DESIGN CONSIDERATIONS FOR SIX PULSE AND TWELVE PULSE DIODE RECTIFIER SYSTEMS OPERATING UNDER VOLTAGE UNBALANCE AND PRE-EXISTING VOLTAGE DISTORTION WITH SOME CORRECTIVE MEASURES

D. Rendusara, A. von Jouanne*, P. Enjeti*, D. A. Paice***

*Power Electronics Laboratory**
Department of Electrical Engineering
Texas A&M University
College Station, TX 77843-3128
Tel: (409) 845-7466
Fax: (409) 845-6259

*Paice & Associates Inc.***
114 Rosewood Court
Palm Harbor, FL 34685
Tel: (813) 786-3598
Fax: (813) 781-0601

Abstract *- In this paper design considerations for six pulse and twelve pulse diode rectifier systems operating under utility voltage unbalance and pre-existing harmonic voltage distortion is discussed. For a six pulse diode rectifier system it is shown that voltage unbalance and pre-existing voltage distortion in the utility generates uncharacteristic harmonics in the line currents. The amplitude of these uncharacteristic harmonics are shown to be amplified if the diode rectifier is operating in discontinuous conduction mode. For a twelve pulse diode rectifier system connected in parallel to feed a common dc link via interphase reactor it is shown that a small amount of impedance mismatch, utility voltage unbalance or pre-existing voltage distortion drastically affects the current sharing capability of the rectifier bridges. This in turn generates additional uncharacteristic and characteristic harmonics thereby increasing the THD. In order to mitigate these effects and ensure proper operation of diode rectifiers, specially designed line reactors termed as Harmonic Blocking Reactors (HBR's) are introduced. The analysis and design procedure for the HBR's are discussed. Simulation results illustrate improved performance. Experimental results from a laboratory prototype system show close agreement with theory.*

1. Introduction

Six pulse and twelve pulse uncontrolled diode rectifiers are commonly used as an interphase between the three phase electric utility and power electronic loads such as adjustable speed ac motor drives, dc motor drives, power supplies, induction heating systems, UPS systems, aircraft VSCF systems, and aircraft maintenance 60 Hz / 400 Hz converter systems. Analysis of the effects of three phase uncontrolled bridge rectifiers on the power system can be found in many standard textbooks. However, most of the analyses are conducted with the assumption of a balanced input power supply condition. This condition is not necessarily true in many practical industrial systems, particularly in the presence of other nonlinear loads.

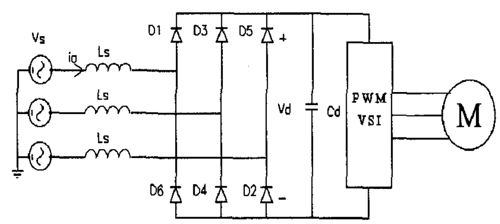


Fig. 1. Three phase six pulse diode bridge rectifier front end.

In order to design more realistic six pulse and twelve pulse diode bridge rectifier systems, particular attention needs to be given to the voltage distortion already present in the electric utilities due to other nonlinear loads and harmonic resonance conditions. In many industrial systems with nonlinear loads, it is not uncommon to measure 1% to 3% voltage unbalance and/or 2.5% to 5% pre-existing 5^{th} and 7^{th} harmonic voltage distortion when a large percentage of loads are nonlinear.

In this paper a detailed analysis of six pulse and twelve pulse rectifier systems is carried out. Input current and output voltage distortion are computed for voltage unbalance and pre-existing voltage distortion. It is shown that for a six pulse rectifier system operating under discontinuous mode such as found in many adjustable speed drive systems in the market today, the presence of small unbalance in the input utility voltage drastically increases the uncharacteristic harmonics in the ac line currents. Additionally the pre-existing 5th and 7th harmonic voltage distortion on a six pulse diode rectifier system increases the level of input current distortion and increases or decreases the average dc output voltage.

In the case of a twelve pulse rectifier system comprised of two six pulse rectifiers in parallel the effects of input voltage unbalance and pre-existing voltage distortion are quite significant. The presence of unbalance and/or pre-existing voltage distortion alters the magnitude of dc-output voltage of the rectifier bridges. It is shown that a change of 1% in the dc output voltage would result in drastic mismatch in current sharing ability of twelve pulse rectifiers. The current sharing ability is further aggravated by mismatches in transformer reactances. This paper includes detailed calculations and evaluates these mismatches. The increase in harmonic current magnitudes as well as the generation of uncharacteristic harmonics is examined. Finally, in order to counter these effects, this paper proposes new Harmonic Blocking Reactors (HBR's) (Fig. 6). The HBR is essentially a shell core construction with three windings on the center limbs. The essential principle of the HBR is that flux generated by the fundamental component of the currents is summed to zero, however, the flux generated by the harmonic currents do not sum to zero thereby resulting in a large impedance for harmonic currents. The concept of HBR has been first introduced in [1] for paralleling two inverter systems. The application of the HBR is shown to create an interdependency between two rectifier bridge currents. With this interdependency it is shown that the two rectifier bridges in a 12-pulse converter share equal currents under supply unbalance/distortion and with transformer leakage impedance mismatches. Experimental results illustrate the drastic improvement in performance with the use of HBR's.

2. Six Pulse Rectifier Front Ends

A three phase bridge rectifier is the preferred choice for high power applications over single phase rectifiers primarily due to its low ripple content in the dc output and higher power handling capability [2]. Fig. 1 shows a typical application of a three phase diode bridge rectifier in a variable speed ac drive system.

Due to the absence of a dc-link inductor, the input current will be highly discontinuous and rich in harmonics, i.e. of 5^{th}, 7^{th}, 11^{th}, 13^{th} , etc. For a three phase diode rectifier with a balanced input voltage source, the frequencies of the harmonic components can be determined by [2]:

$$h = nq \pm 1 \qquad (1)$$

where

h = order of the harmonics
n = 1,2,3,4,...
q = number of pulses of the rectifier system, in this case q = 6.

