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Harmonic Mitigation in Transformers of Twelve-Pulse Rectifier Using Active Filter

Mohammad Rubaiyat Tanvir Hossain, Muhammad Quamruzzaman

Department of Electrical and Electronic Engineering
Chittagong University of Engineering and Technology, Chittagong-4349
E-mail: mrth94@yahoo.com, qzaman359@yahoo.com

Abstract – Researchers proposed several techniques to reduce the harmonics present in the input current of 12-pulse rectifier. But the transformers used in the rectifier contain more low order harmonics in their input currents. In this paper a novel active filtering method for input current wave shaping of the transformers used in a 12-pulse rectifier is proposed. With the proposed method both the rectifier and transformers are shown to draw near sinusoidal input currents from the utility. This active filtering technique uses high switching frequency PWM Boost converter that shapes the input currents by eliminating high frequency harmonic components with the aid of small size LC filters. The size of the LC filters is reduced to a considerable extent with the proposed technique. Detailed design and simulation results are presented to show the effectiveness of the proposed method.

I. Introduction

The advances in the power semiconductor devices have led to the increase in the use of power-electronic converters in various applications such as heating, lighting, ventilating and air conditioning applications, large rated dc drives and ac drives, adjustable speed drives (ASDs), HVDC systems, in process technology such as electroplating, welding units etc., battery charging for electric vehicles, power supplies for telecommunication systems etc [1-4]. And many of these use ac to dc conversion by various rectifiers. Rectifiers are non-linear circuit elements and generate harmonic currents. The non-sinusoidal harmonic currents drawn by the rectifiers are injected into the ac power lines /transformers /source causing a number of problems for the power distribution network and for other electrical systems in the vicinity of the rectifier deteriorating the power quality at the point of common coupling (PCC), thereby affecting the nearby consumers [5-7]. Consequently, design and development of rectifiers with improved waveforms has gained importance for stringent power quality regulation and strict limit on total harmonic distortion (THD) of input current placed by standards such as IEC 1000-3-2 and IEEE 519-1992 [8-10]. Among various methods, the most rugged, reliable and cost-effective solution is to use multi-pulse methods such as 12-pulse rectifier [11, 12]. The essence of these methods is to use multiple converters, which draw currents in a phase-staggered manner, resulting in the cancellation of certain harmonics. 12-pulse rectifiers are widely used in mid- and high-power applications such as large AC or DC drives, HVDC systems to achieve low input current harmonics [12, 13]. However, the 12-pulse rectifier input currents do not meet IEEE 519 harmonic standard without additional filtering [14, 15].Table 1 shows the harmonic components of supply current of a typical 12-pulse rectifier.

Table 1 Harmonic content of a typical 12 pulse rectifier

	12 pulse rectifier load	IEEE-519 Std.
5^{th}	3% - 6%	5.6%
7^{th}	2% - 6%	5.6%
11^{th}	5% - 9%	2.8%
13^{th}	3% - 8%	2.8%
THD	7.5% - 14.2%	7.0%

Also, the individual transformer windings carry non-sinusoidal currents containing large low order harmonics requiring over sizing of these transformers so that transformer windings are not overheated for a certain load. Harmonic filtering is thus needed for 12-pulse rectifier-utility interface to meet IEEE-519 harmonic current limits [14-16].

Several approaches were proposed to reduce input current harmonics of twelve-pulse-rectifiers. Dominant Harmonic Active Filter (DHAF) based on square-wave inverters switching at 5^{th} and 7^{th} harmonic frequencies, which are transformer coupled in series with 11^{th} and 13^{th} harmonic passive filters respectively is one method proposed to cost-effectively meet IEEE 519 harmonic current limits for 12 pulse rectifier loads [15]. Ref. [16] has proposed to eliminate harmonics drawn by a twelve-pulse rectifier through modulation of the dc bus. In addition to the increased component count, disadvantages of the proposed method include higher ripple current in the bridges and requirement of a controller for the modulator. Some approaches [17-20] have been found using and modifying inter-phase reactor results in near sinusoidal utility line currents. But the use of an inter-phase reactor is generally bulky and difficult to design. Autotransformer- based 12-pulse ac-dc converters have been reported [21- 25] for reducing the total harmonic distortion (THD) of the ac mains current, but the high dclink voltage, requiring inter-phase transformers and impedance-matching inductors, resulting in increased complexity and cost.

