〈論文〉 4-5-4

A New 12-Pulse Diode Rectifier System With Low kVA Components For Clean Power Utility Interface

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ABSTRACT

This paper proposes a 12-pulse diode rectifier system with low kVA components suitable for powering switch mode power supplies or ac/dc converter applications. The proposed 12-pulse system employs a polyphase transformer, a zero sequence blocking transformer (ZSBT) in the dc link, and an interphase transformer. Results produce near equal leakage inductance in series with each diode rectifier bridge ensuring equal current sharing and performance improvements. The utility input currents and the voltage across the ZSBT are analyzed and the kVA rating of each component in the proposed system is computed. The 5^{th}, 7^{th}, 17^{th} and 19^{th} harmonics are eliminated in the input line currents resulting in clean input power. The dc link voltage magnitude generated by the proposed rectifier system is nearly identical to a conventional 6-pulse system. The proposed system is suitable to retrofit applications as well as in new PWM drive systems. Simulation and experimental results from a 208V, 10kVA system are shown.

Key Words : Multipulse, three-phase rectifier, harmonic reduction.

1. INTRODUCTION

A number of methods have been proposed to lower harmonics generated by diode rectifier type utility interface to power electronic system.[1-7] One of the design goals in multipulse converters is to increase the pulse number in order to eliminate more harmonics in the input line current.[2,4] Many multipulse converters such as conventional 12-pulse converters (Fig. 1), 18-pulse converters and 24-pulse systems are introduced to achieve clean power.[2,3,4] These multipulse converters are formed by a combination of 6-pulse bridge rectifiers and isolation transformers, which result in large size and cost. Furthermore, in multipulse systems careful attention to practical aspects such as leakage reactances in series with each diode rectifier bridge, interphase transformer winding design and pre-existing utility voltage distortion is important for equal current sharing and elimination of harmonics in the input line currents.

In response to these concerns, a 12-pulse system is proposed (Fig. 2) employing a polyphase transformer (autotransformer), a zero sequence blocking transformer (ZSBT) in the dc link and an interphase transformer (IPT). The employed passive components are relatively low kVA. The function of the ZSBT's is to ensure independent operation of the two diode bridge rectifiers in an auto-connected system as well as to promote equal current sharing. The ZSBT's offer high impedance to zero sequence currents and ensures 120 degree conduction for each diode in a rectifier. The autotransformer employed in the proposed 12-pulse system has a kVA rating of $0.18P_o$[pu] over the conventional system (Fig.1) which drastically reduces the cost, weight and volume.

The dc link voltages generated by the proposed rectifier systems are nearly identical to a conventional 6-pulse diode rectifier system. Additional application for the proposed 12-pulse rectifier system feeding multiple nonlinear loads is also presented. Detailed analysis of the proposed 12-pulse system is discussed. The proposed system is simulated and experimental results for a 208V, 10kVA are provided.

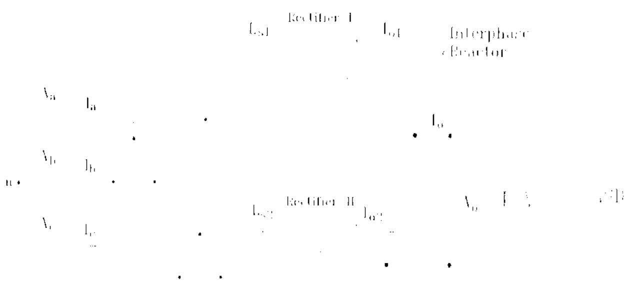
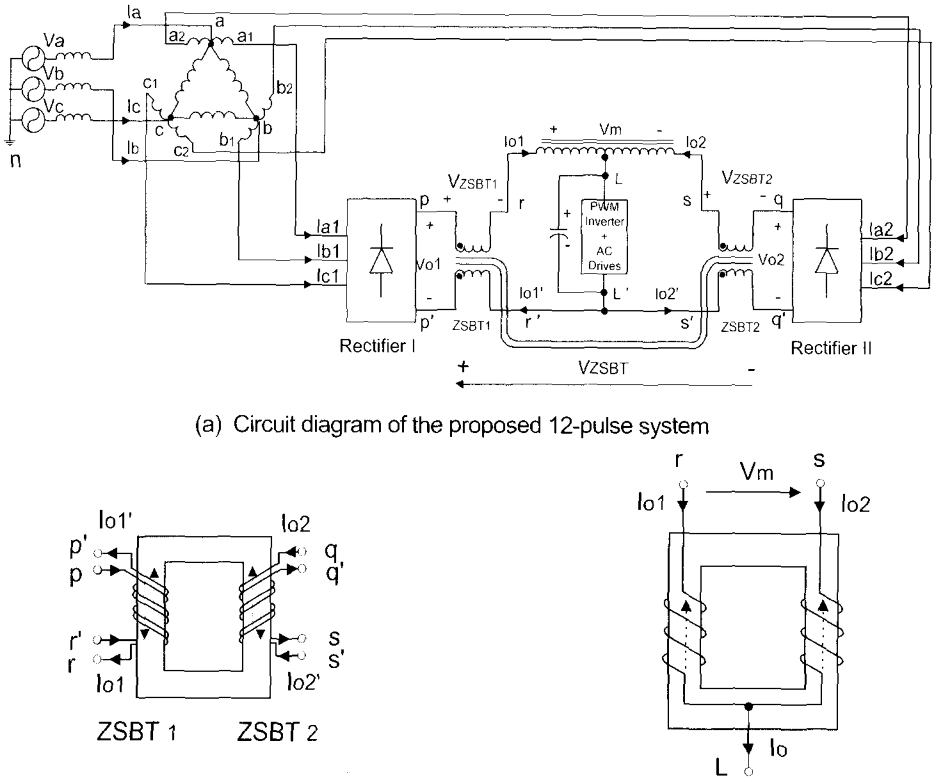


