A Novel Three Phase Hybrid Unidirectional Rectifier for High Power Factor Applications

P. Nammalvar, P. Meganathan

***Abstract*—**This paper presents a hybrid three phase rectifier for high power factor application. This rectifier is composed by zero voltage transition (ZVT) and zero current transition (ZCT) boost converter with three phase diode bridge rectifier, in parallel with a six pulse three phase pulse width modulation (PWM) controlled rectifier. The proposed topology is capable of high power factor with DC output voltage regulation by providing sinusoidal input. Also, it increases the overall efficiency of the new hybrid rectifier to 94.56% and the total harmonic distortion of the hybrid structure varies from 0% to 16% at nominal output power. This topology was simulated in MATLAB/SIMULINK environment and the output waveforms presented with experimental result.

***Keywords*—**Hybrid Rectifier, Total Harmonic Distortion, Power Quality, Pulse Width Modulation (PWM), Unidirectional Rectifier.

I. Introduction

THE term hybrid denotes the series and/or parallel connection. The rectifier is low cost, but it draws the non sinusoidal currents or reactive power from the source. This becomes worse in power quality in form of harmonics [1]. To achieve the cancellation of harmonics distortion, the passive linear filters or power factor correction [1]-[3]. In three phase rectifier, phase shift is introduced in three phase transformer for canceling the harmonics [4], [5].

This paper proposes a new hybrid three phase rectifier with high power factor and DC output voltage regulation by providing sinusoidal input. The hybrid rectifier consists of uncontrolled rectifier in series with controlled rectifier in parallel [6]-[8], [13]. The uncontrolled rectifier along with three phase diode bridges is in series with zero voltage transition (ZVT) and zero current transition (ZCT) is referred to as snubber cell circuit [2], [13]. Presence of ZVT and ZCT in circuit was used to solve the problem as suggested in [9]-[12]. Therefore the main switch turns on with ZVT and turns off with ZCT.

The controlled rectifier works with three arms of six pulses along with three phase PWM rectifier. This controlled rectifier is designed with high switching frequency. Moreover, the uncontrolled rectifier operates in low frequency and controlled rectifier operates in high frequency and also provides higher power rating. The three phase PWM rectifiers meets the international standards for harmonic current limit, providing sinusoidal input currents with low harmonic distortion. It also meets the harmonic content imposed by the IEEE 519 and IEC 61000-3-2/61000-3-4 international standard.

P. Nammalvar, Associate Professor, is with the Department of Electrical and Electronics Engineering, IFET College of Engineering, Villupuram, Tamilnadu 605108, India (Phone: 91 986320077; e-mail: alvar1976@ gmail.com).

P. Meganathan, Assistant Professor, is with the Department of Electrical and Electronics Engineering, Krishnasamy College of Engineering & Technology, Cuddalore, Tamilnadu 607109, India (e-mail: makepet@gmail.com).

II. Hybrid Rectifier

Hybrid rectifier of the proposed system is shown in Fig. 1. This rectifier has parallel connection of three phase diode bridge rectifier and a three phase six pulse PWM rectifier. Since, it is not possible to connect both the rectifiers in directly hybrid rectifier is employed.

The hybrid rectifier consists of uncontrolled rectifier operating at low frequency and controlled rectifier which operates at high frequency. Thus, overall system efficiency is increased.

A. ZVT and ZCT Switch Three Phase Boost Rectifier

The ZVT and ZCT based three-phase boost rectifier, presented in Fig. 2. A new snubber cell turns on and turns off the main switch by ZVT and ZCT respectively. This is imposed in a rectangular shape to the input current wave forms. This ZVT and ZCT switching has the most desirable features of less switching losses, high power density, high power factor, high efficiency and low EMI noise. The proposed snubber cell has low value inductance L_{sa} and L_{sb} which are not magnetic coupled. Therefore there is no leakage inductance problem of the magnetic coupled inductor.

Moreover, it has the advantage of size, number of components and cost. As the switching losses are low, it increases the operating frequency and there by low value of L and C. This new ZVT and ZCT combination is suitable for the power factor correction circuits and also its efficiency is also high.

B. Three Phase Six Pulse Boost Rectifier

The three phase six pulse boost rectifier is presented in Fig. 3. This rectifier is connected in parallel to uncontrolled rectifier. In this line current i_1, i_2, i_3 should be sinusoidal therefore current i_a, i_b, i_c and current i_x, i_y, i_z will be controlled by the line current with sinusoidal. The shape of current i_a, i_b, i_c is imposed by the diode, which is a current to be controlled. The boost converter is operated in conduction mode and boost inductor current is constant reference current. Thus, the current i_x, i_y, i_z is controlled to follow the required reference, resulting in sinusoidal input current.

Thus, the PWM rectifier achieves high power factor at the input. Also, it generates the harmonic free input current.

