IJCTA, 8(3), 2015, pp. 877-887

Analysis of Hysteresis Current Controlled Three Phase PWM Rectifier with Reduced Switching Loss

E M Suhara and M Nandakumar*

Abstract: Pulse Width Modulated (PWM) Rectifiers offer a promising and high end performance for the ac to dc conversion needs of the industry, customer and power grid sectors. This paper presents a reduced switching loss algorithm applied to a hysteresis current controlled PWM rectifier. This acts as an ac to dc boost converter with near unity power factor at the grid side along with regulated and ripple free dc voltage at the output. Adaptive hysteresis technique is incorporated in the hysteresis controller so that near constant frequency of operation is assured. The performance of the converter with reduced loss is compared with that of conventional hysteresis controller with and without adaptive technique. Matlab/Simulink simulation results show a better performance for the converter with modified switching algorithm in terms of switching loss, overall efficiency, dynamic and steady state performance.

Keywords*:* PWM rectifier; Reduced switching loss; Adaptive hysteresis controller.

1. INTRODUCTION

Three phase PWM rectifiers find a plethora of applications such as uninterrupted power supplies with regulated output power, front end converters with bidirectional power flow for variable speed drives, battery chargers, power factor corrector circuits, active filters etc[1]-[3]. The objective of the control circuit in such a rectifier depends primarily on the application. However almost all the ac to dc conversion process concentrates on two factors. Primarily the input side power quality which depends on the harmonic spectrum of the alternating current, voltage and the power factor. Secondly the regulated and ripple free dc power at the output. Various control techniques have been developed [4]-[7] to meet these requirements. The voltage oriented control (VOC) performs the coordinate transformation to maintain the quadrature axis component of input current at zero value. Only the direct axis component is drawn from the input side corresponding to the active power requirement of the load and thus assuring high input power factor and sinusoidal input current. Virtual flux based direct power control (VF-DPC) eliminates the ac voltage sensors and uses virtual flux estimator. It considers the input side comprising of ac source voltage and series inductor as equivalent to a virtual motor and then the integration of voltage determines the virtual flux. The active and reactive power can be calculated using the transformed components of virtual flux and input currents. The reactive power command from the input is set to zero to ensure sinusoidal current at near unity power factor. The switching loss contributes to a major factor in the total losses in a converter. Hence different methodologies are found in literature for reducing the switching losses [8]-[9].

The hysteresis current controllers (fig. 1) offer excellent dynamic and steady state performance for the PWM rectifier with its simple control strategy [10].The phase locked loop generates a unit vector corresponding to the fundamental component of positive sequence phase voltage. The peak values of

Government Engineering College, Thrissur-680 009, Kerala, India
* e-mail: suharanas@gmail.com (or) mnkumar.tcr@gmail.com

reference currents are estimated based on dc link voltage regulation and its phase information can be derived from corresponding unit vectors. The hysteresis controller generates gating pulses for all the switches so that the actual current is made to follow the reference current.

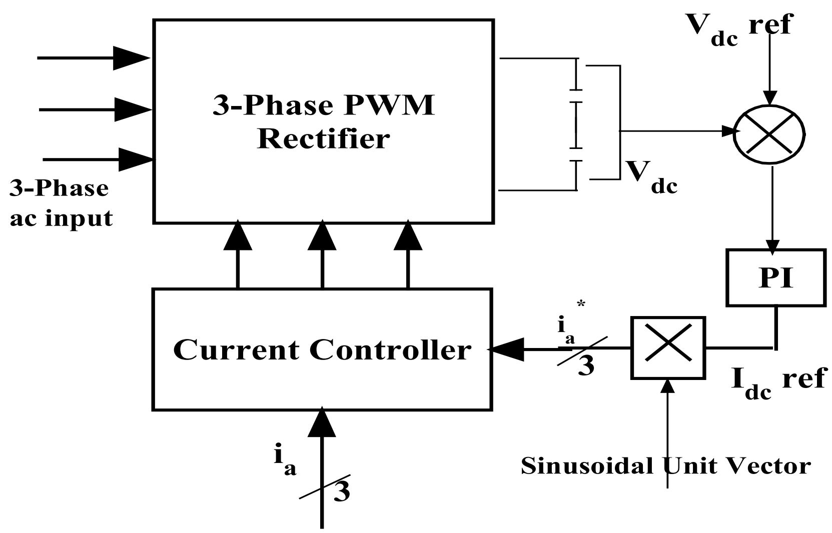

Figure 1: Hysteresis Current Controller for PWM Rectifier

2. REDUCED SWITCHING LOSS ALGORITHM

2.1 Operation of the Converter

The three phase PWM configuration shown in Fig. 2 is considered for analysis. The conventional hysteresis controller controls all the six switches simultaneously. In each phase, the upper or lower switch to be turned on is determined by the hysteresis bandwidth and the instantaneous actual current with respect to the reference value. Moreover the upper and lower switches always act in complement mode. Out of the total six switches, any three are always turned on and the other three are off. Thus the variable switching frequency of the six switches contributes to a high switching loss especially when the hysteresis bandwidth

