{3}-\theta_2, \frac{\pi}{3}k+\frac{\pi}{3}-\theta_1\right) \\ \frac{1}{2}I_d \quad \omega t \in \left[\frac{\pi}{3}k+\frac{\pi}{3}-\theta_1, \frac{\pi}{3}k+\frac{\pi}{3}\right] \end{cases} \tag{36}$$

Define the rms value of the current as

$$I = \sqrt{\frac{1}{T}\int_0^T i^2 dt} \tag{37}$$

where $I$ is the rms value of the current, and $i$ is the instantaneous value of the current.

To set phase **a** as an example, define that the THD of the input line current as

$$\mathrm{THD} = \frac{\sqrt{I_a^2 - I_1^2}}{I_1} \tag{38}$$

where $I_a$ is the rms value of the input line current $i_a$, $I_1$ is the rms value of the fundamental of the input line current $i_a$.

Substituting (35) and (36) into (34), the input line current $i_a$ of the proposed rectifier can be calculated in the time interval of $[0, \pi/2]$. The time interval of $[0, \pi/2]$ is selected because the input line current $i_a$ is symmetrical. Obviously, the THD of current $i_a$ is depended on the parameters $\alpha$, $m$, $\theta_1$ and $\theta_2$.

$$i_a = \begin{cases} 0 \quad \omega t \in [0, \theta_1) \\ \frac{4k_1}{\sqrt{3}}\alpha I_d \quad \omega t \in [\theta_1, \theta_2) \\ \frac{4k_1}{\sqrt{3}} \cdot \frac{m}{1-2\alpha+2m} I_d \quad \omega t \in \left[\theta_2, \frac{\pi}{6}-\theta_2\right) \\ \left(\frac{1}{2}+\frac{k_1}{2\sqrt{3}}+\sqrt{3}k_1\alpha-\alpha\right) I_d \quad \omega t \in \left[\frac{\pi}{6}-\theta_2, \frac{\pi}{6}-\theta_1\right) \\ \frac{1}{2}\left(1+\frac{k_1}{\sqrt{3}}\right) I_d \quad \omega t \in \left[\frac{\pi}{6}-\theta_1, \frac{\pi}{6}+\theta_1\right) \\ \left(\frac{1}{2}+\frac{k_1}{2\sqrt{3}}-\sqrt{3}k_1\alpha+\alpha\right) I_d \quad \omega t \in \left[\frac{\pi}{6}+\theta_1, \frac{\pi}{6}+\theta_2\right) \\ \left(1-\frac{k_1}{\sqrt{3}}\right) \cdot \frac{2m}{1-2\alpha+2m} I_d \quad \omega t \in \left[\frac{\pi}{6}+\theta_2, \frac{\pi}{3}-\theta_2\right) \\ \left(1-\frac{2k_1}{\sqrt{3}}\alpha\right) I_d \quad \omega t \in \left[\frac{\pi}{3}-\theta_2, \frac{\pi}{3}-\theta_1\right) \\ I_d \quad \omega t \in \left[\frac{\pi}{3}-\theta_1, \frac{\pi}{3}+\theta_1\right) \\ \left(1+\frac{2k_1}{\sqrt{3}}\alpha\right) I_d \quad \omega t \in \left[\frac{\pi}{3}+\theta_1, \frac{\pi}{3}+\theta_2\right) \\ \left(1+\frac{k_1}{\sqrt{3}}\right) \cdot \frac{2m}{1-2\alpha+2m} I_d \quad \omega t \in \left[\frac{\pi}{3}+\theta_2, \frac{\pi}{2}-\theta_2\right) \\ \left(1+\frac{k_1}{\sqrt{3}}\right) I_d \quad \omega t \in \left[\frac{\pi}{2}-\theta_2, \frac{\pi}{2}\right] \end{cases} \tag{39}$$

where $k_1$ is equal to $2-\sqrt{3}$.