2.1. Six Pulse Rectifier Analysis Under Utility Unbalance

A set of unbalanced input voltage sources can be defined by eqns. (2) to (4) with the percentage of unbalance defined by eqn. (5),

$$V_{an}(\omega t) = V_{\varphi} \sin(\omega t) \qquad (2)$$

$$V_{bn}(\omega t) = k V_{\varphi} \sin(\omega t - 120) \qquad (3)$$

$$V_{cn}(\omega t) = V_c \sin(\omega t + \theta) \qquad (4)$$

$$\%_{Unbal} = \frac{\max(\,|V_{an} - V_{bn}|, |V_{an} - V_{cn}|, |V_{bn} - V_{cn}|\,)}{V_{an}} \qquad (5)$$

where, k is the percentage magnitude of V_{bn} with respect to V_{an}.

Reference [3] details the analysis of static power converters under unbalance. Specifically, for a diode rectifier as shown in Fig. 1, the absence of a dc link inductor contributes to an increase in input current distortion due to uncharacteristic harmonics. Small amounts of utility voltage unbalance cause uneven conduction of diodes, particularly in discontinuous conduction mode, and a large percentage of uncharacteristic harmonics such as 3rd and 9th are generated. This phenomenon is demonstrated both in simulation (Fig. 3) and experimentally (Fig. 24). Further, Fig. 2 shows the plot of uncharacteristic 3rd harmonic current versus percent unbalance. The y-axis in Fig. 2 is the average 3rd harmonic current in phase a,b and c.

To investigate the effects of different levels of input voltage unbalance under discontinuous conduction mode, simulations in PSpice are carried out and results are plotted in Fig. 2.

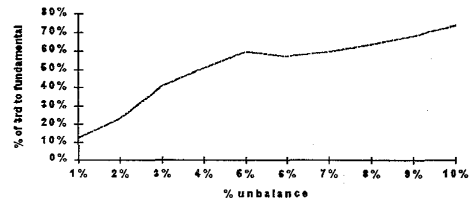
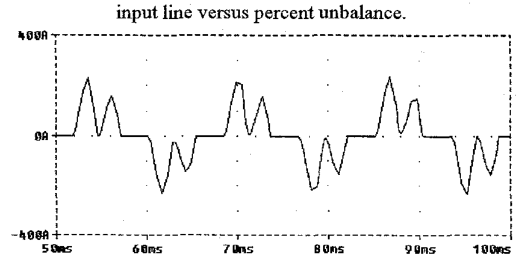
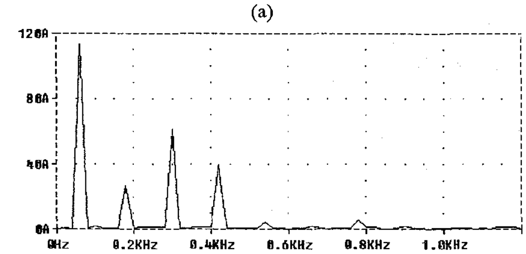


Fig. 2. Average percentage of uncharacteristic 3rd harmonic current in the input line versus percent unbalance.



(a)



(b)

Fig. 3. Input current waveform with 3% input voltage unbalance (a) time (b) frequency domain.

2.2. Six Pulse Rectifier Analysis under Pre-Existing Voltage Distortion

For a six pulse diode bridge rectifier in continuous conduction mode, the variation in the dc output voltage due to pre-existing 5^{th} harmonic can be found by the following procedure:

A set of a balanced input voltages at fundamental frequency can be represented as,

$$V_{an,1}(\omega t) = V_{\varphi} \sin(\omega t) \qquad (6)$$

$$V_{bn,1}(\omega t) = V_{\varphi} \sin(\omega t - \tfrac{2\pi}{3}) \qquad (7)$$

$$V_{cn,1}(\omega t) = V_{\varphi} \sin(\omega t + \tfrac{2\pi}{3}) \qquad (8)$$

Then pre-existing 5^{th} harmonic voltages can be represented as k^{th} percentage of the input voltage and α is the phase angle,

$$V_{an,5}(\omega t) = k V_{\varphi} \sin 5(\omega t + \alpha) \quad (9)$$

$$V_{bn,5}(\omega t) = k V_{\varphi} \sin 5(\omega t - \tfrac{2\pi}{3} + \alpha) \quad (10)$$

$$V_{cn,5}(\omega t) = k V_{\varphi} \sin 5(\omega t + \tfrac{2\pi}{3} + \alpha) \quad (11)$$

In order to calculate the variation in the dc output voltage due to the pre-existing voltage distortion, switching functions $SW_1(\omega t)$, $SW_2(\omega t)$, and $SW_3(\omega t)$ representing the conduction intervals of the six pulse diode bridge rectifier are employed. Then the dc output voltage can be calculated by [3]:

$$\begin{aligned} V_o = {} & SW_1(\omega t)\left\{V_{an,1}(\omega t) + V_{an,5}(\omega t)\right\} \\ & + SW_2(\omega t)\left\{V_{bn,1}(\omega t) + V_{bn,5}(\omega t)\right. \\ & \left. + SW_3(\omega t)\left\{V_{cn,1}(\omega t) + V_{cn,5}(\omega t)\right\}\right. \end{aligned} \quad (12)$$

The dc component in V_o is given as:

$$V_{dc} = \frac{3\sqrt{3}}{\pi} V_{\varphi}(1 - \frac{k}{5}\cos 5\alpha) \quad (13)$$

We can see from eqn. (13), with 3% pre-existing 5^{th} harmonic voltage on the input side, the dc output voltage may vary as much as $\pm 0.6\%$. The calculations shown in eqn. (9) to eqn. (12) can be repeated for pre-existing 7^{th} harmonic voltage and the resulting V_{dc} can be shown to be,

$$V_{dc} = \frac{3\sqrt{3}}{\pi} V_{\varphi}(1 - \frac{k}{5}\cos 5\alpha - \frac{k}{7}\cos 7\alpha) \quad (14)$$

The pre-existing 5^{th}, 7^{th} harmonic voltage distortion therefore can cause small change in the dc output voltage and is insignificant in six pulse rectifier systems. The next section examines the effects on twelve pulse rectifier systems.

