# Harmonic Reduction of Parallel-Connected Thyristor Rectifiers with an Active Interphase Reactor

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**ABSTRACT** - This paper proposes a harmonic reduction technique of the parallel-connected twelve-pulse thyristor rectifiers. The proposed system is an improvement over the diode rectifier system with an active interphase reactor [2]. In this scheme, a low kVA ( 0.15 $P_o$ (PU) ) active current source injects a triangular current into an interphase reactor of a twelve-pulse thyristor rectifier along the phase delay angle. The current injection results in near sinusoidal input current with less than 1% THD. Detailed analysis of the proposed scheme along with design equations is illustrated. Simulation results verify the concept.

## 1. INTRODUCTION

In several cases, the interface to the electric utility is processed with a three-phase thyristor bridge rectifier. Due to the nonlinear nature of the thyristor, the input line currents have significant harmonics. The discontinuous conduction of the thyristor bridge rectifier results in a high THD and can lead to a number of harmonic problems. The recommended practice, IEEE 519, has evolved to maintain utility power quality at acceptable levels [1]. A number of methods have been proposed to overcome the presented problems [2-8]. One approach is to use a conventional twelve-pulse thyristor rectifier which requires two six-pulse thyristor rectifiers connected via Y-Δ and Y-Y isolation transformers. The operation of the conventional twelve-pulse thyristor rectifier results in the cancellation of the 5th and 7th harmonics in the input utility line currents.

The idea of a triangular current injection for the parallel-connected diode rectifier has been introduced in [2] and the application to the thyristor rectifier was also presented [3]. These systems draw near sinusoidal input currents from the electric utility with less than 1% THD. In the reference [3], the autotransformer was employed to reduce the kVA rating of the phase-shifting transformer. However, this scheme is not suitable for the operation in which the load current changes since the injected current can not be obtained at the undefined region. In this paper, a harmonic reduction technique of the parallel-connected twelve-pulse thyristor rectifiers with the Δ-Y transformer is proposed. Further, kVA rating of the injected current source is thoroughly calculated.

The proposed system is an improvement over the diode rectifier system with an active interphase reactor [2]. In this scheme, a low kVA ( 0.15$P_o$ (PU) ) active current source injects a triangular current into the interphase reactor of a twelve-pulse thyristor rectifier along the phase delay angle. The current injection results in near sinusoidal input current with less than 1% THD. The proposed scheme is also well operated under load-varying condition. The injected current is obtained from the detailed analysis and the simulation results of the proposed rectifier system are presented.

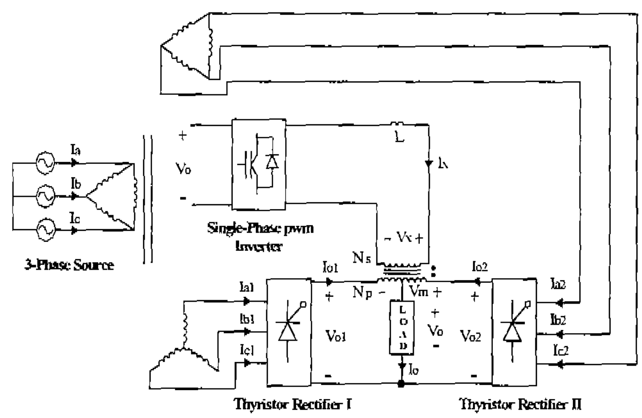



Fig. 1 Circuit diagram of the proposed parallel-connected thyristor rectifier with an active interphase reactor.

