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A ROBUST HARMONIC REDUCTION SCHEME FOR THREE-PHASE ACTIVE POWER-FACTOR-CORRECTION FOR HIGH POWER APPLICATIONS

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***Abstract* —**This paper proposes a robust three-phase active power-factor-correction (PFC) and harmonic reduction scheme suitable for higher power applications. The proposed system is a unique combination of a low kilovoltampere 12-pulse rectifier system with a single-phase boost PFC scheme to shape the input current to near sinusoidal wave shape. The volt ampere rating of the active PFC converter is 0.05 pu and is not exposed to line transients under varying load conditions. The proposed system is suitable for utility interface of higher power rectifiers employed in power supplies and adjustable-speed drive systems which demand clean input power characteristics in the range of 1–500 kW. The proposed system is rugged and, in the event the active control were to fail, the system reverts to 12-pulse operation with fifth and seventh harmonic cancellation. Analysis and design of the system is simulation results on a 10-kVA prototype are shown.

Keywords: power factor correction, harmonic reduction, rectifier

I. Introduction

Conventional offline power converters with diode – capacitor rectifiers have resulted in distorted input current waveforms with high harmonic contents. To solve these problems, several techniques have been proposed to shape the input current waveform of the power converter. A common approach to improve the power factor is a two stage power conversion approach.

The two stage scheme results in high power factor and fast response output voltage by using two independent controllers and optimized power stages. The main drawbacks of the scheme are its relatively higher cost and larger size resulted from its complicated power stage topology and control circuits, particularly in low power applications.

In order to reduce the cost, the single stage approach, which integrates the PFC stage with a dc/dc converter into one stage, is developed. These integrated Single stage PFC converters usually use a boost converter to achieve PFC in discontinuous current mode (DCM) operation. Usually the DCM operation gives a lower total harmonic distortion (THD) of the input current compared to the continuous current mode

(CCM) operation c voltage source (either signal) is connected in series with the rectified input voltage in order to shape the input current. Another technique based on parallel connection of this dither signal, however, the harmonic content can meet the regulatory standard by a small margin.

To overcome the disadvantages of the single-stage scheme, many converters with input current shaping have been presented, in which a high frequency ac voltage source (dither signal) is connected in series with the rectified input voltage in order to shape the input current.

In Most Power electronics applications, diode rectifiers are commonly used in the front end of a power converter as an interface with the electric utility. The rectifiers are nonlinear in nature and, consequently, generate harmonic currents into the ac power source. The nonlinear operation of the diode rectifiers causes highly distorted input current. The non-sinusoidal shape of the input current drawn by the rectifiers causes a number of problems in the sensitive electronic equipment and in the power distribution network. The distorted input current flowing through the system produces distorted voltages at the point of common coupling (PCC). Thus, the increased harmonic currents result in increasing volt ampere ratings of the utility equipment, such as generators, transmission lines, and transformers. In addition to the inefficient use of electric energy, the discontinuous conduction of the bridge rectifier results in a high total harmonic distortion (THD) in the input lines and can lead to malfunctioning of the sensitive electronic equipment. The recommended practice, IEEE-519, and IEC 1000-3 have evolved to maintain utility power quality at acceptable levels [1]–[3]. In order to meet IEEE-519 and IEC 1000-3, a cost-effective and economical solution to mitigate harmonics generated by power electronic equipment is currently of high interest. One approach is to use three single-phase power-factorcorrected rectifiers in cascade [11]–[13]. The main advantage of this configuration is that a well-known single-phase powerfactor=correction (PFC) technique can be used in three-phase applications. However, this approach suffers from several disadvantages, which include the following: 1) cascading three single-phase PFC circuits requires the use of additional diodes; 2) increased component count; 3) complicated input synchronization

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logic; and 4) higher dc-link voltage due to boost current shaping. At best, input THD of 10% can be achieved [14].

Another approach is to employ a single boost switch in conjunction with a three-phase diode rectifier bridge [15].

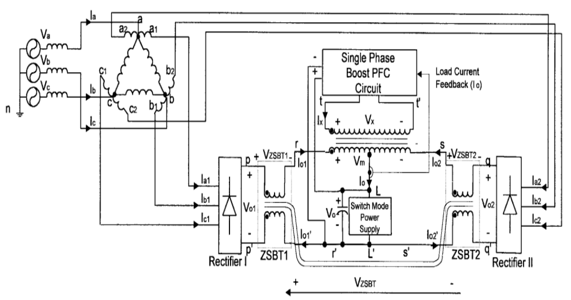


Fig. 1. Circuit diagram. Of the Proposed robust three-phase clean-power rectifier system.