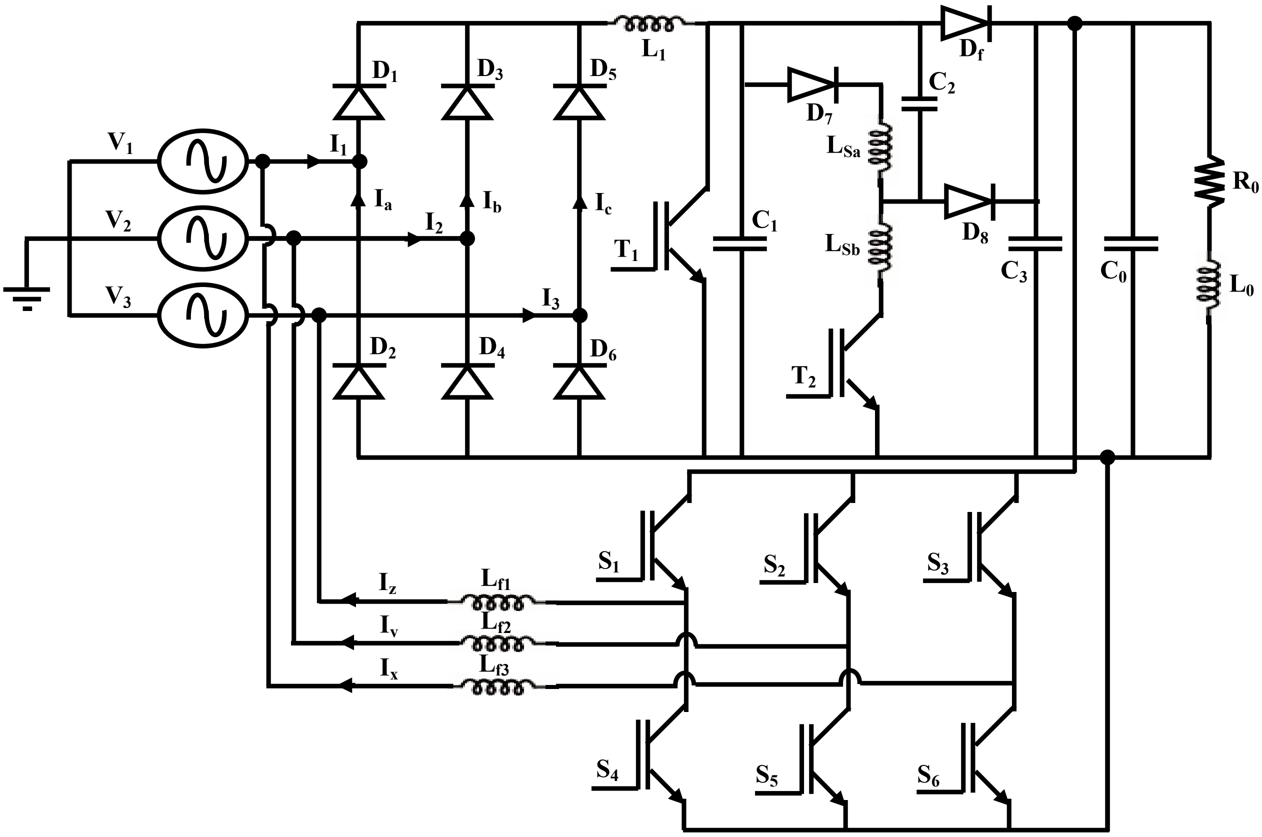

Fig. 1 Proposed Three Phase Hybrid Rectifier

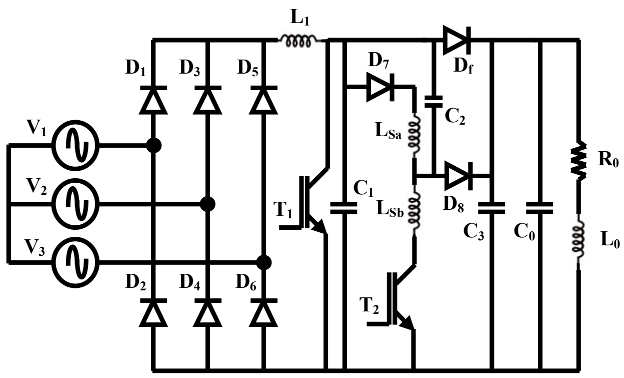

Fig. 2 ZVT – ZCT Switch Three Phase Boost Rectifier

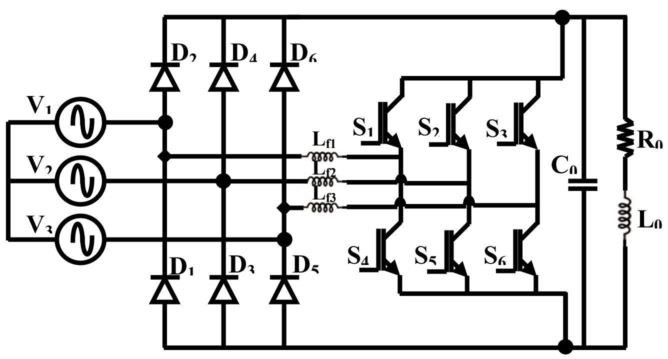

Fig. 3 Three Phase Six Pulse Boost Rectifier

III. Mathematical Analysis

To perform the mathematical analysis from the input current's viewpoint, the output voltage is considered constant. Thus, the simplified circuit presented in Fig. 5 is adopted. The input voltages and input currents are considered to be perfectly sinusoidal and are expressed as

$$\begin{cases} v_1(\mathrm{t}) = V_p \sin(wt) \\ v_2(\mathrm{t}) = V_p \sin(wt - 120°) \\ v_3(\mathrm{t}) = V_p \sin(wt + 120°) \end{cases}$$

and

$$\begin{cases} i_1(\mathrm{t}) = I_p \sin(wt) \\ i_2(\mathrm{t}) = I_p \sin(wt - 120°) \\ i_3(\mathrm{t}) = I_p \sin(wt + 120°) \end{cases} \tag{1}$$