## 2. ANALYSIS

Fig. 1 shows the proposed thyristor rectifier with an active interphase reactor. The main transformer has the conventional primary delta and secondary delta-wye winding configurations. The low kVA current source which can be realized by a single-phase PWM inverter is connected to the secondary winding of the interphase reactor. In this section, waveforms are analyzed to determine the relationship between injected current $I_x$ and input currents $I_a$, $I_b$ and $I_c$. With $I_x = 0$, the system operates as a conventional 12-pulse rectifier and input current $I_a$ can be shown to be [2],

$$I_a = I_{a2} + \frac{1}{\sqrt{3}}(I_{a1} - I_{c1}) \tag{1}$$

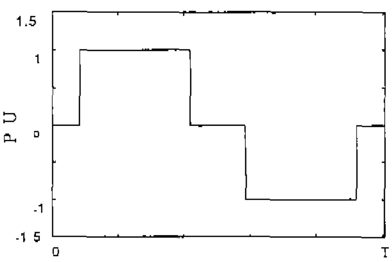



Fig. 2. Switching function $S_{a1}$ for Rectifier I in Fig. 1

Fig. 2 shows switching function $S_{a1}$ for phase "a" of Rectifier-I in Fig. 1. The Fourier series expansion of the switching function $S_{a1}$ is given by,

$$S_{a1}(\omega t,\alpha) = \frac{2\sqrt{3}}{\pi}\left\{\sin\omega t - \frac{1}{5}\sin 5(\omega t-\alpha) - \frac{1}{7}\sin 7(\omega t-\alpha) + \frac{1}{11}\sin 11(\omega t-\alpha) + \frac{1}{13}\sin 13(\omega t-\alpha)\ldots\right\} \tag{2}$$

and for phase "b" and "c", the switching functions can be written as,

$$S_{b1} = S_{a1}\angle -120^\circ \qquad S_{c1} = S_{a1}\angle +120^\circ. \tag{3}$$

Similarly, the switching functions for Rectifier-II in Fig. 1 with a 30 degree phase shift are,

$$S_{a2} = S_{a1}\angle +30^\circ \qquad S_{b2} = S_{b1}\angle +30^\circ \qquad S_{c2} = S_{c1}\angle +30^\circ. \tag{4}$$

The input currents of Rectifier I and II can be expressed in terms of switching functions and rectifier output currents as,

$$\begin{bmatrix} I_{a1} \\ I_{b1} \\ I_{c1} \end{bmatrix} = \begin{bmatrix} S_{a1} \\ S_{b1} \\ S_{c1} \end{bmatrix} I_{o1} \quad \text{and} \quad \begin{bmatrix} I_{a2} \\ I_{b2} \\ I_{c2} \end{bmatrix} = \begin{bmatrix} S_{a2} \\ S_{b2} \\ S_{c2} \end{bmatrix} I_{o2} \tag{5}$$

An active current $I_x$ is now injected into the secondary winding of the interphase reactor as shown in Fig. 1. Analyzing the MMF relationship of the interphase reactor, we have,

$$\frac{N_p}{2}(I_{o2} - I_{o1}) = N_s I_x \tag{6}$$

where $N_p$ and $N_s$ are the numbers of turns of the primary and the secondary windings of the interphase reactor. The load current $I_o$ is,

$$I_o = I_{o1} + I_{o2} \tag{7}$$

From (6) and (7) we have,

$$I_{o1} = \frac{1}{2}I_o - \frac{N_s}{N_p}I_x \tag{8}$$

$$I_{o2} = \frac{1}{2}I_o + \frac{N_s}{N_p}I_x \tag{9}$$

From eqns. (1), (5), (8) and (9), input current $I_a$ can be obtained by,

$$I_a = \frac{1}{2}I_o S_y + \frac{N_s}{N_p}I_x S_x \tag{10}$$

where

$$S_x(\omega t,\alpha) = S_{a2} + \frac{1}{\sqrt{3}}(S_{c1} - S_{a1}) \qquad S_y(\omega t,\alpha) = S_{a2} + \frac{1}{\sqrt{3}}(S_{a1} - S_{c1}) \tag{11}$$

Equation (10) illustrates the relationship between $I_x$ and input current $I_a$. For input current $I_a$ to be sinusoidal,

$$I_x(\omega t,\alpha) = \frac{N_p(I_{a1} - 0.5 I_o S_y)}{N_s S_x} \tag{12}$$

Note $I_a$ is replaced by $I_{a,1}$ ,where $I_{a,1}$ is the fundamental component of $I_a$ and can be expressed as,

$$I_{a.1}(\omega t,\alpha) = \sqrt{2} I_{a.1.rms} \sin(\omega t - \alpha) \tag{13}$$