In this paper an active filtering scheme has been proposed to reduce the total harmonic distortion (THD) of input currents drawn by the transformers of a twelve-pulse rectifier. The Active filtering technique uses high switching frequency PWM Boost converter that shapes the input and transformer currents by eliminating high frequency harmonic components with small size filter. This technique has been used in single-phase and three-phase conventional rectifiers so far. No mention has been found in literature about the technique being used in 12-pulse rectifier. Also filter design has been done to eliminate the high frequency components in the current, which appears as a result of high frequency switching of the Boost converter stage.

II. Twelve-pulse AC-DC Rectifier

The schematic diagram of twelve-pulse rectifier is shown in Fig.1. The 12-pulse rectifier's input circuit consists of two six-pulse rectifiers, displaced by 30 electrical degrees, operating in series. A wye-wye and a delta-wye transformer have been used to give the necessary phase shift to produce the desired twelve-pulse output voltage and to cancel out the low-order harmonics. The turns-ratio of the wye-wye and delta-wye transformers are purposely chosen 1:1 and √3:1 respectively so that the peak output voltages of each transformer secondary are equal.

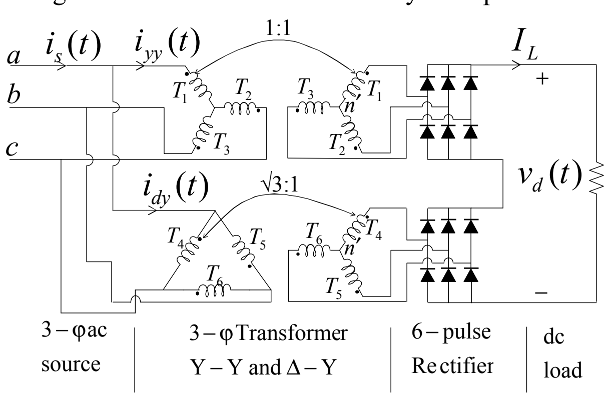

Fig. 1 Schematic diagram of a Twelve-pulse rectifier circuit.

The input currents i_{yy} and i_{dy} of wye-wye and delta-wye transformers respectively, as shown in Fig. 2 (a) & (b) are not sinusoids and have the following harmonic contents,

$$i_{yy}(t)=\frac{2\sqrt{3}}{\pi}I_L(\cos\omega t-\frac{1}{5}\cos5\omega t+\frac{1}{7}\cos7\omega t-\frac{1}{11}\cos11\omega t+\cdots$$

$$i_{dy}(t)=\frac{2\sqrt{3}}{\pi}I_L(\cos\omega t+\frac{1}{5}\cos5\omega t-\frac{1}{7}\cos7\omega t-\frac{1}{11}\cos11\omega t+\cdots$$

The resultant *ac* line current, i_S, as shown in Fig. 2(c), is given by the sum of the two Fourier series of the input currents of the star connected and delta connected transformers

$$i_S(t)=i_{yy}(t)+i_{dy}(t)$$

$$=2\left(\frac{2\sqrt{3}}{\pi}\right)I_L(\cos\omega t-\frac{1}{11}\cos11\omega t+\frac{1}{13}\cos13\omega t-\frac{1}{23}\cos23\omega t+\cdots$$

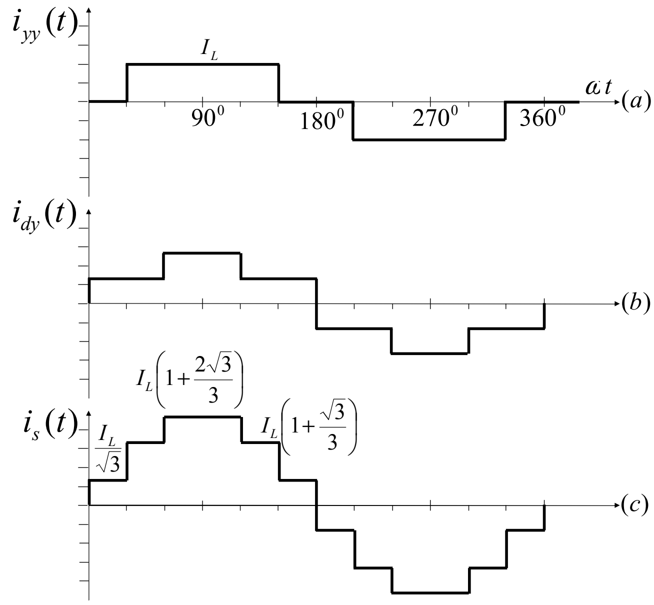

Fig. 2 Current waveforms of 12-pulse rectifier.