Fig. 1 Conventional 12-Pulse System

2. 12-PULSE SYSTEM

The proposed 12-pulse system employing a reduced kVA polyphase transformer is shown in Fig.2. The phase angle between two rectifier voltage sources is chosen such that 5^{th} and 7^{th} harmonics are cancelled in the input line currents. The winding configurations of ZSBT and IPT are shown in Fig.2 (b) and (c), respectively. The operation and function of each component of the proposed 12-pulse system is detailed in the next few sections.



(a) Circuit diagram of the proposed 12-pulse system

(b) Winding configuration of the ZSBT

(c) Winding configuration of the IPT

Fig. 2 Proposed 12-pulse system employing reduced kVA component

Assumptions:

(1) Semiconductor devices are assumed to be ideal.

(2) Overlapping phenomena in the commutation is ignored

(3) Polyphase transformer and interphase transformer are assumed to be ideal, that is, the exciting currents of these can be regarded as zero

(4) The dc smoothing reactor is sufficiently large and the output dc current I_o is ripple free.

2.1 Delta-Connected Polyphase Transformer

The Delta-Connected polyphase transformer arrangement for the proposed 12-pulse approach is shown in Fig.3. The purpose of this transformer is to provide the necessary 30° phase shift between a_1, b_1, c_1 and a_2, b_2, c_2. The proposed transformer is fed from a three phase utility input, and it generates two sets of output voltages. The vector diagram is shown in Fig.3 (a), which illustrates how two sets of output voltages are developed from the three-phase input. The corresponding transformer winding arrangement is shown in Fig.3 (b). From the vector diagram (Fig.3 (a)), it is clear that a vector of length k_1, between a and a_1, determines 15° phase shift. From Fig.3 (a), the length k_1 is shown to be

$$k_1 = tan(15^o) = 0.2679 \qquad (1)$$

Now assuming the input voltages v_a, v_b, v_c to be equal to

$$v_a = v_{pk}\ sin(wt) \qquad (2)$$

$$v_b = v_{pk}\ sin(wt - \frac{2\pi}{3}) \qquad (3)$$

$$v_c = v_{pk}\ sin(wt + \frac{2\pi}{3}) \qquad (4)$$

where v_{pk} is the peak voltage. The input voltages to the rectifier bridges v_{a1}, v_{b1}, v_{c1} and v_{a2}, v_{b2}, v_{c2} can be derived from the vector diagram (Fig. 3 (a)) as follows,

$$v_{a1} = v'_{pk}\ sin\left(wt + \frac{\pi}{12}\right) \qquad (5)$$

$$v_{b1} = v'_{pk}\ sin\left(wt + \frac{\pi}{12} - \frac{2\pi}{3}\right) \qquad (6)$$

$$v_{c1} = v'_{pk}\ sin\left(wt + \frac{\pi}{12} + \frac{2\pi}{3}\right) \qquad (7)$$

and

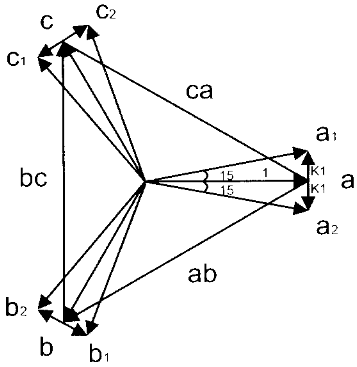
$$v_{a2} = v'_{pk} \sin\left(wt - \frac{\pi}{12} \right) \quad (8)$$

$$v_{b2} = v'_{pk} \sin\left(wt - \frac{\pi}{12} - \frac{2\pi}{3} \right) \quad (9)$$

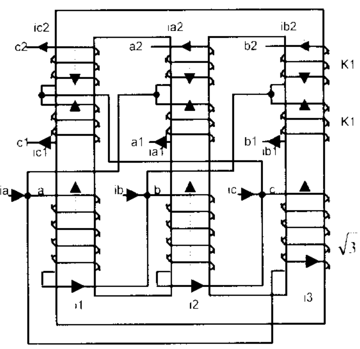
$$v_{c2} = v'_{pk} \sin\left(wt - \frac{\pi}{12} + \frac{2\pi}{3} \right) \quad (10)$$

where $v'_{pk} = \sqrt{1+k_T^2}\, v_{pk}$. (11)

From equations (1) and (11) we have $v'_{pk} = 1.035 v_{pk}$.



(a) Vector diagram



(b) Winding configuration

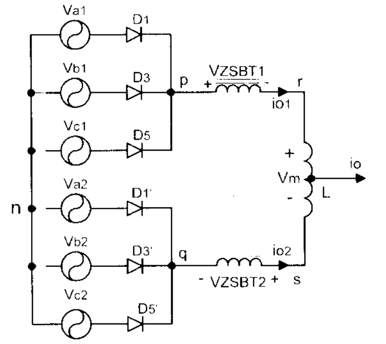
Fig. 3 Delta-connected polyphase transformer of the proposed12-pulse rectifier system

2.2 Output Voltage Analysis

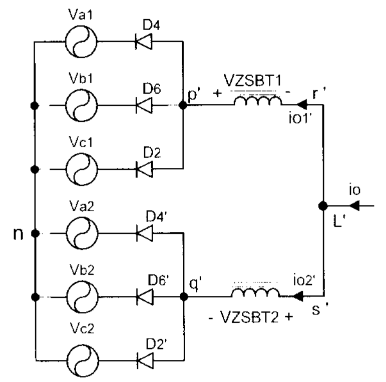
In this section, the voltages across the zero sequence blocking transformer (ZSBT), the interphase transformer (IPT) and the output voltage are analyzed. To ensure independent operation of the two diode rectifiers with input polyphase transformer, a ZSBT and an IPT become necessary. The ZSBT exhibits high impedance to zero sequence currents and provides 120-degree conduction for each rectifier diode. In the following section, voltages are analyzed in detail.