Since input power is equal to output power, we have

$$\sqrt{3} V_{LL} I_{a.1.rms} = V_o I_o \tag{14}$$

where $V_{LL}$ is the rms valve of line to line voltage.
The dc output voltage $V_o$ of the rectifier system is given by,

$$V_o = 1.35 V_{LL} \cos\alpha \tag{15}$$

Therefore, rms value of the fundamental component of the input current becomes,

$$I_{a.1.rms} = 0.7794 \cos\alpha \, I_o \tag{16}$$

Hence, equation (12) describes the exact shape of $I_x$ for a given phase angle $\alpha$ and load current $I_o$.

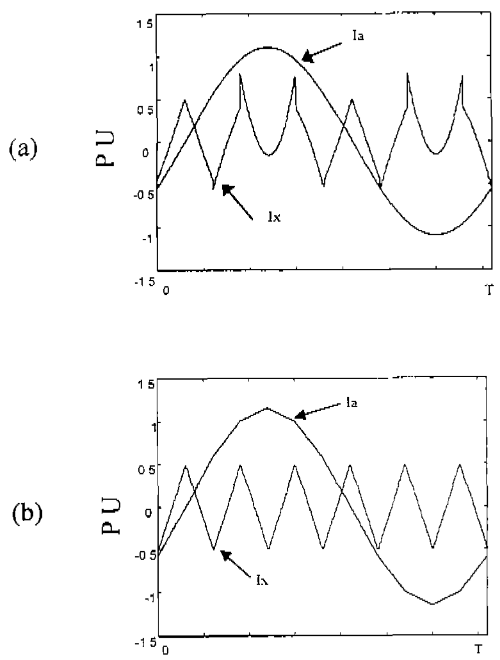



Fig. 3 Calculation results (Assuming $I_o$= 1PU)

(a)Exact injection current $I_x$ and input current $I_a$

(b) Approximated injection current $I_x$ and input current $I_a$

Fig. 3 shows the calculation results of $I_x$ for sinusoidal input current $I_a$. Note that sinusoidal input currents could be drawn with the injection of the exact shape of current $I_x$ into the secondary winding of the interphase reactor as shown in Fig. 3(a). Now, current $I_x$ in Fig. 3(a) is approximated to a triangular wave as shown in Fig. 3(b) and is injected into the secondary winding of the interphase reactor. The input current with the approximated injection current is newly calculated and is shown in Fig. 3(b). Further, the sinusoidal input current can be obtained with the phase delay angle $\alpha$ if injected current $I_x$ is phase shifted and injected according to the phase delay angle $\alpha$.

## 3. KVA RATING OF THE INJECTED CURRENT SOURCE

The rms line to line input voltage $V_{LL}$ and dc output current $I_o$ is assumed to be 1 per unit. The rms value of the voltage across the interphase reactor $V_m$ varies with the phase delay angle $\alpha$ as shown in Fig. 4. The maximum rms value of $V_m$ occurs at $\alpha$ = 90° and its value becomes,

$$V_{m\,rms(max)} = 0.7236 \, V_{LL} \tag{17}$$

The voltage across the interphase reactor secondary winding $V_x$ is given by,

$$V_x = \frac{N_s}{N_p} V_m . \tag{18}$$

Then, from (17) and (18) the rms value of $V_x$ is,

$$V_{x.rms} = 0.7236 \frac{N_s}{N_p} V_{LL} . \tag{19}$$

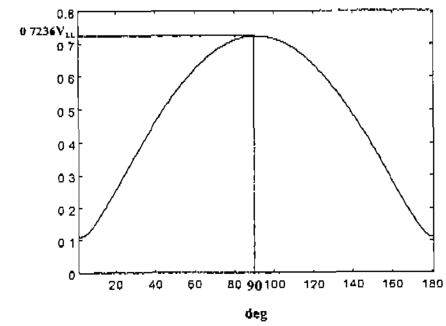



Fig. 4 $V_{m,rms}$ at phase delay angle $\alpha$

From the results in the previous section, the peak value of the current $I_x$ of Fig. 3(a) is 0.5 $I_o$. Therefore, the rms value of $I_x$ with a triangular waveshape is,

$$I_{x,rms} = \frac{0.5}{\sqrt{3}} I_o \frac{N_p}{N_s} = 0.2887 I_o \frac{N_p}{N_s} \qquad (20)$$