3. Twelve Pulse Rectifier Front Ends

Twelve pulse rectifier front ends are common in high power applications for larger sized ac motor drive systems. Two six pulse rectifiers are required and they can be connected in parallel or in series depending on the type of application. In both cases, one rectifier can be connected to the main supply through a Δ-Y transformer and the other is connected via a Δ-Δ transformer. This particular type of transformer interconnection is chosen to provide the necessary phase shift of 30° to achieve twelve pulse operation.

With the 30° phase shift, the utility line current I_A is near sinusoidal in shape and the 5th, 7th harmonic currents cancel. In general, the harmonic components are given by eqn. 1, with q=12.

3.1. Twelve Pulse Rectifier Analysis Under Utility Unbalance

The analysis presented in section 2.1 is repeated for the twelve pulse system shown in Fig. 4. Fig. 5 shows the simulation results which depict the escalation of input current harmonic levels. In particular 5^{th}, 7^{th} harmonic

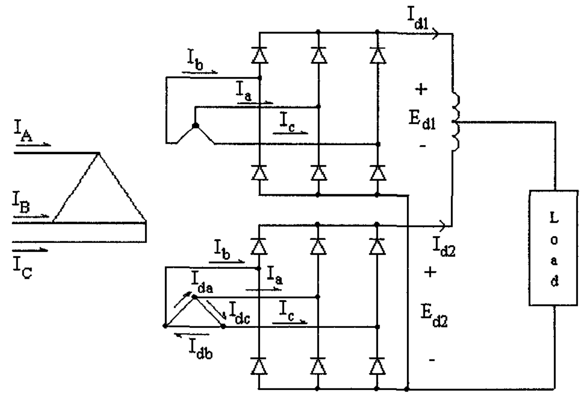


Fig. 4. Twelve pulse rectifier system connected in parallel

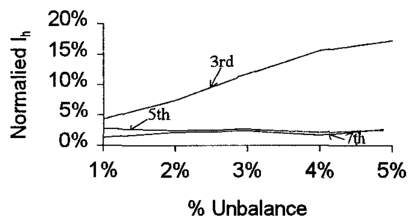


Fig. 5. Effects of electric utility unbalance in twelve pulse rectifier systems connected in parallel

components in the input re-appear. In addition uncharacteristic 3^{rd} harmonic current also appears in the input current. Fig. 5 shows even small amounts of unbalance generates unacceptable levels of line current harmonics.

3.2 Twelve Pulse Rectifier Analysis under Pre-Existing Voltage Distortion

In the case of a twelve pulse rectifier system comprising two six pulse rectifiers in parallel (Fig. 4), small variations in the dc output voltage of each individual six pulse bridge rectifiers has a significant effect on the current sharing. The presence of pre-existing voltage distortion alters the magnitude of the dc output voltage of the rectifier bridges. A change of 1% in the dc output voltage can result in 50% mismatch in current sharing capability. This causes one bridge to have more current stress than the other.

Fig. 6 shows the current sharing between the diode rectifier bridges under 5% pre-existing 5^{th} harmonic distortion. We can see that the output current I_{d1} is more than twice the output current I_{d2}. This drastic mismatch in current sharing contributes to increased stress on one bridge. Further, mismatch in current sharing also nullifies the cancellation of 5^{th}, 7^{th} harmonic components. The overall effect is inefficient performance. The current sharing ability is further aggravated by possible mismatches in the transformer reactances and unequal diode forward voltage drops. For this reason one must consider to design bridge rectifiers with ratings twice the normal requirements as well as introduce methods to prevent saturation of interphase reactors (i.e. introduce an air gap). In order to mitigate these effects, a new harmonic blocking reactor is discussed in the next section.

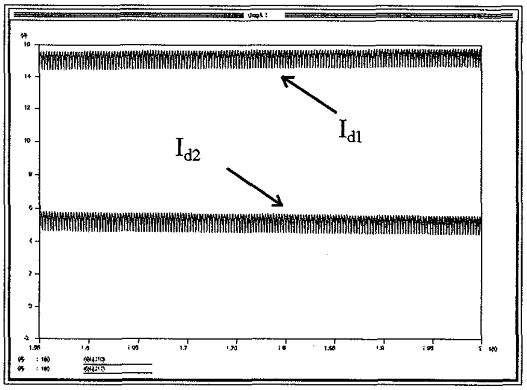


Fig. 6. Current sharing under 5% pre-existing 5th harmonic distortion.

4. Application of Harmonic Blocking Reactor

In order to counter the effects of unbalance and voltage distortion in twelve pulse rectifier systems, a new harmonic blocking reactor (HBR) is proposed (Fig. 7). The essential principle of the HBR is that flux generated by the fundamental component of the currents is summed to zero, however, the flux generated by the harmonic currents do not sum to zero thereby resulting in a large impedance for harmonic currents. The concept of HBR's has been first introduced in [1] for paralleling two inverter systems. However, in this paper the use of HBR's to effectively block harmonic currents and improve current sharing is demonstrated with considerable success.