2.2.1 Voltage across the ZSBT

The ZSBT shown in Fig. 2 (a) is used in the proposed 12-pulse approach to ensure independent operation of the two diode bridge rectifiers in an auto-connected system as well as to promote equal current sharing. To simplify the analysis of the voltage across the ZSBT, the equivalent model shown in Fig. 4 will be used. The equivalent circuit consists of two groups of diodes and they are shown in Figs. 4 (a) and (b), respectively.



(a) Top group of rectifiers I&II



(b) Bottom group of rectifiers I&II

Fig. 4 Equivalent circuits of the proposed 12-pulse system with ZSBT in DC link

In the top group of the rectifiers I&II, the cathodes of the diodes D_1, D_3 and D_5 are at a common potential v_p. Therefore, the diode with its anode at the highest potential will conduct the current i_{o1}. The cathodes of the diodes D_1', D_3' and D_5' are at a common potential v_q. Therefore the diode with its anode at the highest potential will conduct the current i_{o2} and the rest of the diodes are reverse biased. Similarly in the bottom group of the rectifiers I & II the diodes with their cathodes at the lowest potential will conduct and the rest of the diodes are reverse biased. Thus the voltage across the ZSBT depends on conduction sequence of diodes. And the voltage across the $ZSBT_1$, v_{ZSBT1}, is identical to v_{ZSBT2} since they are magnetically coupled with each other. Now from the equivalent circuit (Fig. 4 (b)) we have voltage across the ZSBT as follows,

$$v_{ZSBT} = v_{p'n} - v_{q'n} \tag{12}$$

$$= \begin{cases} v_{a1} - v_{a2} & for\ \frac{8}{12}T \sim \frac{11}{12}T \\ v_{b1} - v_{a2} & for\ \frac{11}{12}T \sim T \end{cases} \tag{13}$$

Where $v_{ZSBT} = v_{ZSBT1} + v_{ZSBT2}$ and T is one period of v_{a1}

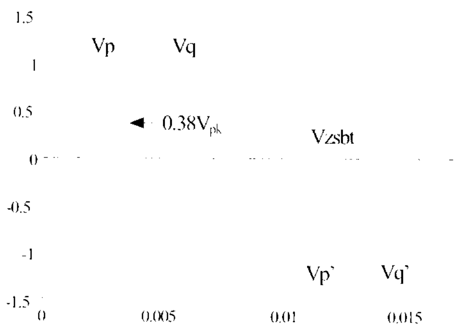


Fig. 5 Voltage across the ZSBT

Fig. 5 shows the instantaneous waveshapes of voltages v_p, v_q, $v_{p'}$, $v_{q'}$ and the voltage across the ZSBT due to the conduction of the top and bottom groups of the rectifiers. v_{ZSBT} can be mathematically derived in Fourier series. The node voltage at p' and q' (Fig. 5) are given by

$$v_{p'n} = -v'_{pk}\frac{3}{\pi}sin\left(\frac{\pi}{3}\right)\left\{1 - \sum_{3,6,9\cdots}^{\infty}\frac{2}{n^2-1}cos\left(\frac{n\pi}{3}\right)cos\,n\left(wt - \frac{3\pi}{12}\right)\right\} \tag{14}$$

$$v_{q'n} = -v'_{pk}\frac{3}{\pi}sin\left(\frac{\pi}{3}\right)\left\{1 - \sum_{3,6,9\cdots}^{\infty}\frac{2}{n^2-1}cos\left(\frac{n\pi}{3}\right)cos\,n\left(wt - \frac{5\pi}{12}\right)\right\} \tag{15}$$

where v'_{pk} is a line to neutral peak voltage at the front end of the diode rectifier.

$$v_{ZSBT} = v_{p'n} - v_{q'n} \tag{16}$$
$$= -v'_{pk}\frac{3}{\pi}sin\left(\frac{\pi}{3}\right)\sum_{3,6,9,\cdots}^{\infty}\frac{4}{n^2-1}cos^2\left(\frac{n\pi}{3}\right)sin\left(\frac{n\pi}{12}\right)sin(nwt)$$

Therefore, the voltage across the ZSBT is written as follows,

$$v_{ZSBT}(wt) = v'_{pk}(-0.2924\,sin(3wt) - 0.0945\,sin(6wt) - \cdots) \tag{17}$$

or

$$v_{ZSBT}(wt) = V_{LL}(-0.2471\,sin(3wt) - 0.0799\,sin(6wt) - \cdots) \tag{18}$$

It should be noted that v_{ZSBT} contains only tripplen frequency components. Hence, if ZSBT is properly designed, it impedes the flow of tripplen harmonic currents. On the other hand, the ZSBT ensures independent six-pulse operation of the two rectifier bridges I and II.