To simplify the analysis, the system is considered loss-free. In this manner, the input active power P_{in} can be expressed as

$$P_{in} = \frac{3V_p I_p}{2} = P_o = V_o I_o \tag{2}$$

where V_p is the peak of the input voltage, I_p is the peak of the input current, P_o is the output power, V_o is the dc output voltage, and I_o is the dc output current.

Substituting (2) into (1) yields

$$\begin{cases} i_1(\mathrm{t}) = \dfrac{2}{3}\dfrac{I_p}{V_p}\sin(wt) \\ i_2(\mathrm{t}) = \dfrac{2}{3}\dfrac{I_p}{V_p}\sin(wt-120°) \\ i_3(\mathrm{t}) = \dfrac{2}{3}\dfrac{I_p}{V_p}\sin(wt+120°) \end{cases} \quad (3)$$

The input currents of the hybrid rectifier are obtained by adding the input currents of the passive rectifier [i_{p1}(t), i_{p2}(t), and i_{p3}(t)] and the input currents of the active rectifier [i_{a1}(t), i_{a2}(t), and i_{a3}(t)].

This addition results in

$$\begin{cases} i_1(t) = i_{a1}(\mathrm{t}) + i_{p1}(\mathrm{t}) \\ i_2(t) = i_{a2}(\mathrm{t}) + i_{p2}(\mathrm{t}) \\ i_3(t) = i_{a3}(\mathrm{t}) + i_{p3}(\mathrm{t}) \end{cases} \quad (4)$$

Substituting (3) into (4) yields

$$\begin{cases} i_{a1}(\mathrm{t}) = \dfrac{2}{3}\dfrac{I_p}{V_p}\sin(wt) - i_{p1}(\mathrm{t}) \\ i_{a2}(\mathrm{t}) = \dfrac{2}{3}\dfrac{I_p}{V_p}\sin(wt-120°) - i_{p2}(\mathrm{t}) \\ i_{a3}(\mathrm{t}) = \dfrac{2}{3}\dfrac{I_p}{V_p}\sin(wt+120°) - i_{p3}(\mathrm{t}) \end{cases} \quad (5)$$

Similarly, at the output, the load current is composed of the sum of currents i_{op} and i_{oa} given by

$$i_o(t) = i_{oa}(t) + i_{op}(t) \quad (6)$$

By analyzing the passive rectifier current of phase 1, which is depicted in Fig. 6, the following expression (7) is obtained:

$$I_L(t) = \frac{P_o}{V_p}\frac{\pi}{3\sqrt{3}} \quad (7)$$

where I_L(t) is the single-switch boost rectifier inductor current and P_{op} is the active power processed by the passive rectifier. The power processed by each rectifier is related to the peak value of its input currents. According to the concept of the hybrid rectifier, the fact that the diode bridge rectifier processes the greatest part of the output power is more interesting. Evidently, to obtain sinusoidal input currents, an optimal power distribution exists and should be discovered.

Substituting (7) into (5) yields

$$i_{a1}(t) = \begin{cases} \dfrac{2}{3}\dfrac{I_p}{V_p}\sin(wt) - \dfrac{P_o}{V_p}\dfrac{\pi}{3\sqrt{3}}, if\, 30° \le wt 150° \\ \dfrac{2}{3}\dfrac{I_p}{V_p}\sin(wt), \begin{cases} if\, 0° \le wt \le 30° \\ if\, 150° \le wt \le 180° \end{cases} \end{cases} \quad (8)$$

Due to the unidirectional characteristic of the PWM rectifier, the instantaneous input power should present only positive values. Analyzing (8), the solution that satisfies this condition is presented as

$$P_{op} \le \frac{\sqrt{3}}{\pi} P_o \approx 0.522 P_o \quad (9)$$

Therefore, the active rectifier's power operation limit is given as

$$P_{oa} \ge (1-0.522)P_o \approx 0.448 P_o \quad (10)$$

where, P_{oa} is the active power processed by the PWM rectifier. Expressions (9) and (10) define the active power sharing between the two converters. If these relationships are not satisfied, the input currents will be distorted.