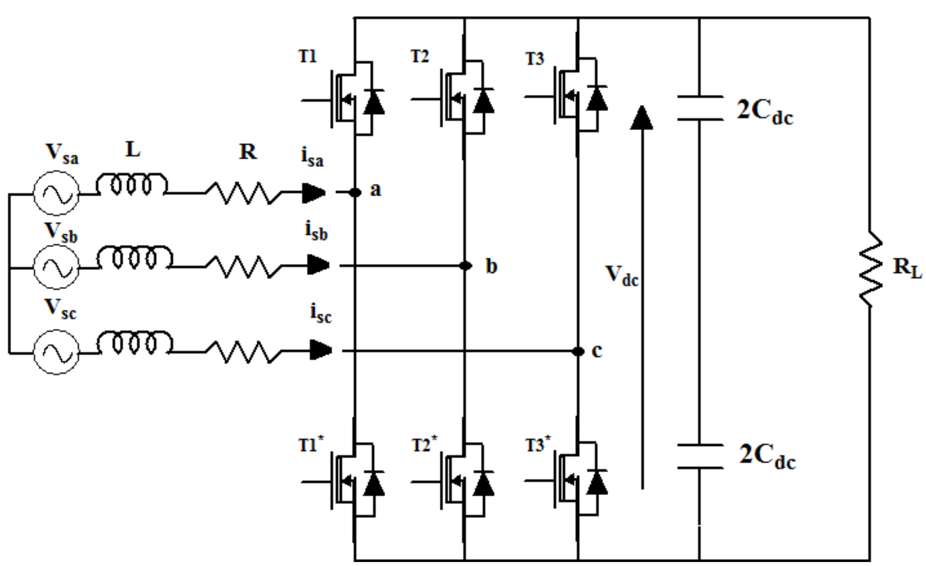

Figure 2: Power Circuit Configuration.

is less. Consider the grid voltage and current waveform for unity power factor operation of the converter shown in fig. 3 In the three phase system, it can be observed that the instantaneous polarity of voltages and hence the currents of any two phases is the same except at zero crossing periods. Thus if the current in the two phases can be controlled, then the third phase need not be controlled [11]. As shown in fig.3, one cycle of the phase voltage waveform has been split into six sectors each with 60° duration with respect to the zero crossing points of voltages. During any sector of phase voltage, voltage polarities of two phases are the same and those phases are selected for control as these results in lowest rate of change of inductor current. The controlled switch in a selected phase can be determined depending on the polarity of current in that sector. The lower switch is controlled for positive current and upper switch is controlled for negative current in a particular phase. Consider the first 60° region, phase A and phase C have same polarity of voltage and so these are the phases to be controlled. The polarity of currents of phase A and phase C are positive and so lower switches T1* and T3* are the controlled switches. The same switching logic for all the sectors results in a complete switching pattern as shown in Table.1.

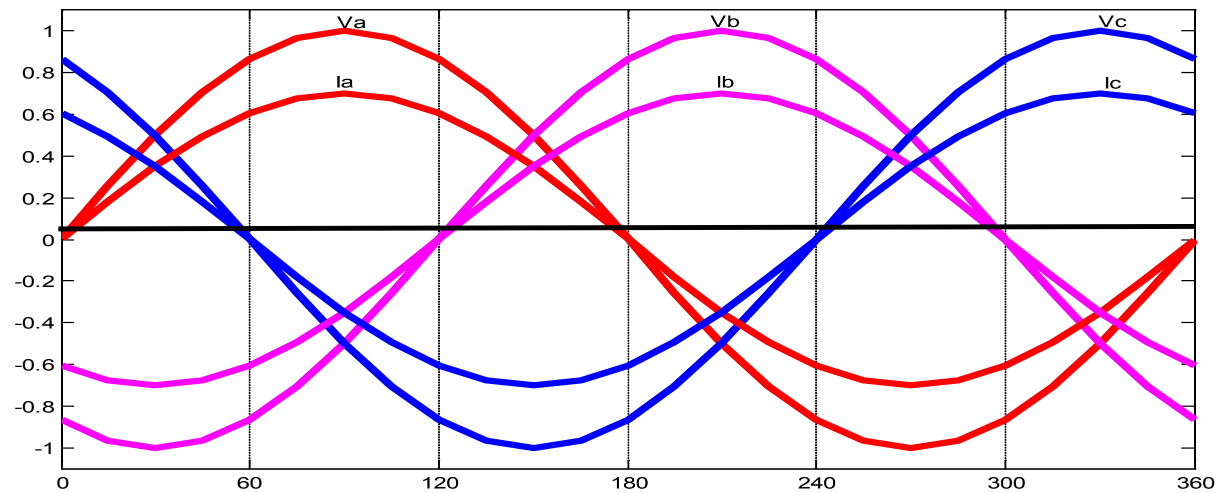

Figure 3: Grid voltage and current for upf operation.