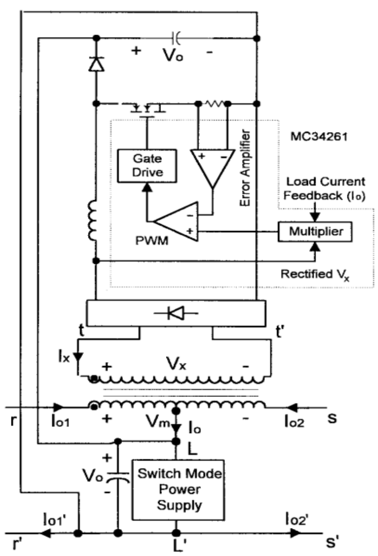


Fig. 2. Proposed robust three-phase clean-power rectifier system. Implementation of the single-phase boost PFC circuit.

II. Proposed System

Fig.1 shows the circuit topology of the proposed rectifier system. The proposed system (Fig.1) combines the unique features of an autotransformer-based 12-pulse rectifier system and a low-cost single-phase boost-type active current-shaping circuitry to achieve clean input power characteristics. An autotransformer is employed to generate 30 phase-shifted voltages to rectifier bridges I and II [16]. Fig. 3 shows the winding configuration of the autotransformer.

This system requires discontinuous operation, resulting in muchhigher dc-bus voltage and high EMI. Both of the above two methods are suitable for 10-kW output power and, hence, not practical in higher power ranges

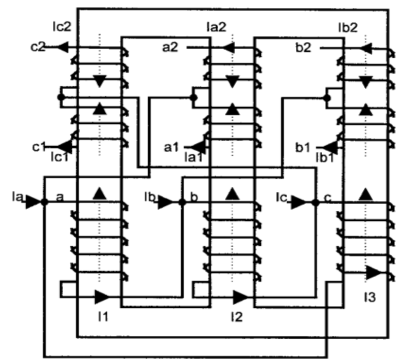


Fig. 3. Reduced kilovoltampere delta-type polyphase autotransformer. (a) Winding configuration.

From the line voltageV_a applied to node "a" (Fig. 3), voltages and are generated due to the interconnection of transformer windings. To achieve 30 phase shift between and is necessary. This arrangement results in low kilovoltamperes, since the autotransformer does not provide isolation. Rectifiers I and II are connected in parallel (Fig. 1) via zero-sequence blocking transformers (ZSBT's) [17] and an active interphase transformer (AIPT) [19]. The purpose of the ZSBT is twofold: 1) to offer high impedance to cross conduction paths between the diodes in rectifiers I and II and 2) offer low impedance and promote independentoperation of rectifier bridges I and II in a parallel-connected non isolated 12-pulse rectifier system. Further, ZSBT's aresymmetrically placed to result in near-equal impedance in the two parallel conduction paths of rectifiers I and II. Power electronic converter loads, such as power supplies (dc/dc converters) and variable-frequency inverters (dc/ac converters) can be connected from the center tap of the AIPT to the negative rail [Fig. 1]. Single-phase boost PFC circuitry is connected across the auxiliary winding of the AIPT [Fig. 1and 2]. The boost converter output is fed back to the dc link. The boost converter is controlled by popular control circuit, such as a Motorola MC34261, to draw a current in phase with the voltage. The auxiliary winding current in the AIPT is then shown to alter the shape of the utility input current to a near-sinusoidal current shape. With the auxiliary winding current set to zero (i.e., boost converter disenabled), the utility input current exhibits 12- pulse characteristics, i.e., fifth and seventh harmonic currents are cancelled. The kilovolt amperes of the boost converter connected across the AIPT is 0.05 pu of the output power, which is low.

III. Analysis

In this section, analysis of the proposed system is presented in detail.

A. Autotransformer Voltage and Current Relationships

Fig. 3 shows the winding configuration and the associated vector diagram of the autotransformer. From Fig. 3, the following equation can be written:

$$V_a = V_{a,p} \sin wt$$
$$V_{a1} = V_{a1,p} \sin(wt + 15°)$$

Where is the line-to-neutral voltage of phase and

$$V_{a1,p} = V_{a,p}\sqrt{1+(k_1)^2} \approx 1.035V_{a,p}$$
$$k_1 = \tan 15° = 0.2679.$$

Also,

$$V_{a1,p} = 1.035\sqrt{\frac{2}{3}}V_{\mathrm{LL}}$$

Where is the rms of the line-to-line voltage. From the autotransformer winding configuration and the following MMF relationship, the input current can be expressed as

$$I_a = I_{a1} + I_{a2} + \frac{k_1}{\sqrt{3}}(I_{c2} - I_{b2} + I_{b1} - I_{c1})$$
$$I_o = I_{o1} + I_{o2}.$$

A detailed analysis of the autotransformer can be found in [16].