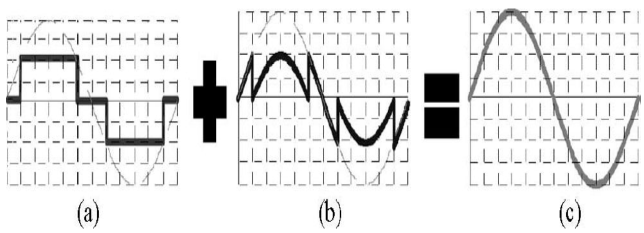

Fig. 4 Expected Current Waveforms of Hybrid System
(a) Current wave form imposed by the ZVT- ZVT switch boost rectifier (Uncontrolled Rectifier) (b) Current wave form generator by six pulse boost rectifier (Controlled Rectifier) (c) Desired sinusoidal waveform

IV. Control Strategy

The control loop scheme of the hybrid rectifier is presented in Fig. 5. Four current control loops and one voltage control loop are used. The dc output voltage regulation is provided by the voltage control loop.

The current from ZVT-ZCT boost rectifier is compared to a constant reference. The error produced is applied to PWM modulator that generates the gate signal. This controls the input current indirectly by sensing the currents i1, i2, and i3. It gives good signal to each phase. The errors produced by the comparisons between the sampled signals and reference signals are applied to their respective compensators, and the PWM modulators thus generate the gate signal.

To obtain perfect sinusoidal currents, it is important that the gains ratio α be adjusted as close to 0.552 as possible as but never greater than this value. If the ratio is greater than 0.552, the imposed line currents will be distorted. The power processed by the PWM rectifier increases as the value of α decrease. At the limit α = 0, the PWM rectifier processes the total load power.

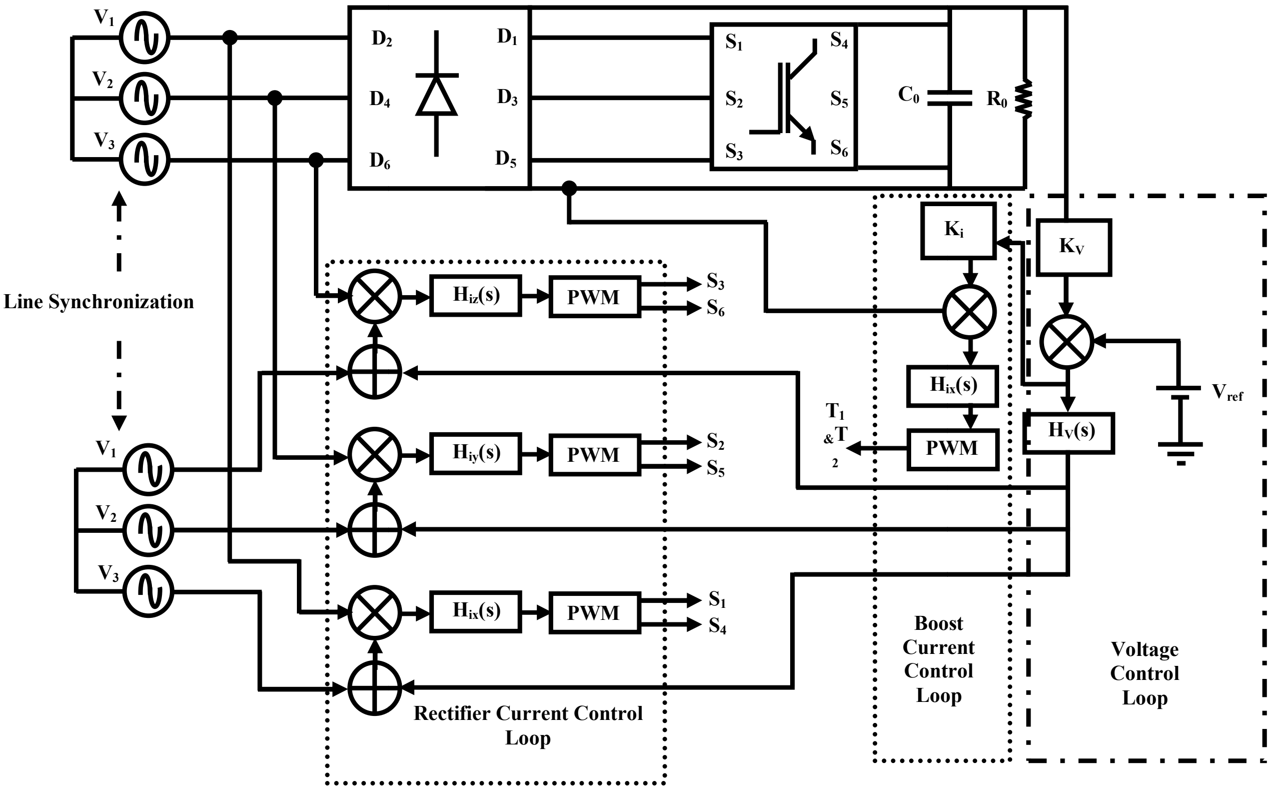

Fig. 5 Control Scheme of Proposed Hybrid Rectifier

V. Simulation Results

A. Waveform of ZVT – ZCT Switch Three Phase Boost Rectifier

The circuit is shown in Fig. 2 is ZVT – ZCT based three phase boost rectifier is sampled as square wave form as shown in the simulation waveform in Fig. 6.