4.1 Flux Cancellation Analysis

Fig. 7 shows the winding arrangements of a harmonic blocking reactor (HBR). The HBR is essentially a shell core construction with three windings on the central limb. The essential principle of the HBR is that the flux generated by the fundamental component of the currents $I_1^{'}$, $I_1^{''}$, and $I_3^{''}$ is summed to zero, however, the flux generated by the harmonic currents (such as 5^{th} and 7^{th}) in $I_1^{'}$, $I_1^{''}$, and $I_3^{''}$ do not sum to zero thereby resulting in a large impedance for the harmonic currents only, and near zero impedance for the fundamental currents.

Conceptual application of three HBR devices in a twelve pulse system is shown in Fig. 8. With the connection shown in Fig. 8, the HBR essentially has zero impedance for 60 Hz currents and high impedance for certain harmonic currents thus providing further attenuation of unwanted harmonic components.

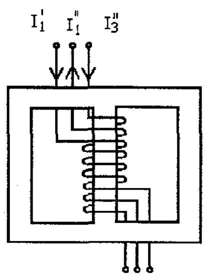


Fig. 7 Harmonic Blocking Reactor

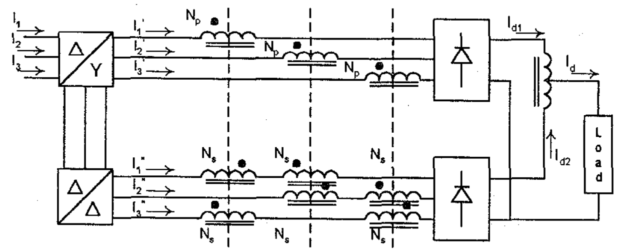


Fig. 8. Interconnection of HBR on twelve pulse systems

The flux cancellation process in the reactor core can be described in the vector diagram of Fig. 9. As we can see in Fig. 8, currents $I_1^{'}$, $I_1^{''}$, and $I_3^{''}$ are coupled together on one HBR core. The mmf equation for the core is given by,

$$\text{Total mmf} = N_1 I_1^{'} - N_2 I_1^{''} + N_3 I_3^{''} \qquad (15)$$

From the above equation, a combination of turns ratios N_1, N_2, and N_3 which result in zero mmf for 60Hz current, can be determined. The same combination of N_1, N_2, N_3 also will result in a large value of mmf generated by 5^{th}, 7^{th} harmonic currents in $I_1^{'}$, $I_1^{''}$, and $I_3^{''}$. Using this criteria and from Fig. 9 we have:

$$\frac{N_1}{N_2} = \sqrt{3},$$

and $N_2 = N_3$

Therefore set $N_1 = N_p$ and $N_2 = N_3 = N_s$.

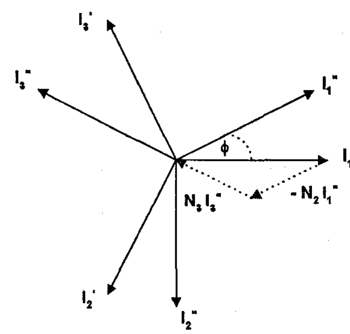


Fig. 9. Vector diagram showing flux cancellation of fundamental ampere-turns

A more important role of HBR's is to create an interdependency between the two rectifier bridge currents which are displaced by 30 degrees. That is the two sets of currents $I_1^{'}$ and $I_1^{''}, I_3^{''}$ are interdependent on each other since they are coupled via an HBR (see Fig. 8). With this interdependency it is shown experimentally in Section 4.3 that the two rectifier bridges in a twelve pulse converter share equal currents under supply unbalance/distortion and with transformer leakage impedance mismatches.

4.2 Simulation Results

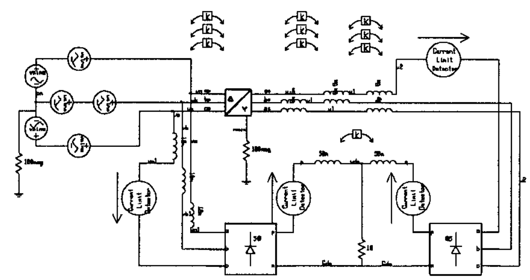


Fig. 10. Circuit model in SABER to simulate application of HBR

The twelve pulse rectifier with HBR application shown in Fig. 10 is simulated on SABER. 5% of 5^{th} harmonic pre-existing voltage distortion is introduced in the input supply. Several simulations were carried out on SABER and the results are discussed in this section. Fig. 11 and Fig. 12 show the two output currents I_{d2} and I_{d1} via the interphase reactor on the dc side. Comparing Fig. 6 with Fig. 11 and 12 it is clear that the HBR contributes to equal dc current sharing between the rectifier bridge under non ideal utility input conditions. Fig. 13 and Fig. 14 show the input current and its FFT.

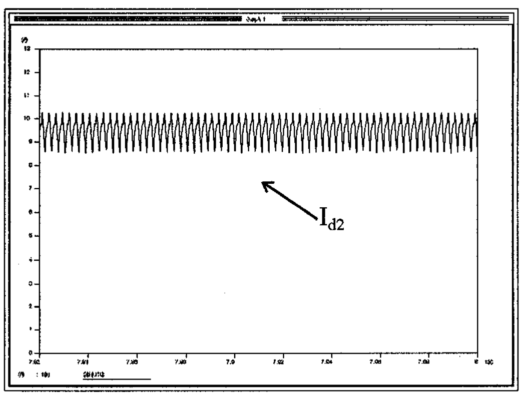


Fig. 11 Output current I_{d2} of twelve pulse diode rectifier (Fig. 8) with 5% pre-existing 5^{th} harmonic voltage.