Actually, there are some relations among the parameters $\alpha$, $m$, $\theta_1$ and $\theta_2$. Because the proposed rectifier is expected to operate as 48-pulse rectifier, the theoretical waveform of the input line current should contain 48 equal-width steps per power supply cycle. Therefore, the first phase angle $\theta_1$ is $\pi/48$, which determines the first time when the MOSFET turns ON. The phase angle $\theta_2$ is $\pi/16$, which determines the first time when the single-phase diode-bridge starts normal operation and when the absolute value of $u_2$ is equal to load voltage $u_d$. From (29) and (31), the relation between $m$ and $\alpha$ can be obtained as

$$m - \alpha = \frac{\sqrt{3}}{(4\sqrt{3}-6)\tan\frac{\pi}{16}} \tag{40}$$

From (37) and (39), the rms value of the input line current $I_a$ is calculated as (41) by the software of Mathcad

$$I_a = \frac{I_d\sqrt{A(\alpha^4-2\alpha^3 m-\alpha^3+\alpha^2 m^2+\alpha^2 m)+B\alpha^2+Cm^2+D}}{\sqrt{6}(2m-2\alpha+1)} \tag{41}$$

where $A = 32(7-4\sqrt{3})$, $B = (68-32\sqrt{3})$, $C = (44-16\sqrt{3})$, $D = 3(4m-8\alpha m-4\alpha+1)$.

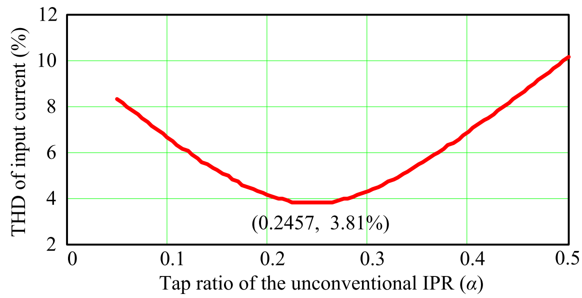



**FIGURE 5.** Relation between the THD and tap ratio when $\theta_1 = \pi/48$ and $\theta_2 = \pi/16$.

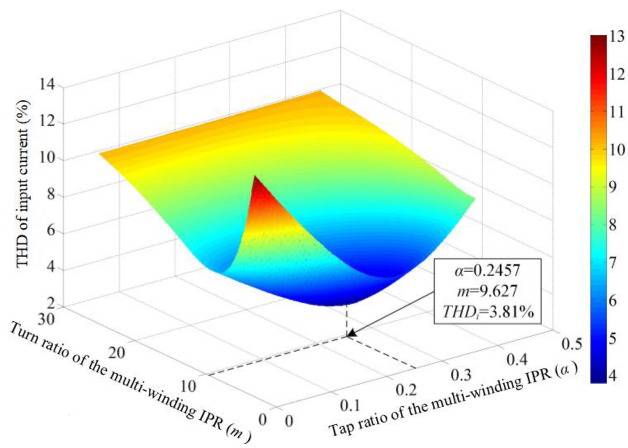



**FIGURE 6.** Relation among the THD, $\alpha$ and $m$.

Using the Fourier series, the rms value of the fundamental of the input line current $I_1$ is also calculated by Mathcad. However, the formula is much too long to display here. The THD of input line current can be obtained by substituting above expression into (38). When $\theta_1 = \pi/48$ and $\theta_2 = \pi/16$, Fig.5 shows the relation between the THD and tap ratio $\alpha$. When $\alpha = 0.2457$, the THD is minimal and the minimum is 3.81%. From (39), the turn ratio of the unconventional IPR is 9.627. Fig. 6 shows the relation among the THD, $\alpha$ and $m$.