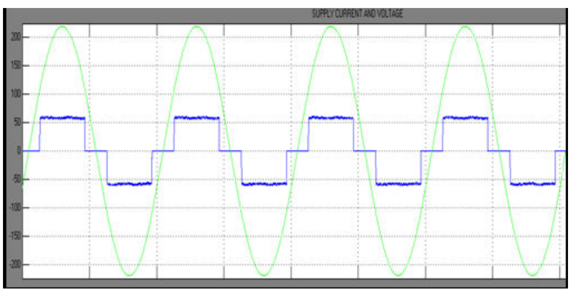

Fig. 6 Current Waveforms of ZVT – ZCT Boost Rectifier

B. Waveform of Three Phase Six Pulse Boost Rectifier

The circuit shown in Fig. 3 is the three phase six pulse boost rectifier which generates injected waveform as shown in Fig. 7.

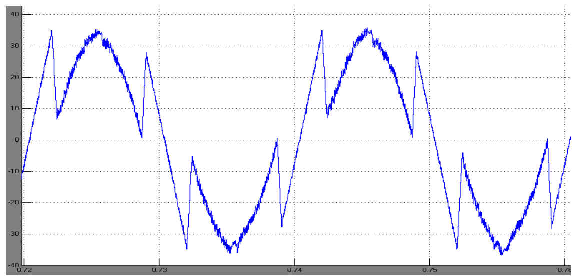

Fig. 7 Injected Current Waveform Six Pulse Rectifier

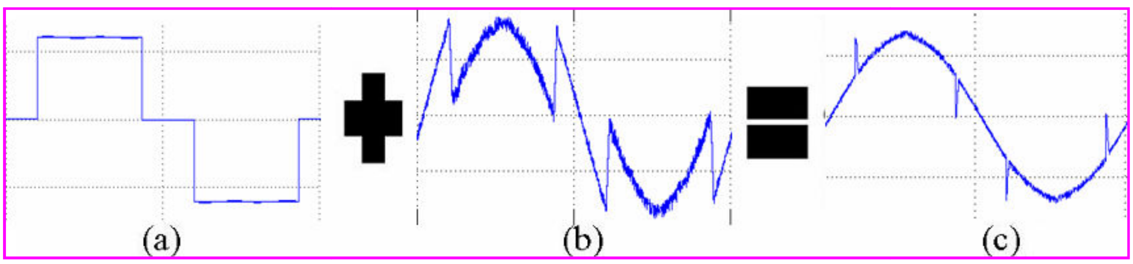

Fig. 8 Simulated Current Waveform of Hybrid Rectifier (a) Current wave form imposed by the ZVT- ZVT switch boost rectifier (Uncontrolled Rectifier) (b) Injected Current wave form generator by six pulse boost rectifier (Controlled Rectifier) (c) Desired sinusoidal waveform

C. Waveform of Hybrid Rectifier

The circuit shown in Fig. 1 is Hybrid rectifier which generates sinusoidal shape waveform as shown in Fig. 9 and three phase sinusoidal current of Hybrid rectifier before compensation and after compensation as shown in Fig. 11.

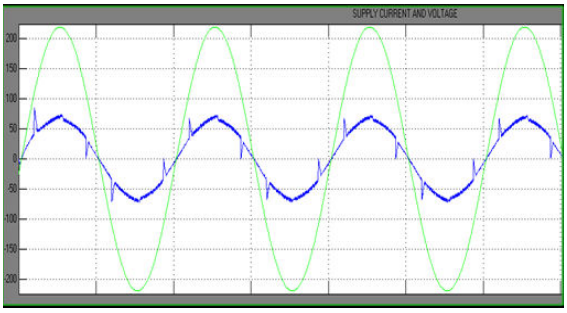

Fig. 9 Sinusoidal Waveform of Hybrid Rectifier

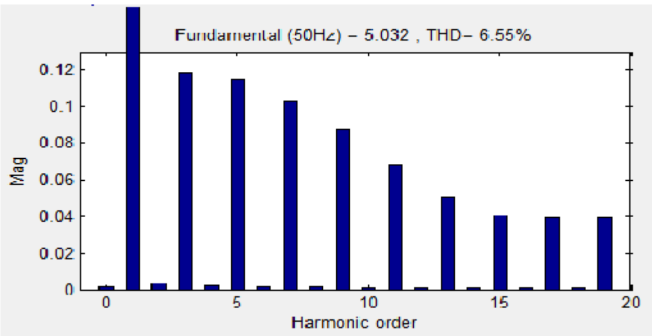

Fig. 10 FFT Analysis of Hybrid Rectifier

D. FFT Analysis of Hybrid Rectifier

This result was obtained from the simulation of current waveform and the THDs obtained from FFT analysis is presented in the Fig. 10.