B. Rectifier Output Voltage Analysis

As explained in the previous section, the ZSBT's exhibit high impedance to zero-sequence currents and ensure independent operation of rectifier bridges I and II and 120 conduction for each rectifier diode [17].

1) ZSBT: For the purpose of detailed voltage analysis, an equivalent circuit of the proposed system in Fig. 1 is developed and is shown in Fig. 4. The equivalent circuit consists of two positive and negative groups of diodes along with ZSBT and AIPT connections [Fig. 4(a) and (b)].

In the positive group, the cathodes of the diodes D_1,D_3 and $D_5$are at a common potential. 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 [Fig. 4(a)]. Therefore, the diode with its anode at the highest potential will conduct the currentI_{o2},and the rest of the diodes are reverse biased. Similarly, in the negative group [Fig. 4(b)], 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 the conduction sequence of diodes. Further, the voltage across the ZSBT,V_{ZSBT1}, is identical to V_{ZSBT2}, since they are magnetically coupled with each other.

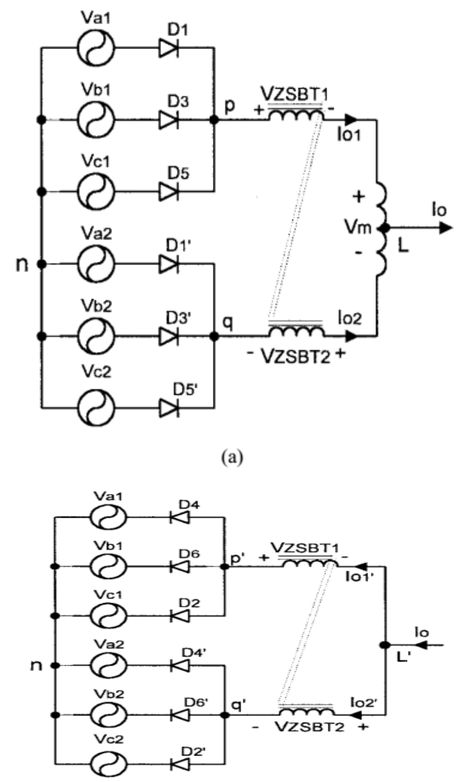
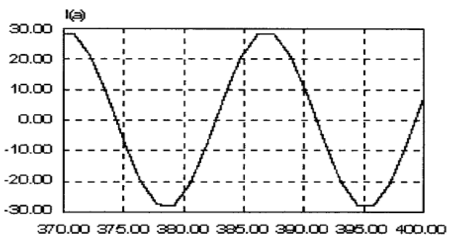


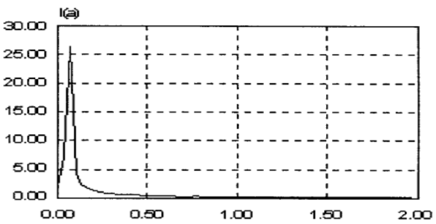
Fig. 4. Equivalent circuit of the dc-side output. (a) Upper side diodes of rectifiers I and II. (b) Lower side diodes of rectifiers I and II.

IV. Simulation Results

The proposed system shown in Fig. 1 has been simulated onthe PSIM simulation program, and the results(N_x/N_m =1)are presented in Figs. 5 and 6. A triangular injection current into the auxiliary winding of the AIPT is shown in Fig. 5(d). Simplifying the injected current I_x to a triangular wave shape yields a near-sinusoidal input current I_a, as shown in Fig. 5(a), and the frequency spectrum of the input current [Fig. 5(b)] demonstrates near-sinusoidal operation in the utility input line currents. Fig. 5(c) shows the respective rectifier input currentI_{a1}. Simulation results are shown in Fig. 6, when the boost PFC circuit fails to inject the active current I_x in the auxiliary winding of the AIPT. Fig.6 (a) demonstrates a 12-pulse operation withthe fifth and seven harmonic cancellations in the utility input line currents when I_x= 0. The dc output voltage to the load is not interrupted. Therefore, the proposed system is very rugged and, in the event the active control were to fail, the system reverts to 12-pulse operation. These results demonstrate the superior characteristics of the proposed system.