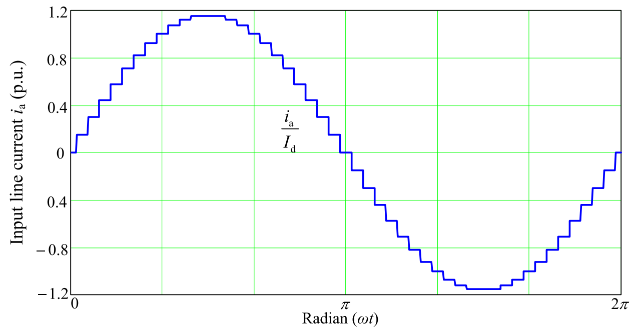



**FIGURE 7.** Input line current under the optimal parameters.

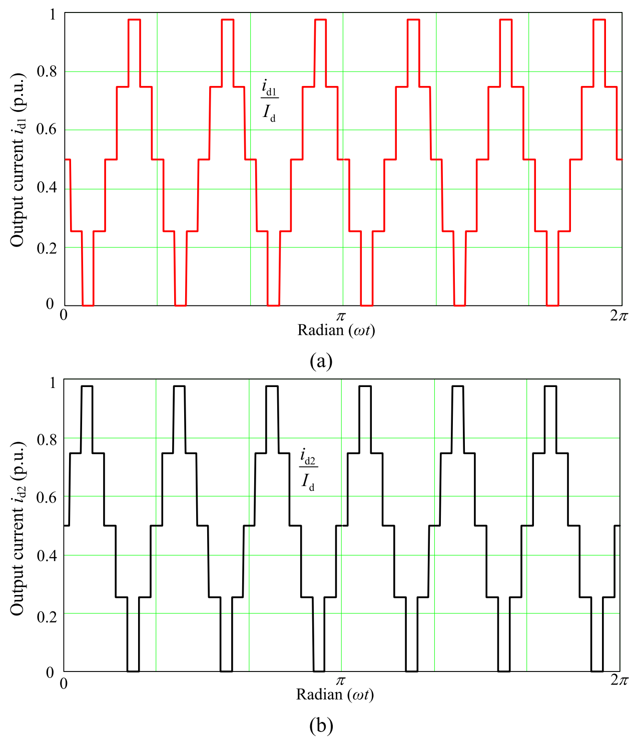



**FIGURE 8.** Output currents of the two three-phase diode-bride rectifiers under the optimal parameters. (a) Current $i_{d1}$. (b) Current $i_{d2}$.

From above analysis, the optimal parameters of proposed rectifier are $\theta_1 = \pi/48$, $\theta_2 = \pi/16$, $\alpha = 0.2457$, and $m = 9.627$. Under the optimal parameters, Fig. 7 shows the input line current, which contains 48 steps with the equal width per power supply cycle. Therefore, according to the theoretical waveform of the input line current, the proposed MPR operates as 48-pulse rectifier. Under the optimal parameters, Fig. 8 shows the output currents $i_{d1}$ and $i_{d2}$ of the two three-phase diode-bridge rectifiers.

According to the analysis of operation modes, Fig. 9 shows the output voltages $u_{d1}$ and $u_{d2}$of the two three-phase diode-bridge rectifiers under the optimal parameters. From the waveforms of voltage $u_{d1}$ and $u_{d2}$, it is different from the MPR with conventional IPR because of the single-phase diode-bridge connected with the secondary winding of

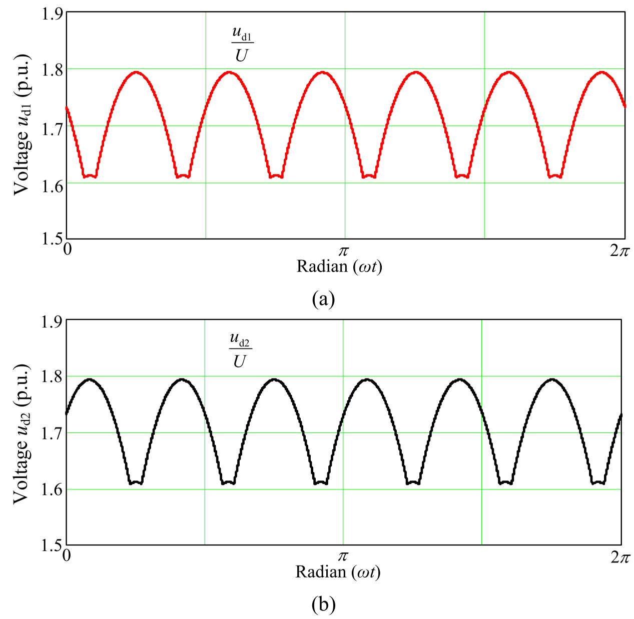



**FIGURE 9.** Output voltages of the two three-phase diode-bride rectifiers under the optimal parameters. (a) Voltage $u_{d1}$. (b) Voltage $u_{d2}$.