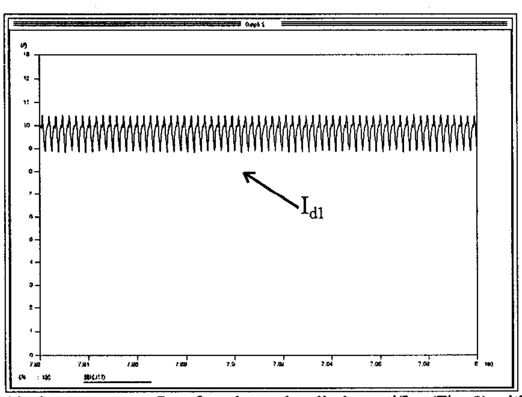


Fig. 12. Output current I_{d1} of twelve pulse diode rectifier (Fig. 8) with 5% pre-existing 5^{th} harmonic voltage.

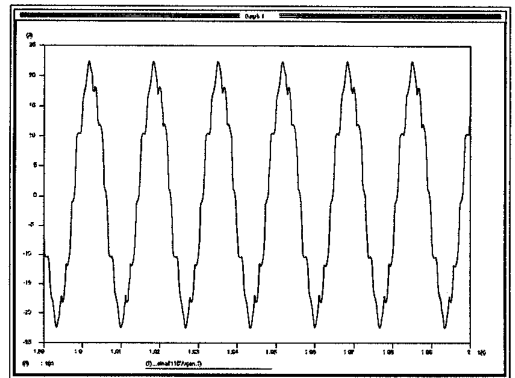


Fig. 13. Input current waveform I_1 with 5% pre-existing 5^{th} harmonic voltage with application of HBR.

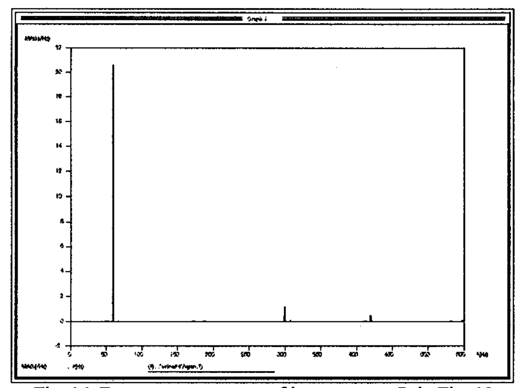


Fig. 14. Frequency spectrum of input current I_1 in Fig. 13. (5% pre-existing 5^{th} harmonic voltage with application of HBR)

4.3 Experimental Results

A 10 kVA, 208V, 60Hz twelve pulse (parallel connected) laboratory prototype rectifier system was constructed with a Δ-Y, Δ-Δ isolation transformer and an interphase reactor as shown in Fig. 8. Fig. 15 shows the resulting dc current sharing without the proposed HBR's under balanced conditions. Fig. 15 illustrates the mismatch in the dc current sharing between the two rectifier bridges. The unequal current sharing under balanced conditions can be attributed to transformer leakage reactance and interphase reactor mismatches. Fig. 16 shows the transformer secondary currents, I_1' and I_1'' , where I_1'' is leading. Again, notice the mismatch in the current amplitudes. Fig. 17 (a) and (b) shows the twelve pulse transformer input current in the time and frequency domains respectively. Notice the small amount of 5th and 7th harmonic appearing in the input current as a result of the current imbalance.

Fig. 18 shows the resulting dc current sharing with the proposed HBR's. It can be seen that the HBR's provide immunity against the inherent unbalance of the twelve pulse transformer. This is also evident in the transformer secondary currents I_1' and I_1'' shown in Fig. 19. Fig. 20 (a) and (b) shows the utility line current (I_1) in the time and frequency domains using the HBR's. Notice the reduction in the input harmonic components. Fig. 21 (a) and (b) shows the voltage across the HBR's and the frequency spectrum. Fig. 21 (b) clearly depicts that 60Hz voltage drop across the HBR is negligible demonstrating flux cancellation for 60Hz currents.

Fig. 22 shows the resulting dc current sharing with 3% pre-existing 5th harmonic in the input current (see Fig. 23). It is clear from Fig. 22 that the HBR's contribute to equal current sharing even with pre-existing harmonics. Finally, Fig. 24 verifies experimentally the asymmetric input current waveform shown in Fig. 3, and the occurrence of uncharacteristic 3rd harmonic for a six pulse rectifier load with 3% input voltage unbalance.

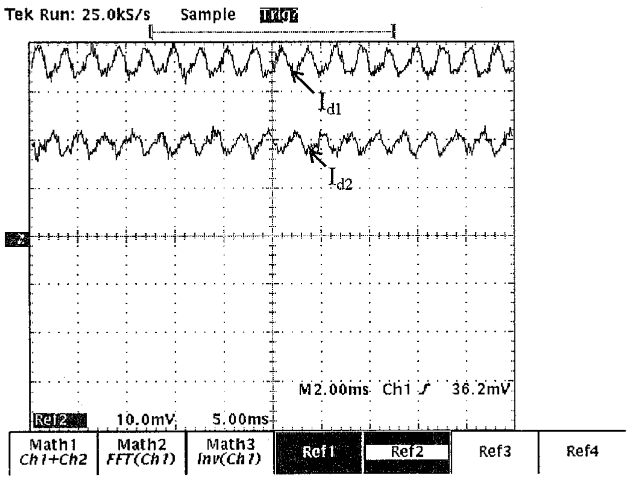


Fig. 15 Current sharing under balanced conditions without HBR's (2A/div).