It is noted that the individual transformer windings of the 12-pulse rectifier circuit carry non-sinusoidal currents containing large low order harmonics such as 5th, 7th etc. This requires over sizing of these transformers so that transformer windings are not overheated for a certain load. In the resultant input *ac* current the 5th, 7th, 17th, 19th, etc. harmonics are eliminated and it contains 1st, 11th, 13th, 23rd, 25th, etc. harmonics. Consequently, the input line current for the twelve-pulse rectifier is close to sinusoidal waveform. However, 12 pulse rectifier front ends do not meet IEEE-519 harmonic standard without additional filtering. Thus filtering scheme is required to improve the performance of the twelve-pulse rectifier circuit.

III. Proposed Active Filtering Scheme

Fig. 3 shows the schematic diagram of the proposed active filtering scheme for the twelve-pulse rectifier configuration. In the proposed method a high switching frequency (5 KHz) PWM Boost converter is used at the output of the two six pulse rectifiers with ac LC filters at the 6-pulse rectifier inputs for reducing the total harmonic distortion of the input current and the transformer currents. The boost switch is turned on at constant frequency. A dc *L-C* filter is added at the output side in order to reduce the ripple content of the output voltage.

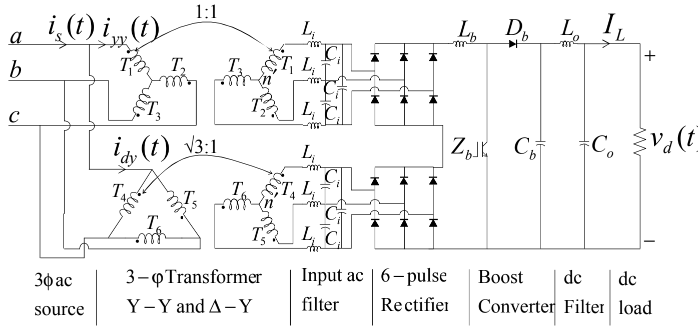

Fig. 3 Proposed active filtering scheme for 12-pulse rectifier configuration.

During the period when the boost switch is turned on, a symmetrical short circuit occurs at the rectifier input through the rectifier diodes, the boost inductor and the boost switch. Consequently the phase currents build up linearly at a rate determined by the input source voltages and the boost inductor, independently of each other, and the magnitude is proportional to the respective phase voltage amplitude. This means that the positive phase voltages cause positive currents through the upper diodes of each 6-pulse rectifier, which return as negative currents through the lower diodes that are caused by the negative phase voltages.

Again when the boost switch is turned off, the phase current through the boost inductor flows to the output capacitor decreases linearly at a rate determined by the input voltage, output dc voltage and the inductor. The input currents in all three phases contain the fundamental (50 Hz) component and a band of high frequency unwanted components centered around the PWM switching frequency of the boost switch. The discontinuous phase current pulses at high PWM frequency with the sinusoidal locus of the peak values can be filtered with a small *LC* filter to obtain a sinusoidal average current ideally.

A. PWM module design

Fig. 4 shows the schematic diagram of the PWM module which has been used to generate gating signals for switching the boost converter switch at varying duty cycles in order to enhance the continuity of the input current by providing it an alternate path through closing of the switch. The PWM module mainly consists of an opamp, an opto-coupler and BJT. The gate pulses are generated by comparing a saw-tooth wave with a reference dc voltage. Changing the reference voltage changes the duty cycle. The opto-coupler is used to provide necessary ground isolation between the PWM module and the switch while producing the pulses. The BJT amplifier is connected for increasing the voltage level at about 10 volts to drive the switch.