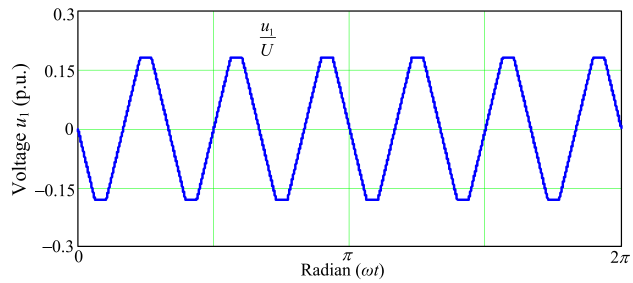



**FIGURE 10.** Voltage across primary winding of the unconventional IPR.

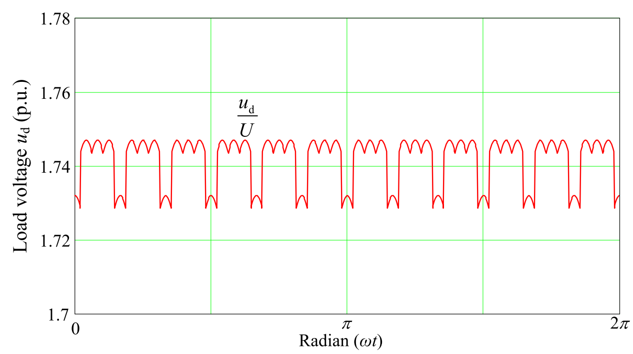



**FIGURE 11.** Load voltage under the optimal parameters.

unconventional IPR. Fig. 10 shows the voltage $u_1$ across the primary winding of the unconventional IPR.

Under the optimal parameters, the load voltage $u_d$ can be illustrated as shown in Fig.11. From the waveform of the load voltage, it has 48 pulses with equal width per power supply cycle. However, there are 12 pulses are different from other pulses in load voltage, because the unconventional operates as conventional central-tapped IPR and proposed rectifier operates as conventional 12-pulse rectifier in this time interval. Therefore, the value of load voltage in operation mode I is lower than in other modes.

### C. KVA RATING OF THE UNCONVENTIONAL IPR

In this part, the kVA rating of the unconventional IPR is calculated when the proposed MPR operates as 48-pulse rectifier under the optimal parameters. From the operation modes of the unconventional IPR and Fig. 10, the rms value of the voltage across its primary winding is calculated as

$$U_1 \approx 0.128U \tag{42}$$

From Fig. 2, the primary winding of the unconventional IPR is comprised of four little windings (winding AT, winding OT, winding OT' and winding BT'). The currents through the winding AT and winding BT' are equal to $i_{d1}$ and $i_{d2}$, and their rms values are calculated as

$$I_{d1} = I_{d2} = I_d\sqrt{\frac{8\alpha^2+3}{16} + \frac{m^2}{2(2m-2\alpha+1)^2}} = 0.579I_d \tag{43}$$

From the operation modes of the unconventional IPR and the output currents expression of the two three-phase diode-bridge rectifiers, the rms value of the current through the winding TT' is calculated as

$$I_{TT'} = \frac{I_d\sqrt{8\alpha^2-8\alpha+3}}{4} = 0.308I_d \tag{44}$$

Furthermore, under the optimal parameters, the rms value of the voltage across the secondary winding of the unconventional IPR is calculated as

$$U_2 = mU_1 \approx 1.232U \tag{45}$$

From the operation modes of the unconventional IPR, the rms value of the current through the secondary winding of the unconventional IPR is calculated as

$$I_n = \frac{(1-2\alpha)I_d}{2(2m-2\alpha+1)} = 0.013I_d \tag{46}$$

Therefore, the kVA rating of the unconventional IPR is calculated as

$$\begin{aligned} S_{uIPR} &= 0.5 \times [2 \times (0.5-\alpha) \times 0.128U \times 0.579I_d \\ &\quad +2\alpha \times 0.128U \times 0.308I_d + 2 \times 1.232U \times 0.013I_d] \\ &= 0.0446UI_d = 2.56\%U_dI_d \end{aligned} \tag{47}$$