2.2.2 Voltage across the IPT and the Output Voltage

The Fourier series expansions of the voltages with respect to the neutral point n, v_{pn}, v_{qn} and v_{pq} (Fig. 5) can be given by.

$$v_{pn} = \frac{3v'_{pk}}{\pi}sin\left(\frac{\pi}{3}\right)\left\{1 - \sum_{3,6\cdots}^{\infty}\frac{2}{n^2-1}cos\left(\frac{n\pi}{3}\right)cos\,n\left(wt + \frac{\pi}{12}\right)\right\} \tag{19}$$

$$v_{qn} = \frac{3v'_{pk}}{\pi}sin\left(\frac{\pi}{3}\right)\left\{1 - \sum_{3,6\cdots}^{\infty}\frac{2}{n^2-1}cos\left(\frac{n\pi}{3}\right)cos\,n\left(wt - \frac{\pi}{12}\right)\right\} \tag{20}$$

$$v_{pq} = \frac{3v'_{pk}}{\pi}sin\left(\frac{\pi}{3}\right)\sum_{3,6,\cdots}^{\infty}\frac{4}{n^2-1}cos\left(\frac{n\pi}{3}\right)sin\left(\frac{n\pi}{12}\right)sin(nwt) \tag{21}$$

Now from the equivalent circuit shown in Fig. 4 (a) the voltage across the IPT, v_m, becomes,

$$v_m = v_{pq} - v_{ZSBT} = \frac{3v'_{pk}}{\pi}sin\left(\frac{\pi}{3}\right)\times$$
$$\times\sum_{3,6,\cdots}^{\infty}\frac{4}{n^2-1}cos\left(\frac{n\pi}{3}\right)sin\left(\frac{n\pi}{12}\right)\left[\left(1 + cos\left(\frac{n\pi}{3}\right)\right)sin(nwt)\right] \tag{22}$$

Therefore, the voltage across the IPT is rewritten as follows,

$$v_m(wt) = v'_{pk}(0.189\,sin(6wt) - 0.0205\,sin(18wt) + \cdots) \tag{23}$$

Fig. 6 shows the voltage across the IPT, v_m. The lowest frequency component of the voltage across the IPT is 360Hz, which results in smaller size, weight and volume.

The average output voltage at node L (Fig. 2 (a)) is,

$$V_L = \frac{1}{2}(V_{pn} + V_{qn}) = 0.8270v'_{pk} \tag{24}$$

where V_{pn} and V_{qn} are average output voltages with respect to neutral point.

Similarly, the average output voltage $V_{L'}$ at node L' (Fig. 2 (a)) is as follows,

$$V_{L'} = \frac{1}{2}(V_{p'n} + V_{q'n}) = -0.8270v'_{pk} \tag{25}$$

Therefore, the average dc output voltage V_o of the proposed 12-pulse system is,

$$V_o = V_L - V_{L'} = 1.654v'_{pk} = 1.3981V_{LL} \tag{26}$$

Where V_{LL} is the rms value of the line to line utility voltage ($V_{LL} = \frac{\sqrt{3}}{\sqrt{2}} v_{pk}$). The output voltage is approximately 3.5% higher than a conventional 6-pulse system.

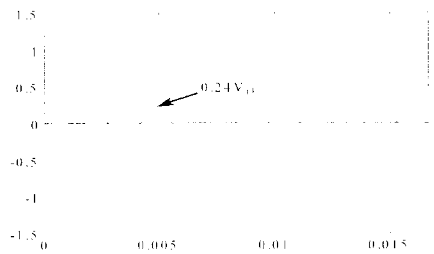


Fig. 6 Voltage across the IPT, v_m

2.3 Input Current Analysis

In this section, the input line currents are analyzed using Fourier series expansions. Analytical results using the spectrum of currents defined by Fourier expansion are useful when knowledge of individual harmonics is required.

2.3.1 Transformer MMF Equations

The winding configuration of the transformer is shown in Fig. 3 (b). Each limb has three windings: one long winding of $\sqrt{3}$ turn [pu] and two short windings of k_1 turn [pu]. The MMF equation of the first limb of the transformer can be developed from Fig. 3 (b) and are shown in equation (27)

$$\sqrt{3} i_1 = k_1 (i_{c2} - i_{c1}) \tag{27}$$

Similarly, the MMF equations of the other limbs can be expressed as,

$$\sqrt{3} i_2 = k_1 (i_{a2} - i_{a1}) \tag{28}$$

$$\sqrt{3} i_3 = k_1 (i_{b2} - i_{b1}) \tag{29}$$

Using the KCL, the utility input current i_a is expressed as follows,

$$i_a = i_1 + i_{a1} + i_{a2} - i_3 \tag{30}$$

From equations (27) - (30) the utility input current i_a is expressed in terms of rectifier input currents as follows,

$$i_a = i_{a1} + i_{a2} + \frac{k_1}{\sqrt{3}} (i_{c2} - i_{b2} + i_{b1} - i_{c1}) \tag{31}$$

Similarly, the utility input line currents i_b and i_c become,

$$i_b = i_{b1} + i_{b2} + \frac{k_1}{\sqrt{3}} (i_{a2} - i_{c2} + i_{c1} - i_{a1}) \tag{32}$$

$$i_c = i_{c1} + i_{c2} + \frac{k_1}{\sqrt{3}} (i_{b2} - i_{a2} + i_{a1} - i_{b1}) \tag{33}$$