TABLE I
SIMULATION RESULTS

Description	Value
True power	1 kW
Power factor	Almost Unity
Efficiency	Max 94.56 %
Input AC Voltage	220 V
Output DC Voltage	650 V
Voltage THD	0.09 %
Current THD of Bridge rectifier	31 %
Current THD of Controlled rectifier	39.18 %
Current THD of Hybrid rectifier	11.71 %

TABLE II
LOAD VARIATION PERFORMANCE

Resistance	Power Factor	Efficiency
5	0.2051	44.45
10	0.9899	92.69
15	0.9800	93.70
20	0.9999	94.56

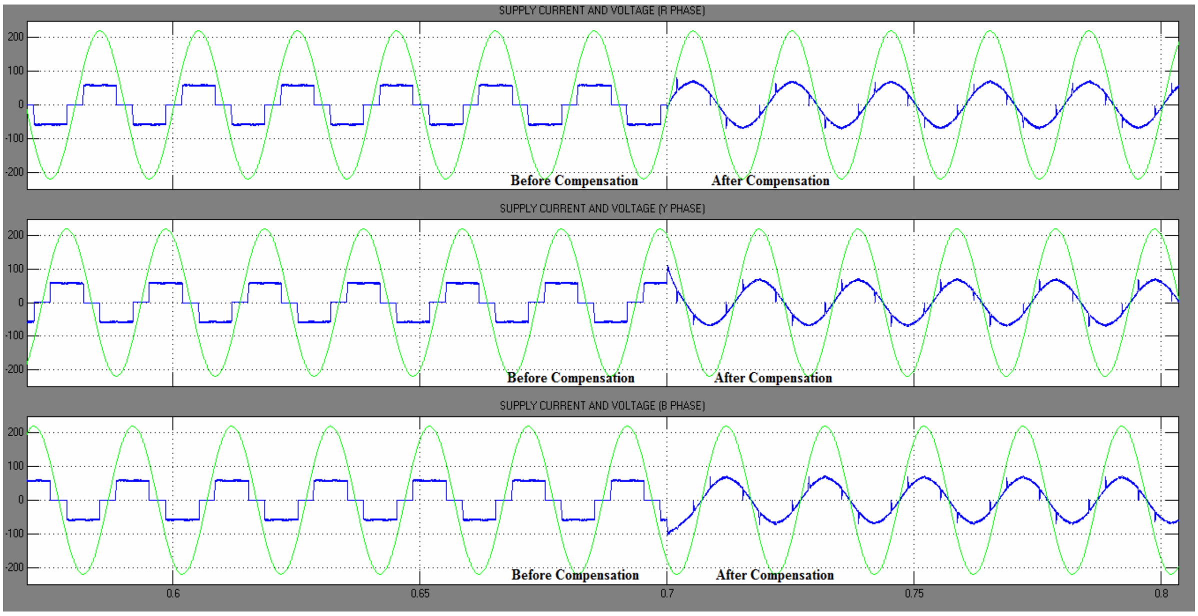

Fig. 11 Sinusoidal Three Phase Current Waveform of Proposed Hybrid Rectifier

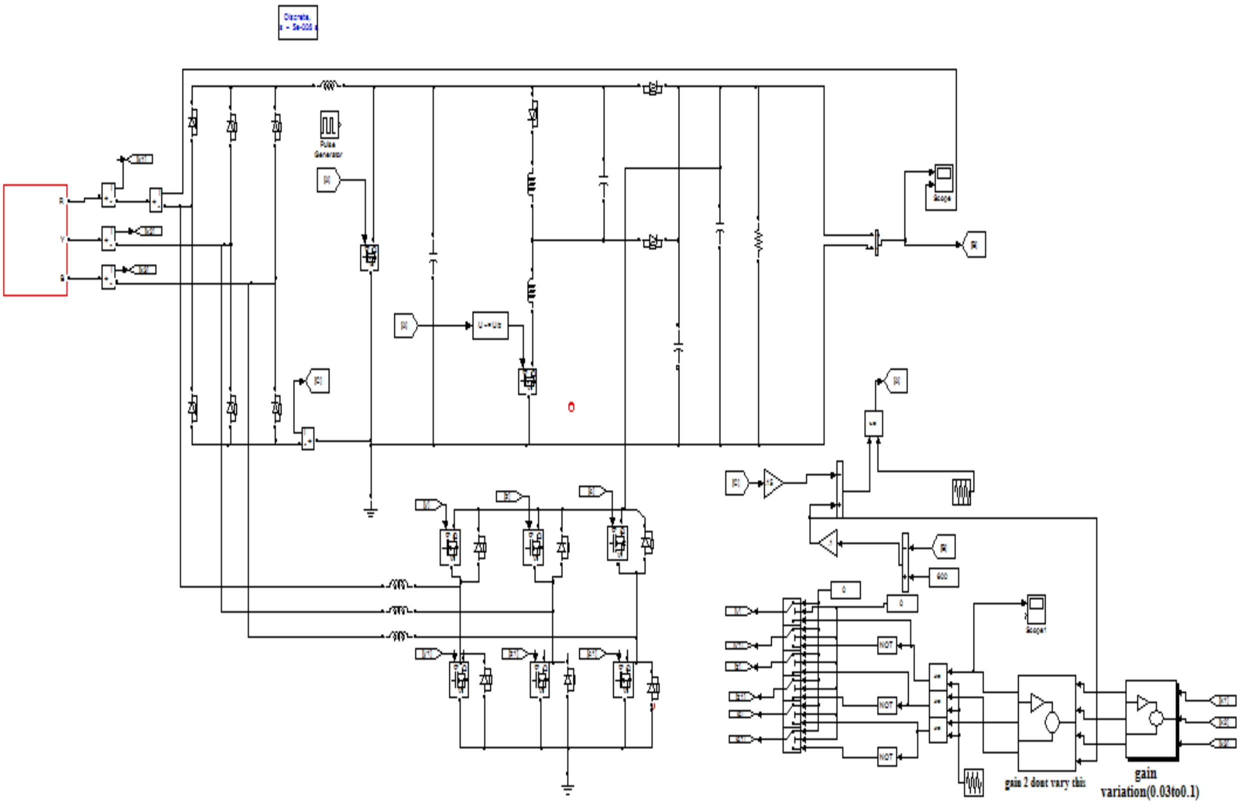

Fig. 12 Simulation Circuit of Proposed Hybrid Rectifier

VI. Experimental Results

A 100 Watts laboratory prototype of the proposed structure is presented in Fig. 13. The parameter of the components used in rectifier are: inductors L_1 and L_2 are 2 mH/50 A, inductors L_{f1}, L_{f2} and L_{f3} are 2.7 mH/15 A; output capacitors are 8 x 2200μF/450 V; the three phase controlled rectifier with six pulse controlled bridge is the MOSFET module and the diode bridge.

The control circuit was implemented using the commercial analog integrated circuit for power factor correction applications. The experimental result for the current generated by the ZVT-ZCT based boost rectifier is shown in Fig. 14 and the current generated