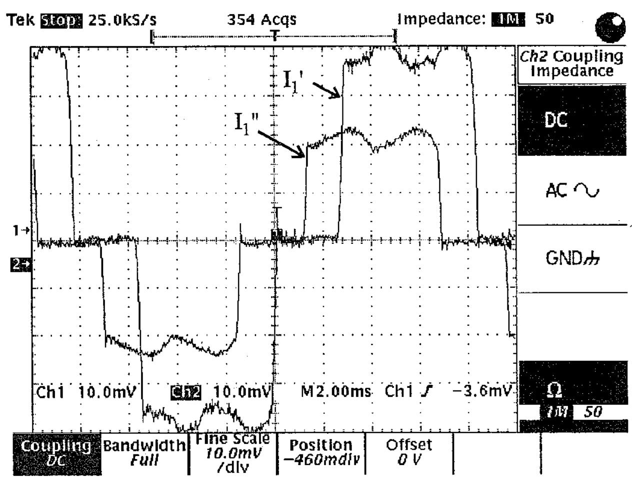


Fig. 16 Transformer secondary currents I_1' and I_1" under balanced conditions without HBR's (2A/div).

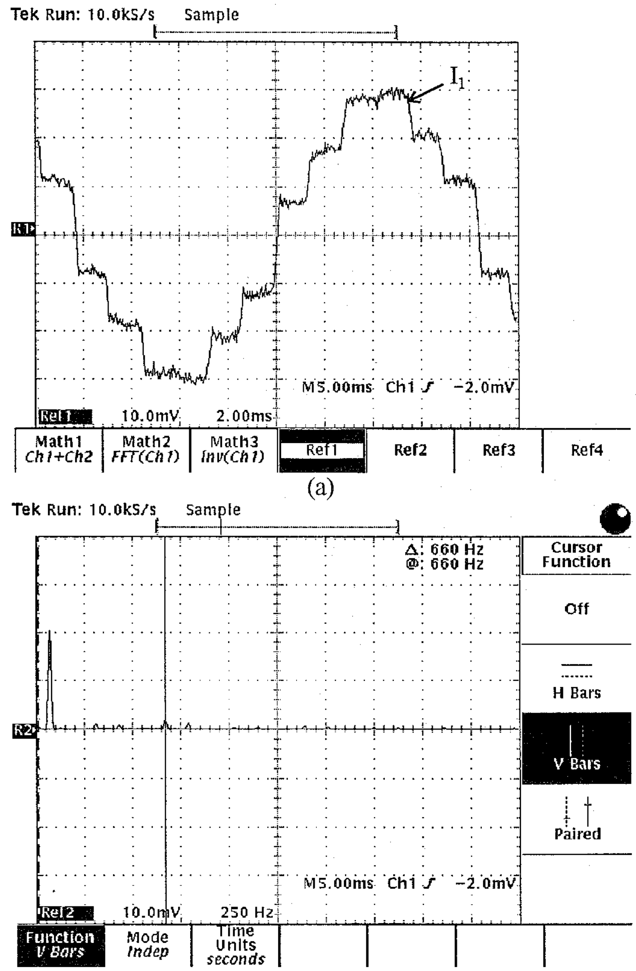


Fig. 17 Utility line current I_1 (Fig. 8) without HBR's (5A/div) (a) time (b) frequency domain.

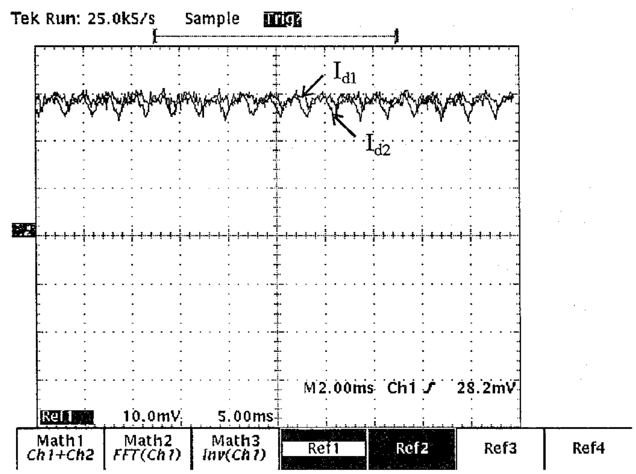


Fig. 18 Current sharing with the application of proposed HBR's (2A/div).