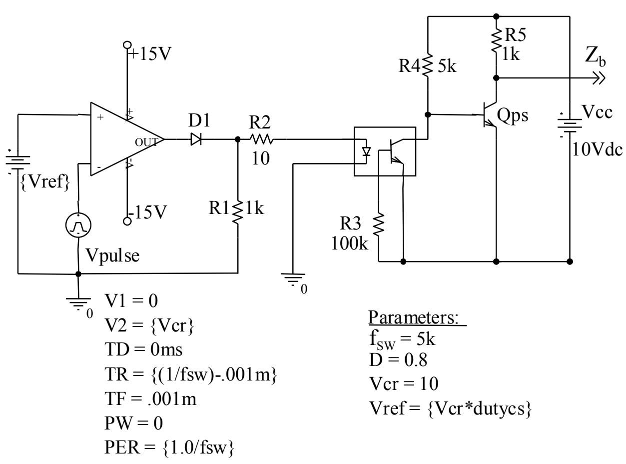

Fig. 4 Schematic diagram of PWM module for Active Filtering Scheme.

B. Output Filter design

A simple dc *LC* filter is used to reduce the 12-pulse ripple content of the output voltage of 12-pulse rectifier. Considering only the harmonic components, the equivalent circuit of rectifier with dc *LC* filter can be found as shown in Fig. 5.

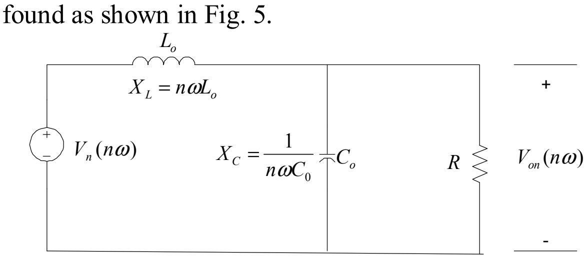

Fig. 5 Equivalent circuit for voltage harmonics.

The amount of reduction in the ripple voltage can be estimated as

$$\frac{V_{on}}{V_n} = \left| \frac{1}{1-(2\pi f_r)^2 L_o C_o} \right|$$

Where V_n is the ripple voltage before filtering, V_{on} is the ripple voltage after filtering, and f_r is the ripple frequency. Considering the ripple voltage to be reduced to 1% after filtering, the L-C constant can be found as $L_o C_o = 6.97\times10^{-6}$. Again, for the *n*th harmonic ripple current to pass through the filter capacitor, the capacitance value should be so chosen that the load impedance must be much greater than that of the capacitor. That is, $R >> \frac{1}{2\pi f_r C_o}$. Considering a dc load of 750Ω if $C_o = 1000\mu F$, the value of L_o is found as $6.97mH \approx 7mH$.

C. Input Filter design

To find the values of an *LC* input filter to limit the amount of input ripple current, considering only the harmonic components, the equivalent circuit per phase for the *n*th harmonic component of the rectifier system is given in Fig. 6.

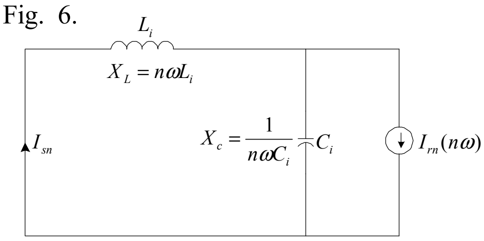

Fig. 6 Equivalent circuit for harmonic current.

Due to active filtering action all three input ac currents consist of the fundamental (50 Hz) component and a band of high frequency unwanted components at $f_{sw} - f_i = 4.95KHz$ and $f_{sw} + f_i = 5.05KHz$ centered around the PWM switching frequency, $f_{sw} = 5KHz$, where $f_i = 50Hz$ is the supply frequency. To reduce this unwanted high frequency components to 1% at the supply and transformers, the value of filter constant $L_i C_i$ is found as -

$$L_iC_i = \frac{1}{(n\omega)^2}\left[\frac{I_{rn}}{I_{sn}} - 1\right] = \frac{1}{(2\pi \times 4.95\times 10^3)^2}\left[\frac{100}{1} - 1\right] = 10234\times 10^{-9}$$

Where I_{sn} is the rms value of the nth harmonic current appearing in the supply and I_{rn} is the rms value of the nth harmonic current of the rectifier.