Fig. 9 (c) shows a rectifier input current i_{a1}, assuming that the system has a highly inductive load. If the average load current is I_o, then the rectifier input currents i_{a1} and i_{a2} that feed the two converter bridges will ideally have the amplitude of $I_o/2$. Each rectifier input current will have a conduction period of 120°, and i_{a2} will lead i_{a1} by 30°. The Fourier series expansions of rectifier input currents (Fig. 9 (c)) for the Rectifier-I are as follows,

$$i_{a1}(wt) = \sum_{n=1,3,5\ldots}^{\infty} \frac{2I_o}{n\pi} cos (\frac{n\pi}{6}) sin n(wt) \tag{34}$$

$$i_{b1}(wt) = \sum_{n=1,3,5\ldots}^{\infty} \frac{2I_o}{n\pi} cos (\frac{n\pi}{6}) sin n(wt - \frac{2\pi}{3}) \tag{35}$$

$$i_{c1}(wt) = \sum_{n=1,3,5\ldots}^{\infty} \frac{2I_o}{n\pi} cos (\frac{n\pi}{6}) sin n(wt + \frac{2\pi}{3}) \tag{36}$$

For the Rectifier-II, the rectifier input currents are given by,

$$i_{a2}(wt) = \sum_{n=1,3,5\ldots}^{\infty} \frac{2I_o}{n\pi} cos (\frac{n\pi}{6}) sin n(wt - \frac{\pi}{6}) \tag{37}$$

$$i_{b2}(wt) = \sum_{n=1,3,5\ldots}^{\infty} \frac{2I_o}{n\pi} cos (\frac{n\pi}{6}) sin n(wt - \frac{\pi}{6} - \frac{2\pi}{3}) \tag{38}$$

$$i_{c2}(wt) = \sum_{n=1,3,5\ldots}^{\infty} \frac{2I_o}{n\pi} cos (\frac{n\pi}{6}) sin n(wt - \frac{\pi}{6} + \frac{2\pi}{3}) \tag{39}$$

The average output current is

$$I_o = I_{o1} + I_{o2} \tag{40}$$

Substituting (34) to (40) into (31), the utility input current becomes,

$$i_a = \sum_{n=1,3,5\ldots}^{\infty} \left[\frac{2I_o}{n\pi} cos\left(\frac{n\pi}{6} \right) \right] g_n \, cos(nwt - \alpha_n) \tag{41}$$

where

$$g_n = \sqrt{d_n^2 + n_n^2} ,$$

$$d_n = \frac{2k_1}{\sqrt{3}} sin\left(\frac{2n\pi}{3} \right) \left(cos\left(\frac{n\pi}{6} \right) - 1 \right) - sin\left(\frac{n\pi}{6} \right),$$

$$n_n = 1 + cos\left(\frac{n\pi}{6} \right) - \frac{k_1}{\sqrt{3}} cos\left(\frac{5n\pi}{6} \right), \ \alpha_n = tan^{-1}\left(\frac{n_n}{d_n} \right)$$

Assuming output current $I_o=1$ (PU), the Fourier expression of the utility input current, i_a, for the proposed 12-pulse system is rewritten as,

$$i_a = 1.14\cos(wt - 105^o) + 0.10\cos(11wt - 75^o) + 0.09\cos(13wt - 105^o) + 0.03\cos(23wt - 75^o) \quad (42)$$

Equation (42) can be rewritten in terms of sine functions as follows

$$i_a = 1.14\sin(wt - 15^o) + 0.10\sin(11wt + 15^o) + 0.09\sin(13wt - 15^o) + 0.03\sin(23wt + 15^o) \quad (43)$$

From equation (43), 5, 7, 17 and 19 harmonics become zero and only 12-pulse characteristic harmonics ($n = 12k \pm 1$, where k=1, 2, 3...) remain in the utility input line currents. Input current THD is calculated to be 14.7%. From equation (34), the rectifier input current i_{a1} has been regarded as a reference for deriving utility input current equation (43). Since line-to neutral voltage v_{an} leads the voltage $v_{a1\text{-}n}$ by 15°, line-to-neutral voltage v_{an} is given by

$$v_{an} = v'_{pk}\sin(wt - 15^o) \quad (44)$$

Therefore, from equations (43) and (44), true power factor is obtained as,

$$PF = \frac{P_{ave}}{V_{rms} I_{rms}} = 0.9913 \quad (45)$$

2.4 Equivalent kVA Ratings

In this section, the kVA ratings of the polyphase transformer, the ZSBT and the IPT for the proposed delta-connected 12-pulse system are calculated.

2.4.1 VA Rating of the Polyphase Transformer

The rms current through the winding of k1 (Fig. 9 (c)) is

$$I_{a1} = \sqrt{\frac{2}{3}}\,\frac{1}{2} I_o = 0.4082 I_o \quad (46)$$

The rms rectifier input currents I_{b1}, I_{c1}, I_{a2}, I_{b2} and I_{c2} have the same value as I_{a1} given in equation (46). From the MMF equations of the winding configuration of the polyphase transformer shown in equation (27), the current (i_1) through the long winding of the winding configuration (Fig.3 (b)) is obtained as shown in Fig. 7.