Table 1
Switching table (C-Controlled)

Region	T_1	T_1^*	T_2	T_2^*	T_3	T_3*
0-60°	–	C	–	–	–	C
60-120°	–	–	C	–	C	–
120-180°	–	C	–	C	–	–
180-240°	C	–	–	–	C	–
240-300°	–	–	–	C	-	C
300-360°	C	–	C	–	–	–

The equivalent circuit of the converter for this region (0-60°) is as shown in fig.4.It can be seen that only two switches are controlled and the third phase current is carried through the diode which is uncontrolled. Hence it can be seen that during the operation of the converter in dual boost mode, only two switches are switched at high frequency at any point of time and hence the reduced switching loss can be achieved.

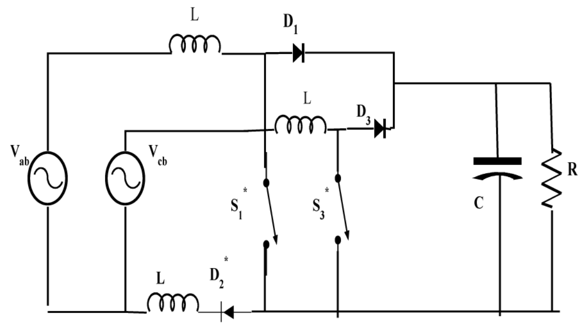

Figure 4: Equivalent Circuit during 0-60°

1.2 GENERATION OF CONTROL LOGIC

The block diagram representation of the control logic with reduced switching loss algorithm is shown in Fig. 5. The voltage sector is identified depending on the instantaneous value of the sensed grid voltage. A zero crossing detector can be used to generate logic function corresponding to the polarity of measured phase currents. In order to implement the switching table as in Table 1, proper combination of AND OR logic operation is performed in the logic controller which provides enabling signals for the switches. The pulses from the hysteresis generator are made available to the corresponding switches only when that particular switch is enabled by the logic controller. The information of current polarity along with voltage sector identifier makes the input power factor control possible.

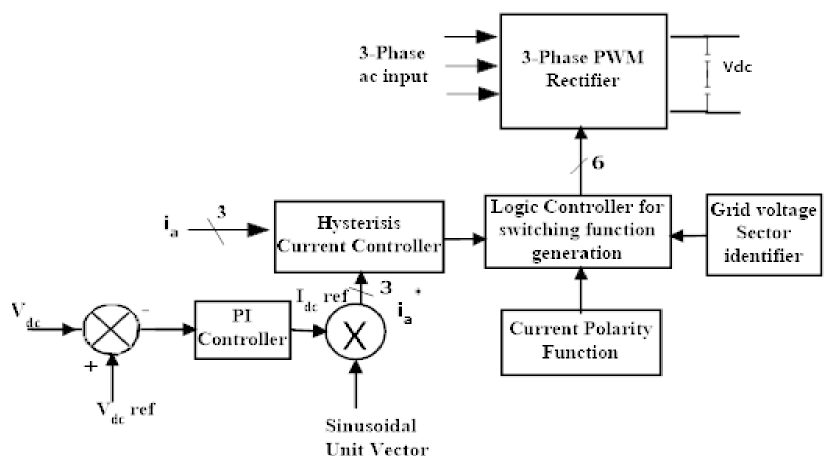

Figure 5: Hysteresis Control with reduced switching loss Algorithm

2.3 ADAPTIVE HYSTERISIS BAND CONTROLLER

The conventional hysteresis current controller (fig.6) operates with a fixed value of bandwidth. The top switch in a particular phase is turned on when the current in that phase $i_x > i_x^* + HB$ and the bottom switch is turned on when the current $i_x < i_x^* + HB$, where i_x is the phase current, and HB represents the hysteresis bandwidth. It offers good dynamic and steady state performance, but the switching frequency varies depending on the instantaneous value of current relative to the fixed bandwidth. Again as the bandwidth decreases the range of variation of switching frequency increases. This variable switching frequency results in increased switching losses as well as it makes the input filter design more complex. Adaptive Hysteresis Band current controller makes use of a variable bandwidth in order to maintain near constant switching frequency.