Without active filtering action, the 11^{th} order harmonic is considered to be dominant. So to reduce the total harmonic distortion (THD) of the input line current to 1% and thereby reducing the THDs of transformer currents using only passive filter or ac input filter, the value of L_iC_i can be found as $L_iC_i = 6.42\times 10^{-7}$.

IV. Simulation Results

The proposed scheme is simulated using Orcad at different duty cycles. Fig. 7 shows the simulated waveforms of supply and transformer currents of 12-pulse rectifier without filter and Fig. 8 shows those with active filtering scheme under the following conditions:

Input phase voltage (peak value) = 300 V
Input frequency = 50 Hz
Duty cycle, $D = 0.4$
PWM switching frequency = 5 KHz
Input filter inductance = 5 mH
Input filter capacitance = 20 μF
Boost inductance = 1 mH
Boost capacitance = 10 μF
Output filter inductance = 7 mH
Output filter capacitance = 1000 μF

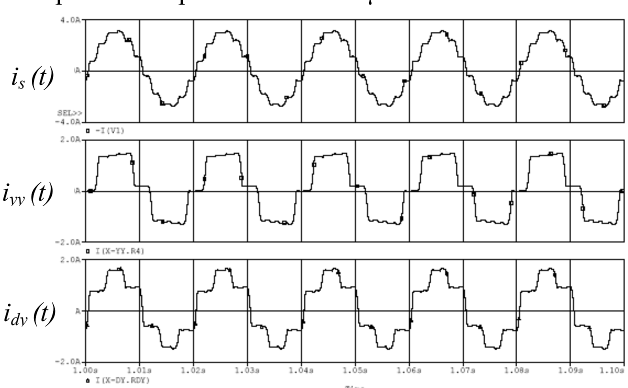

Fig. 7 Input current wave shapes of supply, wye-wye and delta-wye transformer of 12-pulse rectifier without filter.

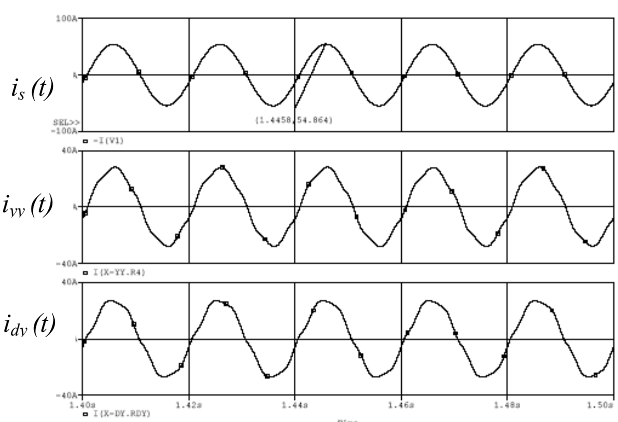

Fig. 8 Input current wave shapes of supply, wye-wye and delta-wye transformer of 12-pulse rectifier with the active filtering scheme.

From the simulation results it is found that with the proposed active filtering scheme the supply current, I_s and the transformer currents I_{yy} and I_{dy} approach sinusoidal wave shape. The total harmonic distortions (THD) of these current waveforms are significantly reduced for smaller input filter elements Li=5mH and Ci=20uF.

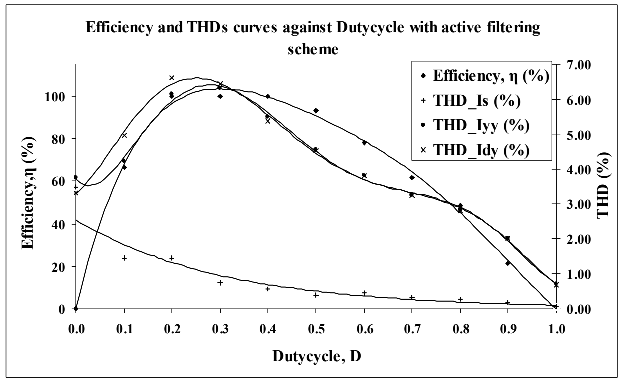

Fig. 9 Efficiency and THD curve against Duty cycle for the 12-pulse rectifier circuit with active filtering scheme.