The rms current through the long winding of the winding configuration I_1 is obtained as,

$$I_1 = \frac{k_1}{2\sqrt{3}}\sqrt{\frac{1}{3}}\, I_o = 0.0447 I_o \quad (47)$$

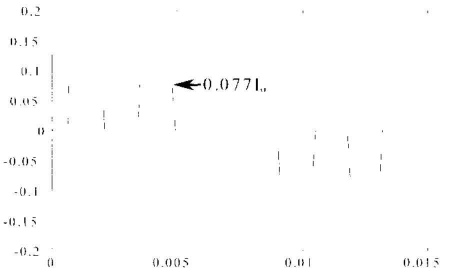


Fig. 7 Current I_1 shown in the figure 3 (b)

The rms voltage of the winding k_1, $V_{a,a1}$, is,

$$V_{a,a1} = k_1 \frac{V_a}{\sqrt{2}} = 0.1106 V_o \quad (48)$$

The rms voltage of the delta connected winding, V_{ab}, is

$$V_{ab} = \frac{\pi}{3\sqrt{2} \times 1.035} V_o = 0.7154 V_o \quad (49)$$

Thus from equations (46) to (49) the equivalent VA rating of the polyphase transformer is calculated using the equation (50).

$$VA_{TR} = \frac{6 I_{a1} V_{a,a1} + 3 I_1 V_{ab}}{2} = 0.1834 P_o \quad (50)$$

where P_o is the output power ($V_o \times I_o$). Thus, the polyphase transformer in the proposed 12-pulse system is rated 18% of the output power, which is 82% smaller than that of the conventional system resulting in drastically reduced cost, weight and volume.

2.4.2 VA Ratings of ZSBT and IPT

From equation (18) we have the rms voltage across the ZSBT given by,

$$V_{ZSBT} = 0.1321 V_o \quad (51)$$

The rms current through the ZSBT as shown in Fig. 9 (d) is given by

$$I_{o1} = I_{o2} = \frac{I_o}{2} \quad (52)$$

Therefore the VA rating of the ZSBT is calculated as follows,

$$VA_{ZSBT} = \frac{V_{ZSBT}}{2}(I_{o1} + I_{o2}) = 0.066 P_o \quad (53)$$

From equation (23) the rms voltage of the IPT, V_m, is given by

$$V_m = 0.0814V_o \tag{54}$$

Substituting equations (52) and (54) into (55), the VA rating of the proposed IPT is obtained as,

$$VA_{IPT} = \frac{1}{2}\left(\frac{V_m}{2}(I_{o1} + I_{o2})\right) = 0.020P_o \tag{55}$$

Obtained VA ratings of the IPT and the ZSBT are $0.02P_o$ and $0.066P_o$ respectively. Therefore the proposed 12-pulse system shown in Fig. 2 results in high performance with much reduced VA components and offers clean power utility interface suitable for powering Switch Mode Power Supplies (SMPS) or AC/DC converter applications.

2.4.3 Design Example

Assuming that output power P_o is 30kW, 3-phase line-to-line voltage V_{LL} is 240V and the load is highly inductive, the output voltage V_o of the proposed rectifier system are calculated by equation (26),

$$V_o = 1.3981V_{LL} = 335.54[V] \tag{56}$$

The output current I_o is given by,

$$I_o = \frac{P_o}{V_o} = 89.41[A] \tag{57}$$

The VA ratings of the components in the proposed system are obtained and listed in Table-1 to Table-3.

Table 1 VA rating of the polyphase transformer

Polyphase transformer	Expression	rms value
Primary winding Current (I_1)	$0.0447I_o$	4.0 [A]
Primary winding Voltage(V_{ab})	$0.7154V_o$	240 [V]
Secondary winding Current (I_{a1})	$0.4082I_o$	36.5 [A]
Secondary winding Voltage ($V_{a,a1}$)	$0.1106V_o$	37.1 [V]
VA rating (VA_{TR})	$0.1834P_o$	5502 [VA]

Table 2 VA rating of the ZSBT

ZSBT	Expression	rms value
Voltage across the ZSBT (V_{ZSBT})	$0.1321V_o$	44.3 [V]
Current through $ZSBT_1$ (I_{o1})	$0.5I_o$	44.7 [A]
VA rating (VA_{ZSBT})	$0.066P_o$	1980 [VA]

Table 3 VA rating of the IPT

IPT	Expression	rms value
Voltage across the IPT (V_m)	$0.0814V_o$	27.3 [V]
Output current (I_{o1} or I_{o2})	$0.5I_o$	44.7 [A]
VA rating (VA_{IPT})	$0.02P_o$	600 [VA]

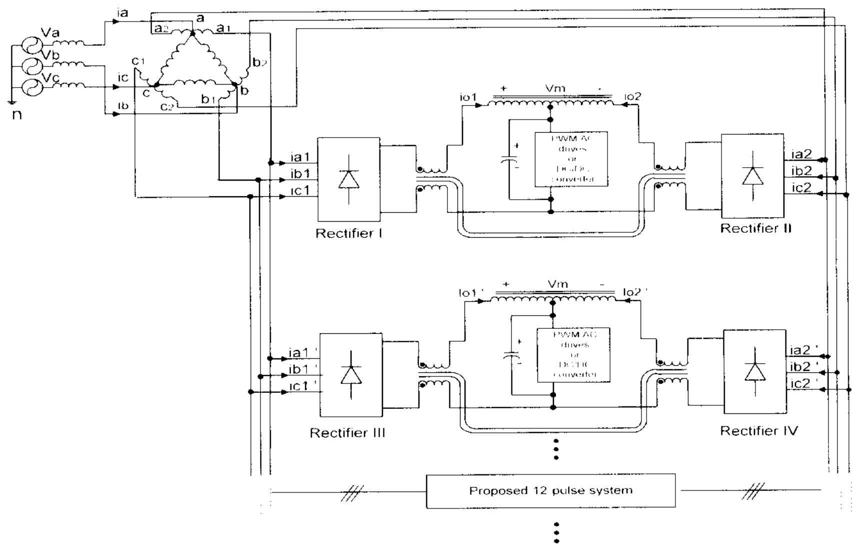


Fig. 8 Distributed structure of the proposed 12-pulse systems

2.5 Other Applications of the Proposed 12-Pulse Rectifier System

The proposed 12-pulse rectifier systems can be applied to parallel operation for separate loads such as telecommunication applications and adjustable speed ac motor drives as shown in Fig. 8. From equation (31), the utility input current becomes,