Note that the rms value of $I_x$ can be reduced by adjusting turns ratio ($N_p/N_s$) between the primary and the secondary windings of the interphase reactor.

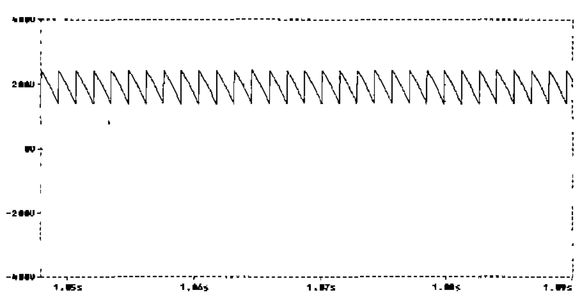
From (19) and (20), the kVA rating of the injected current source, $kVA_{INV}$, can be computed as,

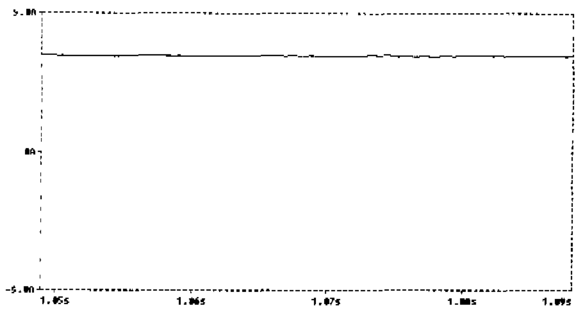
$$kVA_{INV} = V_{x,rms} I_{x,rms} = 0.1547 P_o (PU) \qquad (21)$$

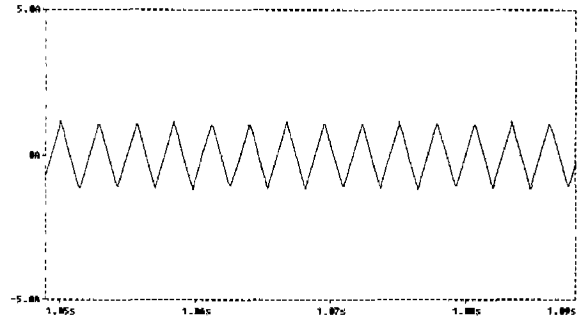
Equation (21) shows that the kVA rating of the injected current source $I_x$ is a small percentage of the output power.