The curves shown in Fig. 9 summarize the results showing the efficiency and THD curve at different duty cycles. It is found that duty cycle in the range of 0.2 to 0.5 gives the high efficiency (above 90%) for the module and the highest of 100% efficiency is found at 0.2 to 0.4 duty cycle. The THD of input current decreases exponentially as the duty cycle increases and THDs of the transformer currents are about 6% at 0.2 and 0.4 duty cycle and thereafter THD decreases gradually. At the highest efficiency of 100% the THDs of supply current and wye-wye and delta-wye transformer currents have been found 0.55%, 5.48% and 5.37% respectively.

V. Discussion

For harmonic mitigation in transformers of a twelve-pulse rectifier using active filter the performance of both passive and active filtering schemes have been studied through simulation. The simulation results and different performance parameters including total harmonic distortion (THD), efficiency etc. obtained thereof for different filter combinations at different positions have been compared in order to find a better harmonic mitigation method. Fig. 10 shows the THDs (%) of input currents in 12-pulse rectifier without and with different filtering schemes at respective maximum efficiency point.

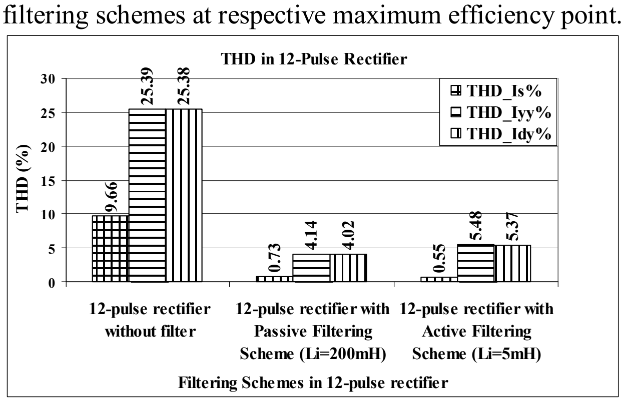

Fig. 10 THDs (%) of 12-pulse rectifier input currents with different filtering schemes at respective maximum efficiency point.

From the bar chart it is found that in 12-pulse rectifier without input-output filter the THDs of the input and transformer currents are about 9%, 25% and 25% respectively which do not meet IEEE-519 harmonic standard. Using passive filters at the rectifier inputs the minimum value of ac input LC filter inductance required is $L_i = 200\,mH$ for fixed $L_iC_i = 6.42\times10^{-7}$ to get the maximum rectifier efficiency of 99.06% and lower total harmonic distortion of the supply current and wye-wye and delta-wye transformer currents of 0.73%, 4.136% and 4.02% respectively. With active filtering scheme using single boost converter with ac input LC filter inductance $L_i = 5mH$ and capacitance, $C_i = 20\mu F$ the THDs of supply current and wye-wye and delta-wye transformer currents have been found 0.55%, 5.48% and 5.37% respectively at the highest efficiency of 100% at 0.4 duty cycle. Thus Incorporating active filtering scheme considerably reduces THDs of input and transformer currents with smaller size of ac input filter compared to passive filtering scheme. The passive filtering scheme would require 40 times higher value of inductance that would be more weightier than that of active filtering scheme to get lower THDs of input currents and highest efficiency of the rectifier circuit.

VI. Conclusion

In this paper an active filtering scheme using high switching frequency PWM Boost converter has been designed to reduce the total harmonic distortion (THD) of input currents drawn by the transformers of a twelve-pulse rectifier. Performance evaluation of the proposed scheme has been carried out and compared with the passive filtering scheme under similar conditions. It is evident that the proposed active wave shaping technique is a simple, cheap and efficient method for harmonic mitigation in transformers of 12-pulse rectifier. However, there are opportunities of extending this work in future to meet other goals. The proposed active filtering scheme may be implemented practically to investigate its actual potential. Investigation can be extended to regulate the output voltage. Investigation may also be made to see how twelve-pulse rectifier with proposed filtering scheme performs under actual operating conditions with unbalanced input line voltages.

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