In the proposed 48-pulse MPR, because the modulation effect of the MOSFETs and the single-phase diode-bridge rectifier, the kVA rating of the unconventional IPR is slightly smaller than other unconventional IPR with central tap or double taps in primary winding.

**TABLE 1. Rectifier specifications and components for experiment.**

| Parameter | Value |
|---|---|
| Input phase voltage (rms) | 120V |
| Line frequency | 50Hz |
| Load filtering inductance | 10mH |
| Primary tapped ratio ($\alpha$) of the unconventional IPR | 0.25 |
| Turn ratio ($m$) of the unconventional IPR | 9.625 |
| Rated output power | 3kW |
| Rated output current | 10A |

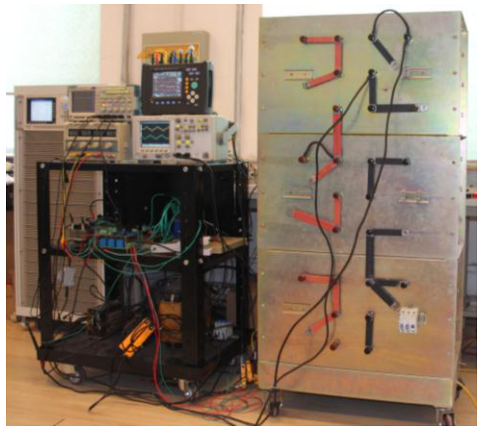
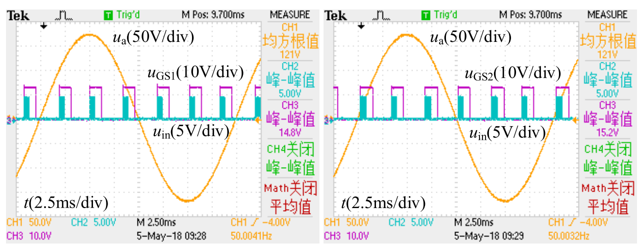


**FIGURE 12. Photograph of experimental setup.**




(a) (b)

**FIGURE 13. Gate driving signals of MOSFETs. (a) Gate driving signal $u_{GS1}$. (b) Gate driving signal $u_{GS2}$.**

## IV. EXPERIMENTAL RESULTS

In order to validate the theoretical analysis, an experimental setup with 3 kW is designed. Table 1 shows the rectifier specifications and components, and Fig. 12 shows the photograph of experimental setup. The input of MPR is from Chroma programmable AC source 61511, and the power quality analyzer is HIOKI 3196.

Synchronization circuit is mainly used to generate PWM control signals of MOSFETs with adjustable output pulse width and phase-shifting angle. The synchronous circuit consists of three-phase-shifting control circuit and pulse width control circuit. Three-phase-shifting control circuit is based on integrated chip TC787AP. Pulse width control circuit consists of dual monostable multivibrators with Schmitt-trigger inputs.

Under the rated conditions listed in Table 1, Fig. 13 (a) and Fig. 13 (b) show the gate driving signals of MOSFET

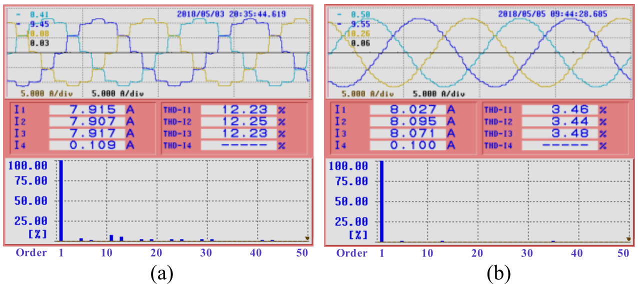



**FIGURE 14.** Input line current and its spectrum. (a) Without the unconventional IPR. (b) With the unconventional IPR under the optimal parameters.