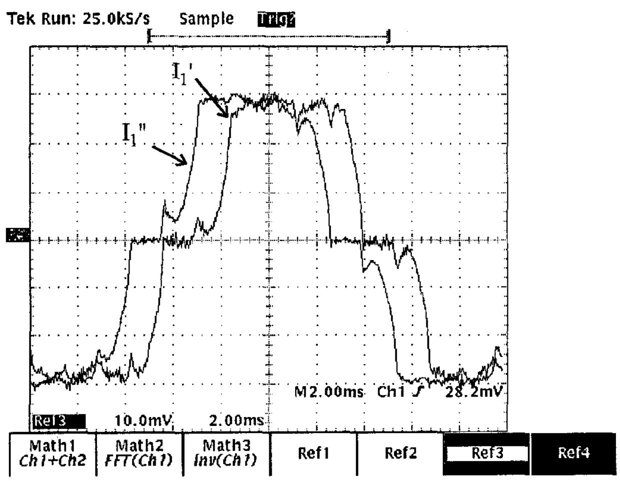
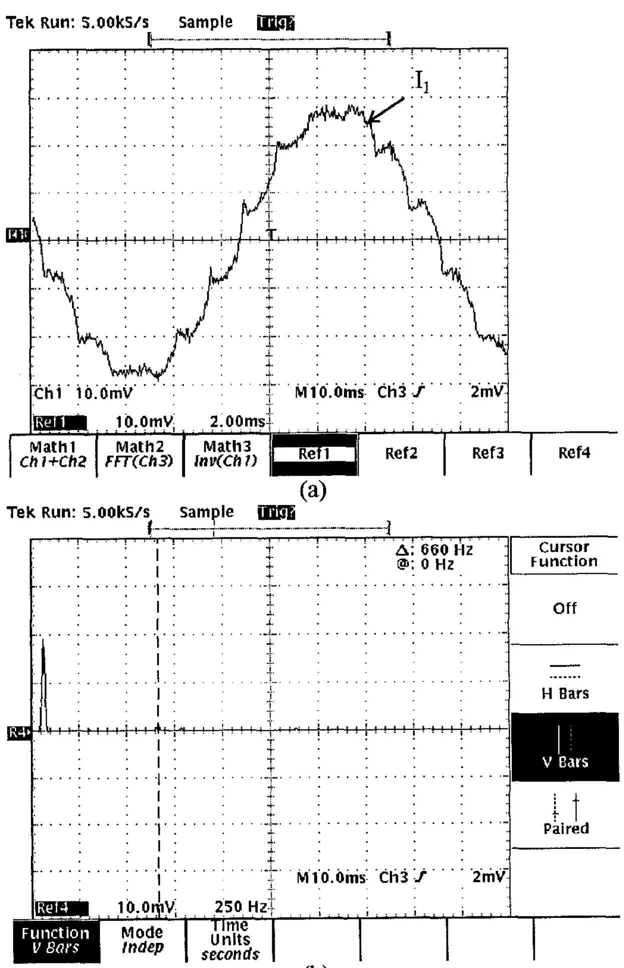
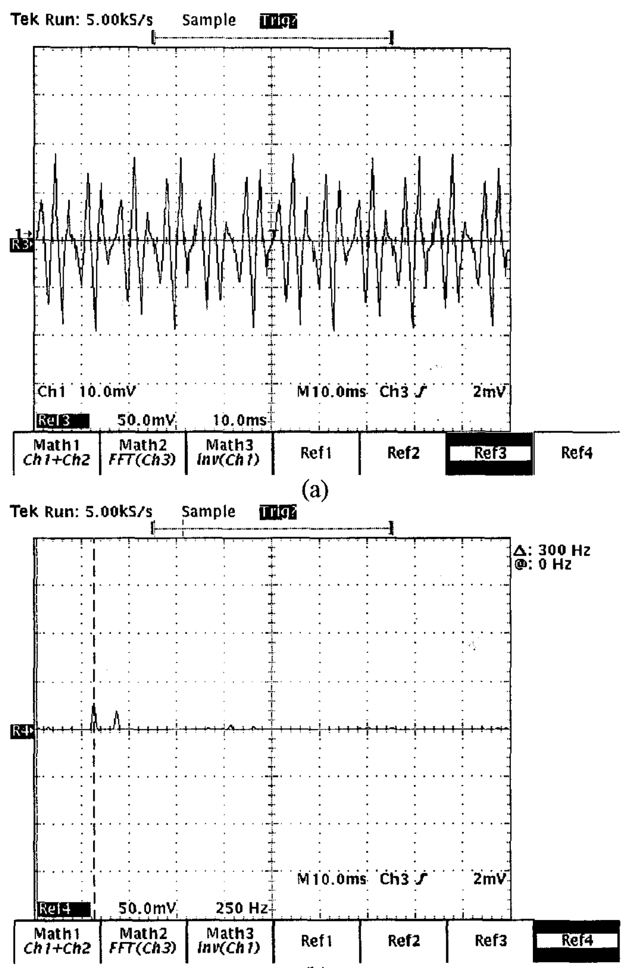


Fig. 19 Transformer secondary currents I_1' and I_1" with HBR's (2A/div).



(b)

Fig. 20 (a) Transformer input current (I_1) with HBR's (b) frequency spectrum of I_1. (5A/div)



(b)

Fig. 21 Voltage across HBR's (25V/div) (a) time (b) frequency domain.

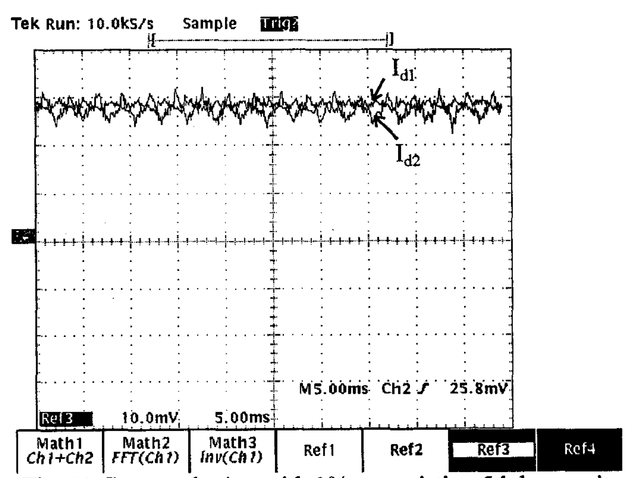


Fig. 22 Current sharing with 3% pre-existing 5th harmonic with HBR's (2A/div).