(a)



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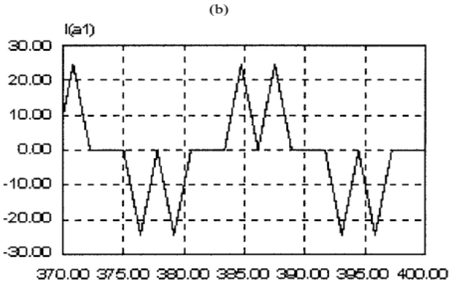
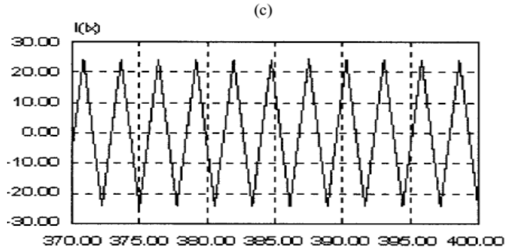
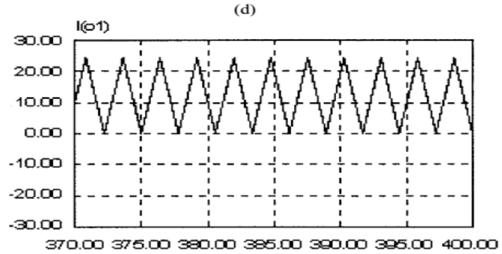


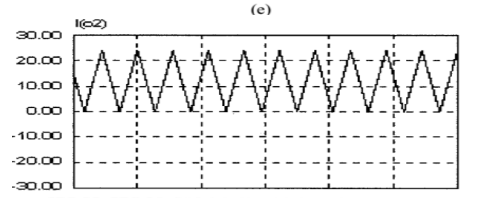
(c)



(d)

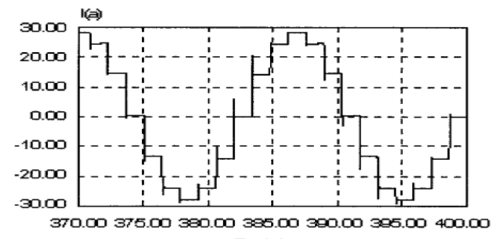


(e)

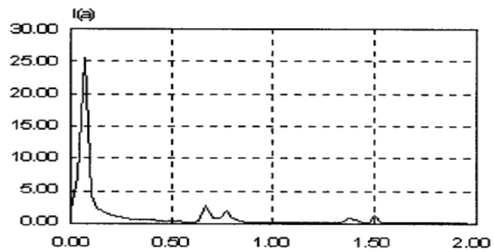


(f)

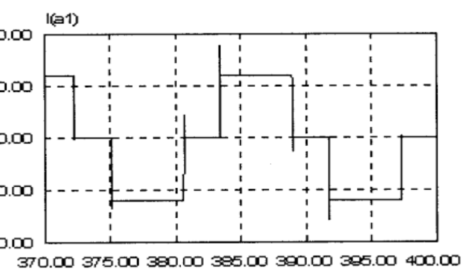
Fig. 5. Simulation results after Ix is injected. (a) Input line current Ia. (b) Frequency spectrum of Ia. (c) Rectifier I input current Ia1. (d) Triangular-shaped injected current Ix. (e) Rectifier I output current Io1. (f) Rectifier II output current Io2.



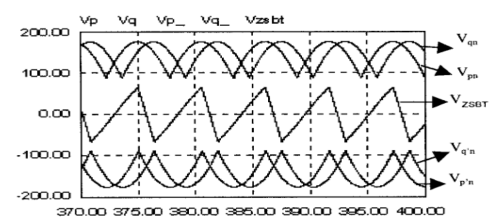
(a)



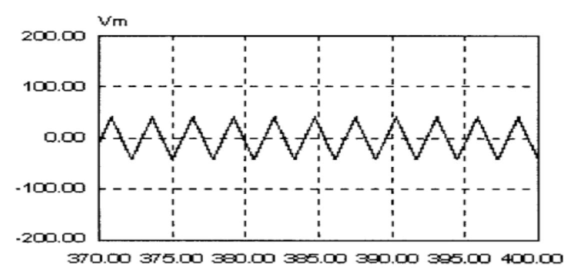
(b)



(c)



(d)



(e)

Fig. 6. Simulation results with Ix = 0. (a) Input line current Ia. (b) Frequency spectrum of Ia. (c) Rectifier I input current Ia1. (d) Vpn; Vqn; Vpn0 ;V 0 qn; and the voltage across the ZSBT, VZSBT. (e) voltage across the AIPT, Vm.

V. Conclusion

In this paper, a robust three-phase active PFC and harmonic reduction scheme has been proposed. The proposed system consists of fewer components with lower kilo volt ampere magnetics. It has been shown that by injecting a low kilo volt ampere active current source into the AIPT, near-sinusoidal input currents with 1% THD can be obtained. Further, the active pulse width modulation (PWM) inverter unit is not directly exposed to line transients. In the event the active PWM control were to fail, the proposed system reverts to 12-pulse operation with fifth and seventh harmonics cancellation in the input utility line current. The resultant system exhibits clean-power characteristics suitable for utility interface of high-power ac motor drives and switch mode power supplies. A detailed analysis of the proposed scheme, along with design equations, have been presented.

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