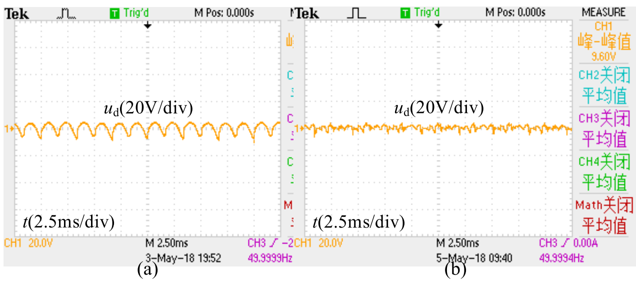



**FIGURE 15.** Load ripple voltage. (a) Without unconventional IPR. (b) With unconventional IPR under the optimal parameters.

Q$_1$ and Q$_2$. In Fig. 13, waveform $u_a$ is the input voltage for phase "a" of the proposed rectifier. The output of TC787AP are six channel modulation pulse signals, then these signals are after OR gate operation shown as waveform $u_{in}$ in Fig. 13. According to the definition of $\theta_1$, the first phase angle $\theta_1$ is $\pi/48$ and the phase difference of the gate driving signals $u_{GS1}$ and $u_{GS2}$ is $\pi/6$. The pulse width of both gate driving signals is 1.25ms.

Fig. 14 (a) shows the input line currents and their THD without unconventional IPR and the proposed rectifier operates as 12-pulse rectifier. Fig. 14 (b) shows the input line currents and their THD with unconventional IPR under optimal parameters and the proposed rectifier operates as 48-pulse rectifier. The experimental values of THD are less than that of the theoretical value due to the filtering effect of leakage inductance of autotransformer and inductance of IPR and ZSBT. Compared with Fig. 14 (a), the unconventional IPR is effective on reducing harmonic distortion of the rectifier input currents.

Fig. 15 shows the load ripple voltage of the proposed rectifier. The load ripple voltage decreases when the unconventional IPR operating under the optimal parameters.

Fig. 16 shows the measured waveforms. Fig. 16 (a) and Fig 16 (b) show the primary winding currents $i_{m1}$, $i_{m2}$ and $i_{m3}$ of the unconventional IPR. Fig. 16 (c) and Fig. 16 (d) show the secondary single-phase diode-bridge rectifier currents $i_{n1}$, $i_{n2}$ and $i_n$ of the unconventional IPR. Fig. 16 (e) shows the output currents $i_{d1}$ and $i_{d2}$ of the two three-phase diode-bridge rectifier. Fig. 16 (f) shows the input currents $i_{a1}$ and $i_{b2}$ of the three-phase diode-bridge rectifier (REC I)