by the PWM controlled rectifier as sinusoidal waveform is shown in Fig 15. This result was obtained from the prototype as expected and the mains currents present a sinusoidal shape. The harmonic analysis is compared with the current harmonics with standards. The THDs obtained from the fluke meter are presented in the Fig. 16.

This result was obtained from the prototype as expected the mains currents present a sinusoidal shape. The harmonic analysis is compared the current harmonics with standards.

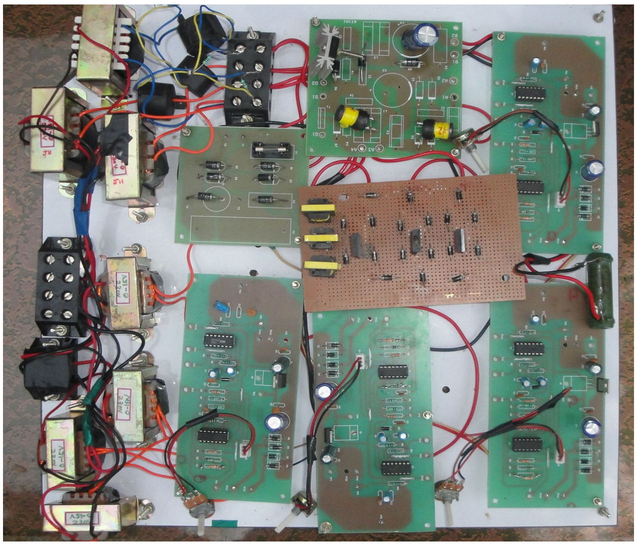

Fig. 13 Prototype of Hybrid Rectifier

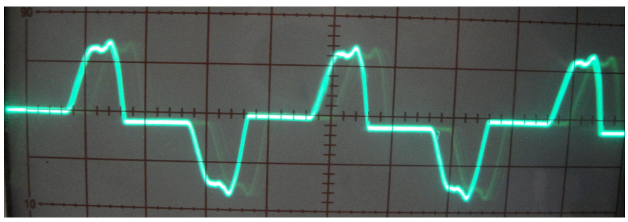

Fig. 14 Current Waveform of Bridge Rectifier

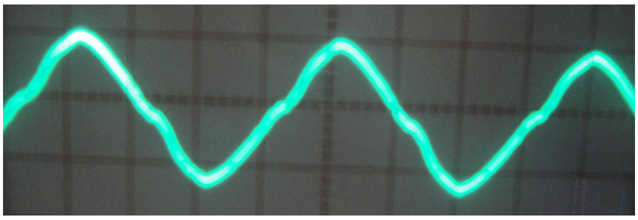

Fig. 15 Sinusoidal Current Waveform of Hybrid Rectifier

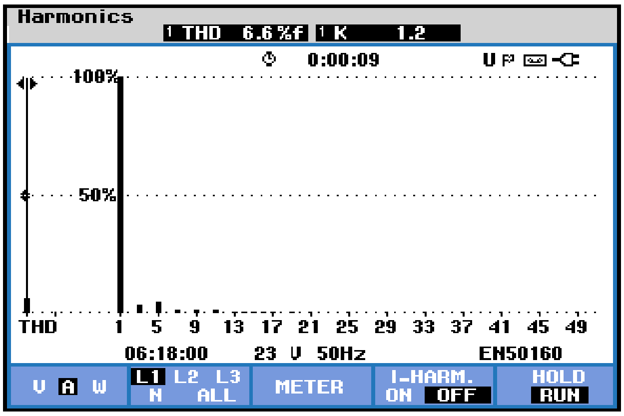

Fig. 16 THD Values of Current of Hybrid Rectifier

VII. Conclusions

This paper presents new topology of hybrid three-phase rectifier suitable for medium and high power applications. The rectifiers employ a three-phase diode bridge with ZVT – ZCT based boost rectifier. The six pulse three phase rectifier is connected in parallel. The advantage of this hybrid system brings high power levels due to the parallel connection of the rectifiers. Moreover, the efficiency of the system is also increased.