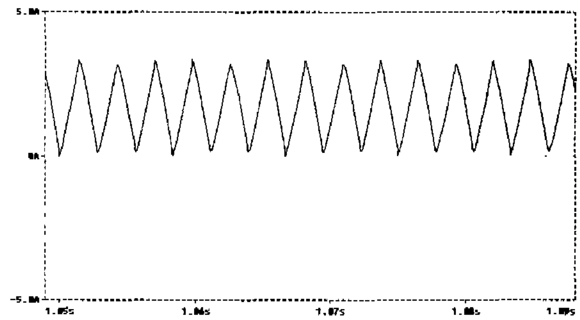
## 4. SIMULATION RESULTS

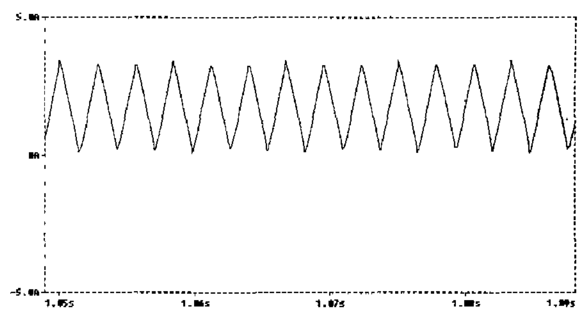
The proposed active interphase reactor approach shown in Fig. 1 is simulated on PSPICE and the results are presented in this section. Fig. 5(a) shows the output voltage waveform at phase delay angle α=45°. Fig. 5(b) shows the output current $I_o$ and Fig. 5(c) shows injection current $I_x$. Generation of the triangular injection current $I_x$ can be accomplished by means of a PWM-controlled single phase inverter. Rectifier output currents $I_{o1}$ and $I_{o2}$ are shown in Fig. 5(d) and (e), respectively. Fig. 5(f) shows the rectifier input current of the rectifier blocks I. Finally, Fig. 5(g) and (h) show input current $I_a$ and FFT of $I_a$. It should be noted that injecting current $I_x$ which is triangular in shape yields near sinusoidal input currents of less than 1% THD.

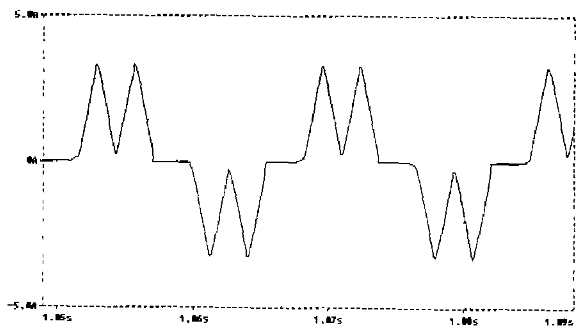

(a) Output voltage $V_o$


(b) Output current $I_o$

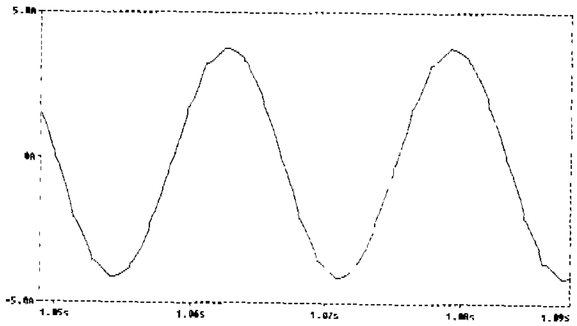

(c) Injected current $I_x$


(d) Rectifier output current $I_{o1}$

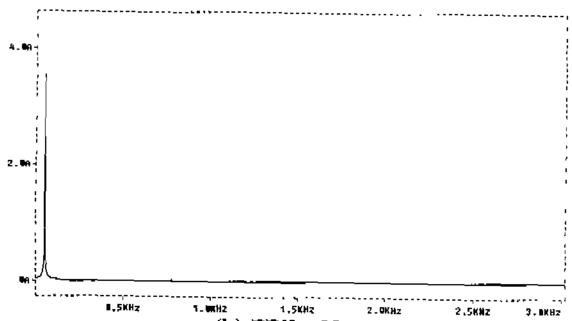

(e) Rectifier output current $I_{o2}$



(f) Rectifier Input current $I_{a1}$



(g) Input current $I_a$



(h) FFT of $I_a$

Fig. 5 Simulation results of the proposed Scheme ($\alpha$=45°)

## 5. CONCLUSION

In this paper a new active interphase reactor for parallel-connected thyristor rectifiers has been proposed. It has been shown that by injecting a low kVA ( 0.15 $P_o$ (PU) ) triangular shaped current $I_x$ into the interphase reactor of the rectifier system near sinusoidal input currents with less than 1% THD could be obtained. Further, the sinusoidal input current could be obtained with the phase delay angle $\alpha$ if injected current $I_x$ is phase s(a) Output voltage $V_o$ hifted and injected according to the phase delay angle $\alpha$. The kVA rating of the injected current source has been thoroughly calculated. Simulation results have been shown to verify the proposed concepts.

## 6. REFERENCES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