$$i_a = \bar{i}_{a1} + \bar{i}_{a2} + \frac{k_1}{\sqrt{3}}(\bar{i}_{c2} - \bar{i}_{b2} + \bar{i}_{b1} - \bar{i}_{c1}) \quad (58)$$

where $\bar{i}_{a1} = i_{a1} + i'_{a1} + \cdots$, $\bar{i}_{b1} = i_{b1} + i'_{b1} + \cdots$,

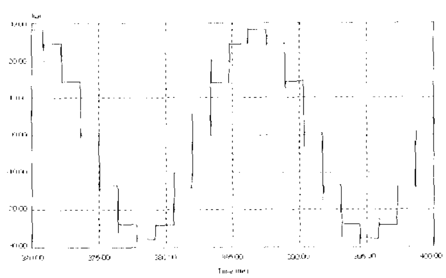
$\bar{i}_{c1} = i_{c1} + i'_{c1} + \cdots$, $\bar{i}_{a2} = i_{a2} + i'_{a2} + \cdots$,

$\bar{i}_{b2} = i_{b2} + i'_{b2} + \cdots$, $\bar{i}_{c2} = i_{c2} + i'_{c2} + \cdots$

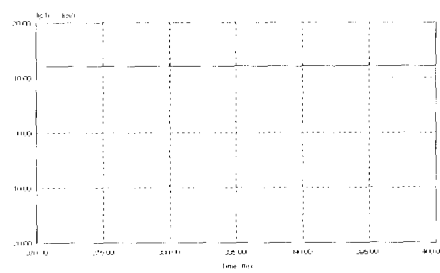
The main rectifier input current ($\bar{i}_{a1}$) is sum of each rectifier input currents ($i_{a1}, i'_{a1}, i''_{a1}, \cdots$). The magnitude of $\bar{i}_{a1}$ depends on each rectifier input currents. However, since the diode commutation angles of the rectifiers (rectifier I and rectifier III) are same with respect to the split three-phase input voltage (V_{a1}, V_{b1}, V_{c1}), the utility input currents maintain the 12-pulse characteristics under varying load conditions. Thus, the proposed 12-pulse rectifier approach can be built on distributed structure regardless of load conditions.

3. SIMULATION RESULTS

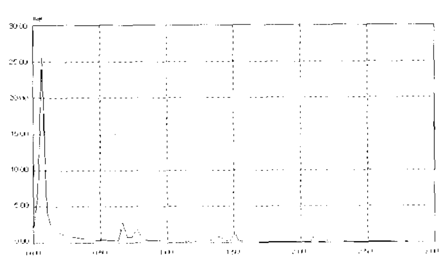
The proposed 12-pulse system shown in Fig.2 was simulated and the results are discussed in this section. The simulated results (a) and (b) show utility input current i_a and its frequency spectrum, respectively. Note that the 5th and 7th harmonics are cancelled in the input currents. Fig. 9 (e) shows the voltage across the ZSBT depicting tripplen components. Rectifier input current i_{a1} is shown in Fig. 9 (c). The simulation results verify the detailed analysis.



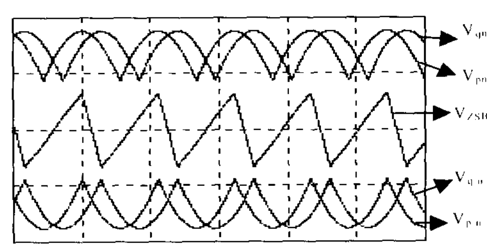
(a) Utility input current i_a



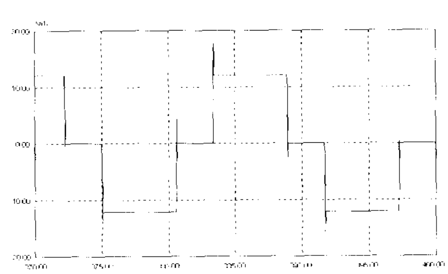
(d) Output current i_{o1} (i_{o2})



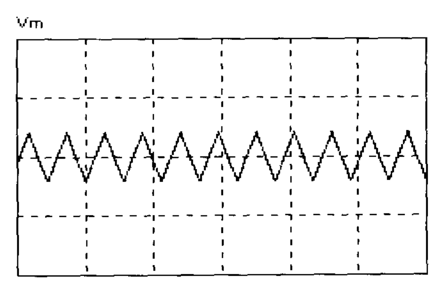
(b) Frequency spectrum of i_a



(e) ZSBT voltage (V_{ZSBT})



(c) Rectifier input current i_{a1}

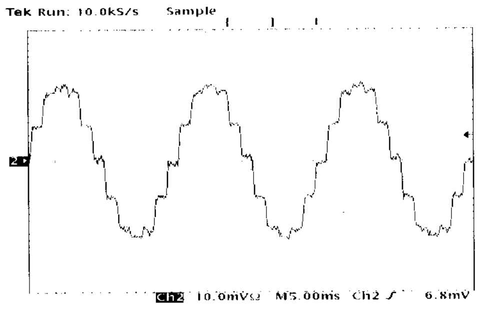


(f) IPT voltage (V_m)