The THD values are also measured from the fluke meter as shown. By using ZVT – ZCT has advantages of size, number of components and cost. Also, it reduces the switching losses and voltage stress. The control strategy regulates the output and controls the input currents to achieve the high power factor.

TABLE III
Hardware Results

Description	Value
True power	100 W
Input AC voltage	15 V
Output DC voltage	15 V min to 30 V max
Current THD of Bridge rectifier	< 11 %
Current THD of Controlled rectifier	< 16 %
Current THD of Hybrid rectifier	< 6.55 %

The prototype of the three phase hybrid rectifier is obtained from 1 kW and the result shows high power factor and dc voltage regulation. The disadvantage of the system is the control scheme by using the additional current sensor and current control loop.

References

[1] Ricardo LuizAlves and Ivo Barbi. “Analysis and Implementation of a Hybrid High-Power-Factor Three-Phase Unidirectional Rectifier”, IEEE Transactions on Power Electronics, vol. 24, no. 3, March 2009.

[2] Ismail Aksoy, HaciBodur,Member IEEE and A. FarukBakan, A New ZVT ZCT-PWM DC–DC Converter In IEEE Transactions on Power Electronics, vol. 25, no. 8, August 2010.

[3] Carlos Henrique IllaFont,IEEE Student member and Ivo Barbi,Senior Member IEEE “A New High Power Factor Bidirectional Hybrid Three-Phase Rectifier” in IEEE Transactions on Power Electronics, vol. 22, no. 4, July 2007.

[4] M. E. Villablanca, J. I. Nadal, and M. A. Bravo, “A 12-pulse AC–DC rectifier with high-quality input/output waveforms,” IEEE Trans. Power Electron., vol. 22, no. 5, pp. 1875–1881, Sep. 2007.

[5] B. Singh, S. Gairola, B. N. Singh, A. Chandra, and K. Al-Haddad, “Multipulse AC–DC converters for improving power quality: A review,” IEEE Trans. Power Electron., vol. 23, no. 1, pp. 260–281, Jan. 2008.

[6] R. L. Alves, C. H. Illa Font and I. Barbi. “Novel Unidirectional Hybrid Three-phase Rectifier System Employing Boost Topology”. In Proc. Of PESC 2005 – The 36th Annual IEEE Power Electronics Specialists Conference, pp. 487-493, 2005.

[7] Madhav D. Manjrekar, Peter K. Steimer and Thomas A. Lipo. “Hybrid Multilevel Power Conversion System: a Competitive Solution for Highpower Applications”. IEEE Transactions on Industry Applications, vol. 36, no. 3, pp. 834-840, May/June 2000.

[8] J. W. Kolar and H. Ertl. “Status of the Techniques of Three-phase Rectifier Systems with Low Effects on the Mains”. In Proc. of INTELEC 2001 – International Telecommunications Energy Conference, pp. 16, 1999.

[9] C. M. Wang, “Novel zero-voltage-transition PWM DC-DC converters,” IEEE Trans. Ind. Electron., vol. 53, no. 1, pp. 254–262, Feb. 2006.

[10] W. Huang and G. Moschopoulos, “Anewfamily of zero-voltage-transition PWM converters with dual active auxiliary circuits,” IEEE Trans. Power Electron., vol. 21, no. 2, pp. 370–379, Mar. 2006.

[11] H. Yu, B. M. Song, and J. S. Lai, “Design of a novel ZVT soft-switching chopper,” IEEE Trans. Power Electron., vol. 17, no. 1, pp. 101–108, Jan. 2002.

[12] P. Das and G. Moschopoulos, “A comparative study of zero-currenttransition PWM converters,” IEEE Trans. Ind. Electron., vol. 54, no. 3, pp. 1319–1328, Jun. 2007.

[13] P.Nammalvar and S.Annapoorani,”Three phase high power Quality two stage boost rectifier,” International Journal of Engineering Science and Technology,Vol.4,no. 4,pp-1702-1712,April 2012.

P. Nammalvar was born in Tamilnadu, India in 1976. He received his B.E degree in Electrical and Electronics Engineering from Annamalai University, Chidambaram and M.E degree (Power Electronics & Drives) from Adhiparasakthi Engineering College, Melmaruvathur. He is currently employed as Associate Professor, in Department of Electrical and Electronics Engineering at IFET College of Engineering, Villupuram, Tamilnadu 605108, India. Currently, he is also working for a Ph.D. degree in the area of solar power conditioning.

His research interests are in the fields of renewable energy systems, Power factor corrections, DC/DC converters and Power Quality improvement.He is a life time member of ISTE.

P. Meganathan was born in Tamilnadu, India in 1983. He received his B.E degree in Electrical and Electronics Engineering in 2004 and M.E degree in Power System Engineering in 2013. He is currently working as Assistant Professor in the Department of Electrical and Electronics Engineering at Krishnasamy College of Engineering and Technology, Cuddalore, Tamilnadu 607109, India. His interests are Power Quality, Power System Controland Power Transmission Control.