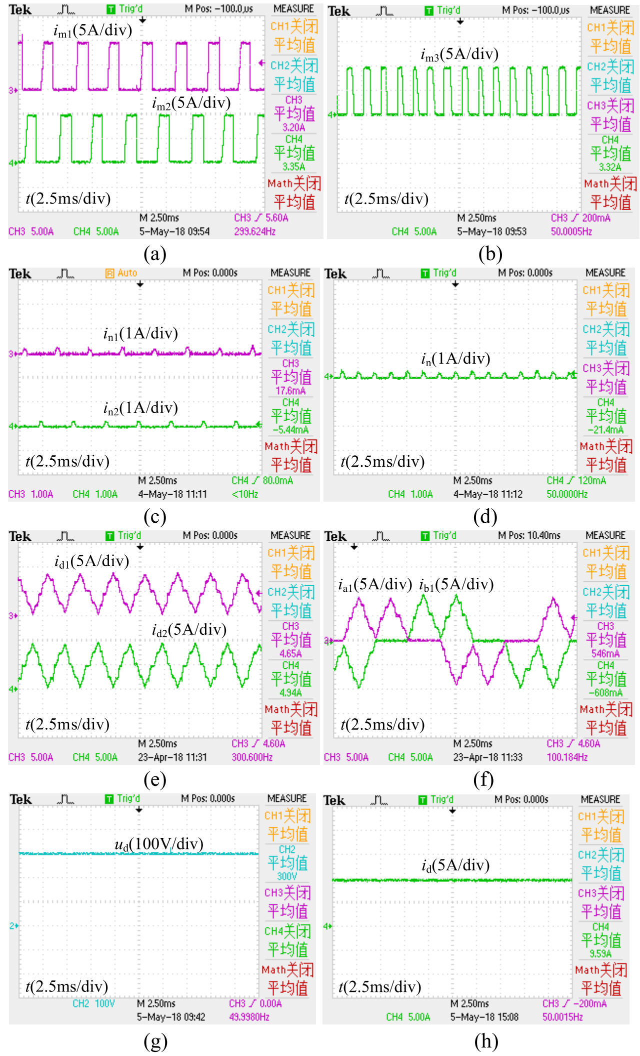



**FIGURE 16.** Measured waveforms of the proposed rectifier. (a) Currents $i_{m1}$ and $i_{m2}$ of diodes $D_{11}$ and $D_{12}$. (b) Current $i_{m3}$ of diode $D_{m13}$. (c) Input currents $i_{n1}$ and $i_{n2}$ of the single-phase diode-bridge rectifier. (d) Output current $i_n$ of single-phase diode-bridge rectifier. (e) Output currents $i_{d1}$ and $i_{d2}$ of the two three-phase diode-bridge rectifier. (f) Input currents $i_{a1}$ and $i_{b1}$. (g) Load voltage $u_d$. (h) Load current $i_d$.

for phase "a" and "b". The currents $i_{d1}$ and $i_{d2}$ are modulated obviously when the unconventional IPR with optimal parameters. Consequently, the input currents of the two three-phase diode-bridge rectifier are also changed and the input current of the MPR is modulated near sinusoidal. Fig. 16 (g) and Fig. 16 (h) show the load voltage and load current respectively.

Table 2 shows the comparison of the proposed rectifier with other MPRs in terms of input line current THD, load power and efficiency. From Table 2, the experimental THD of input line current is decreased as the pulse number of load voltage and the step number of input line current increasing. According to the experiment results, the efficiency of proposed 48-pulse rectifier with unconventional IPR is slightly improved.

**TABLE 2.** Comparison of the proposed rectifier with other MPRs.

| Topologies | Input line current THD | Load Power | Efficiency |
|---|---|---|---|
| 12-pulse rectifier with conventional IPR | 12.23% | 2932.1W | 96% |
| 24-pulse rectifier with double-tapped IPR | 5.93% | 2941.2W | 96.3% |
| 24-pulse rectifier with unconventional IPR | 5.62% | 2944.3W | 96.4% |
| 36-pulse rectifier with unconventional IPR | 4.34% | 2965.6W | 97.1% |
| The proposed 48-pulse rectifier | 3.46% | 2971.7W | 97.3% |

## V. CONCLUSION

This paper proposed a novel 48-pulse rectifier combining a 12-pulse rectifier and an unconventional IPR with an auxiliary single-phase diode-bridge rectifier at dc link. The primary winding of the unconventional IPR is triple-tapped and the secondary winding is connected with single-phase diode-bridge rectifier. When the unconventional IPR is designed optimally, under ideal condition, the proposed rectifier operates as a 48-pulse rectifier and draws near sinusoidal input line currents. The operation mode, the optimal parameters of the unconventional IPR are analyzed and derived in this paper. Under the optimal parameters condition, the pulse number of load voltage and step number of input line current are 48 simultaneously. The theoretical THD of input line current is about 3.81% and the experimental THD is about 3.46%. In addition, the current through the secondary winding of the unconventional IPR is very small. Above all, compared with the 12-pulse rectifier with the conventional IPR, the harmonic reduction ability of the proposed rectifier is improved significantly, and the proposed rectifier is easy and simple to realize.

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