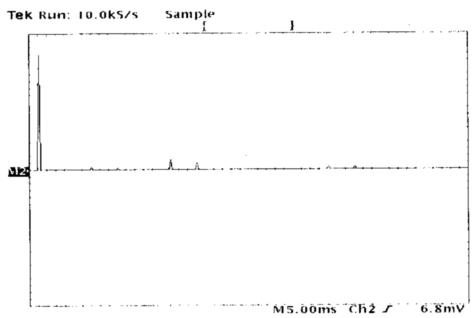
Fig. 9 Simulation results of the proposed 12-pulse rectifier system

4. EXPERIMENTAL RESULTS

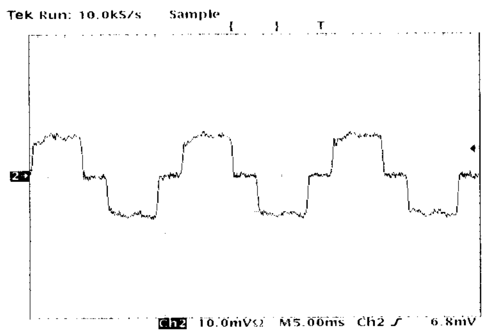
A 208V, 10kVA laboratory prototype system (Fig.2) has been constructed in the laboratory and is connected to supply a bank of dc-link capacitors. A resistive load bank is then used to load the dc link and simulate an inverter fed ac drive load. Fig. 10 (a) to (g) illustrate the results. The utility input current and its frequency spectrum are shown in Fig. 10 (a) and (b), respectively.



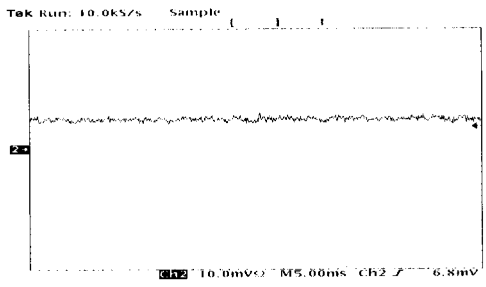
(a) Utility input current, i_a (THD=11.7%)



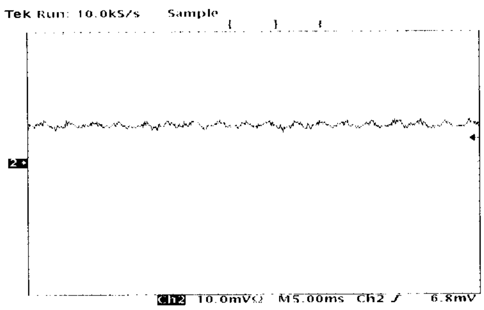
(b) Frequency spectrum of, i_a



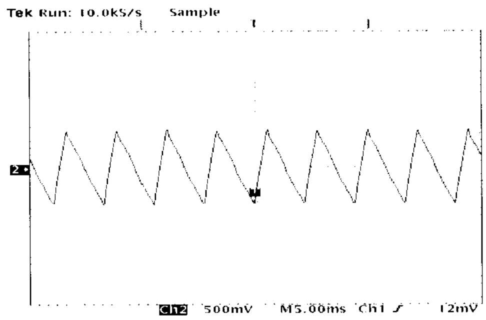
(c) Rectifier input current, i_{a1}



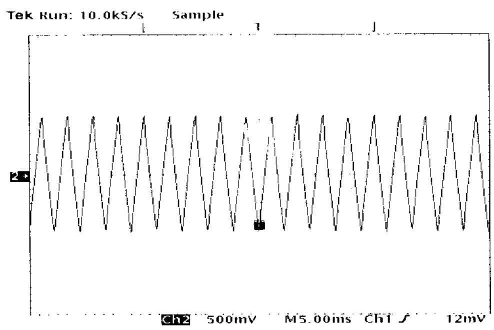
(d) Output current, i_{o1}



(e) Output current, i_{o2}



(f) Voltage across ZSBT, v_{ZSBT1} (or v_{ZSBT2})



(g) Voltage across IPT, v_m

Fig. 10 Experimental results of the proposed 10kVA 12-pulse system (20A/div, 25V/div)

The input current THD of 11.7% was recorded at full load and the 5th and 7th harmonics are cancelled in the utility input line currents. The rectifier-I output current i_{o1} (Fig. 10 (d)) and the rectifier-II output current i_{o2} (Fig. 10 (e)) are nearly identical in magnitude, indicating balanced operation of the two rectifiers. Further, Fig. 10 (c) shows the rectifier-I input current i_{a1} depicting 120° conduction of rectifier bridge. Fig. 10 (f) shows the voltage across the ZSBT. The triangular shaped voltage is primarily 180Hz. Fig. 10 (g) shows the voltage across the IPT, v_m, indicating the operation in the linear region. It is clear that proposed 12-pulse system exhibits superior performance and clean input power characteristics.

5. CONCLUSION

In this paper, a new 12-pulse diode rectifier system with reduced kVA capacities has been presented for harmonic current reduction in high power rectifier utility interface systems, which results in 5th and 7th harmonic cancellation in the utility input line currents. Detailed analysis of the system along with the calculation of VA ratings of components has been described. It has been shown that 12-pulse operation can be realized with a polyphase transformer kVA of $0.18P_o$ [pu] resulting in 82% reduction in weight, volume and cost. The resultant system shows high performance with improved equal output current sharing. Simulation results verified the concept and experimental results were provided from a 208V, 10kVA rectifier system.

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