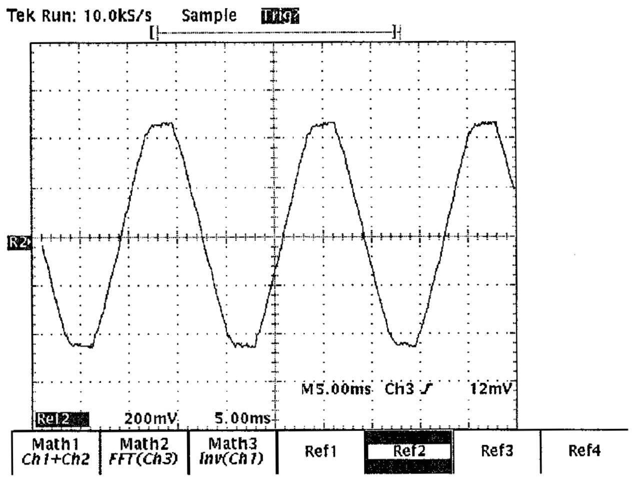
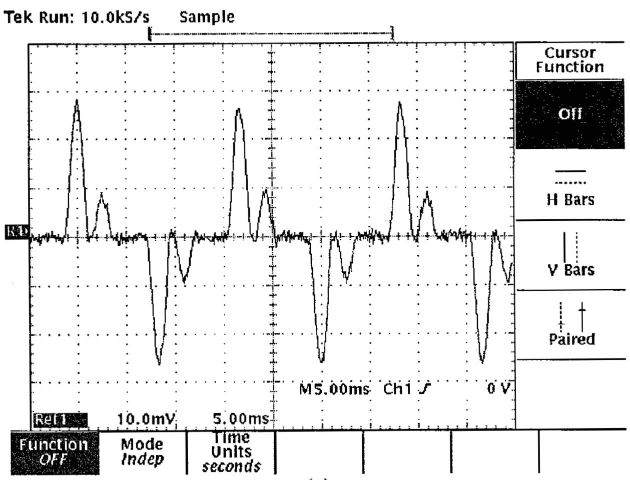
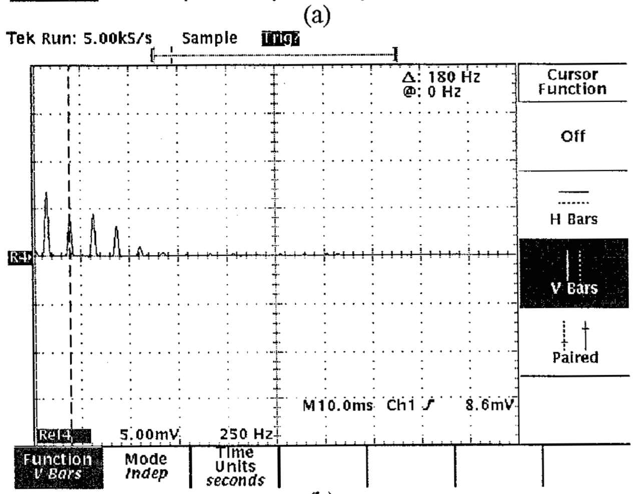


Fig. 23 Input voltage with 3% pre-existing 5th harmonic (100V/div).



(a)



(b)

Fig. 24 Six pulse input current with 3% voltage distortion (20A/div) (a) time (b) frequency domain.

5 Conclusion

In this paper, design considerations for six pulse and twelve pulse three phase diode rectifier systems operating under voltage unbalance and pre-existing voltage distortion have been investigated. It has been shown via simulations that small percentages of voltage unbalance and pre-existing voltage distortion have significant effects on the increase of harmonic components generated in the six pulse and twelve pulse diode rectifier systems.

Further, small percentages of pre-existing utility voltage distortion and transformer leakage impedance imbalance have been shown to cause unequal current sharing between the two rectifier bridges in twelve pulse systems. Simulation results on SABER and experimental results from a 10 kVA laboratory prototype system demonstrate the effectiveness of the developed methods.

6. References

[1] U. H. Meier, "Combining inverters for harmonic reduction", U.S. Patent No. 3,792,286. , Oct. 12, 1971.

[2] D. E. Rice, "Adjustable Speed Drive and Power Rectifier Harmonics - Their Effect on Power Systems Components", IEEE Trans. on IA, Vol. 22, No. 1, January/February 1986, pp. 161-177.

[3] P. Enjeti and P. D. Ziogas, "Analysis of a Static Power Converter Under Unbalance - A Novel Approach", IEEE Trans. on Ind. Elect., Vol. 37, No. 1, Feb. 1990, pp. 91-93.

[4] D.A.Paice, *"Power Electronic Converter Harmonics: Calculations and Multipulse Methods"*, Paice & Associates Inc., Palm Harbor, Florida, 1994.

[5] M. Sakui, H. Fujita, "Harmonic Analysis of a capacitor-Filtered three Phase Three-Phase Diode-Bridge Rectifier with Complex Source Impedance", IEEE Trans. on IA, Vol. 39, No. 1, February 1986, pp. 80-81.

[6] De Haan, etal., "Analysis of the Effect of Source Voltage Fluctuations on the Power Factor in Three-Phase Controlled Rectifiers", IEEE Trans. on IA, Vol. IA-22, No. 2, March/April 1986, pp. 259-266

7. Appendix

$$SW_1(\omega t) = \frac{2\sqrt{3}}{\pi}\left(\sin\omega t - \frac{1}{5}\sin 5\omega t - \frac{1}{7}\sin 7\omega t + \frac{1}{11}\sin 11\omega t + \ldots\right)$$

$$SW_2(\omega t) = \frac{2\sqrt{3}}{\pi}\left(\sin(\omega t - \tfrac{2\pi}{3}) - \frac{1}{5}\sin 5(\omega t - \tfrac{2\pi}{3}) - \frac{1}{7}\sin 7(\omega t - \tfrac{2\pi}{3}) + \frac{1}{11}\sin 11(\omega t - \tfrac{2\pi}{3}) + \frac{1}{13}\sin 13(\omega t - \tfrac{2\pi}{3}) - \ldots\right)$$

$$SW_3(\omega t) = \frac{2\sqrt{3}}{\pi}\left(\sin(\omega t + \tfrac{2\pi}{3}) - \frac{1}{5}\sin 5(\omega t + \tfrac{2\pi}{3}) - \frac{1}{7}\sin 7(\omega t + \tfrac{2\pi}{3}) + \frac{1}{11}\sin 11(\omega t + \tfrac{2\pi}{3}) + \frac{1}{13}\sin 13(\omega t + \tfrac{2\pi}{3}) - \ldots\right)$$