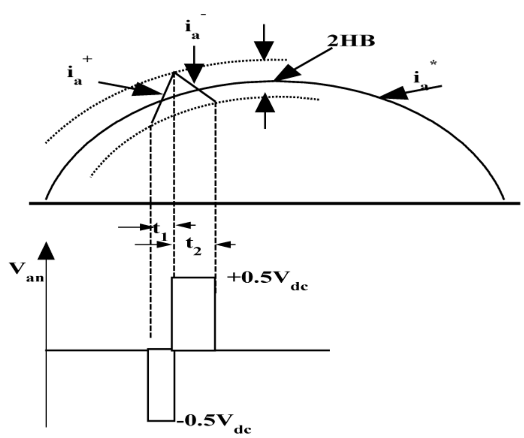

Figure 6: Current and voltage wave with constant HB

The adaptive hysteresis bandwidth can be calculated from the system steady state performance equations and assuming a near constant switching period [5].From the basic per phase b

$$v_s(t) - L\frac{di_a^{+}}{dt} + \frac{V_{dc}}{2} = 0 \tag{1}$$

$$v_s(t) - L\frac{di_a^{-}}{dt} - \frac{V_{dc}}{2} = 0 \tag{2}$$

The slope of the current can be obtained from fig.6 as

$$\frac{di_a^{+}}{dt}t_1 - \frac{di_a^{*}}{dt}t_1 = 2HB \tag{3}$$

$$\frac{di_a^{-}}{dt}t_2 - \frac{di_a^{*}}{dt}t_2 = -2HB \tag{4}$$

$$HB = \frac{V_{dc}}{8Lf}\{1 - \frac{4L^2}{V_{dc}^{\ 2}}[\frac{v_s(t)}{L} - m]^2\} \tag{5}$$

where m is the slope of the reference current wave, Vdc is the dc bus voltage and L is the filter inductance. Here the hysteresis bandwidth varies depending on the instantaneous value of the system parameters as given by (5) so that the switching frequency f is maintained constant.

2.4 DESIGN OF THE PI CONTROLLER

The magnitude error in dc voltage is used to regulate the dc voltage at a fixed value. Consider the RC circuit at the output side, the equivalent diagram of the dc voltage regulation loop can be as shown in fig. 7. The output current

$$i = k_1\Delta V_{dc} + \int k_2\Delta V_{dc}dt \tag{5}$$

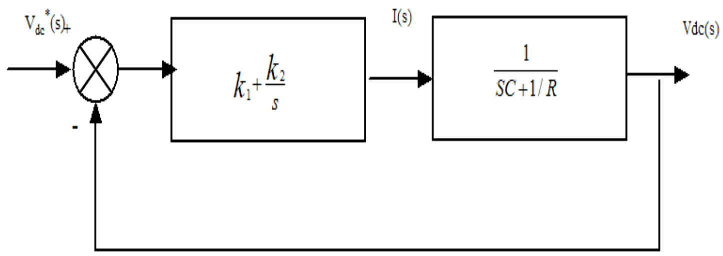

Figure 7: PI controller for dc voltage regulation

where k_1 and k_2 are the proportional and integral gains of the loop respectively.Closed loop transfer function is given by

$$\frac{V_{dc}(s)}{V_{dc}^*(s)} = \frac{k_1 R(s + \frac{k_2}{k_1})}{(s^2 + 2\xi\omega_n s + \omega_n^2)} \tag{7}$$

Where $k_1 = 2\xi\omega_n C - 1/R$ and $k_2 = \omega_n^2 C$

3. SIMULATION RESULTS AND ANALYSIS

In order to evaluate the performance of the reduced switching loss algorithm based PWM rectifier, it has been simulated using Matlab/Simulink with the system parameters given in Table 2. The test model consists of three leg power converter with IGBT and antiparallel diodes.Firstly the capability of the converter with reduced switching algorithm in providing regulated and ripple free dc output for varying loads is checked. In addition, the total harmonic distortion (THD) and disturbance in utility grid amid the varying load conditions is also analysed. Secondly a comparative study of the converter has been made with a conventional hysteresis controller and with the adaptive controller with and without the reduced switching loss algorithm.

3.1. Performance of the Adaptive Hysteresis Controller With Reduced Switching Loss Algorithm

To evaluate the dynamic performance of the converter, the load current, load voltage and grid currents are observed during start up and for a sudden load change during steady state and then for a reference load voltage change. Fig.8 shows the waveforms of output voltage along with reference, load current and per phase grid current with a step change in output voltage from 700V to 600V at t=0.125 sec and a change in load current from 50% to 100% of full load at t=0.25sec. Also the steady state grid voltage per phase scaled down to one tenth and grid current are shown in fig.9, indicates that the current is in phase with the corresponding phase voltage. Fig.10 illustrates the current and voltage variation of a controlled switch. As it can be seen, the switch is kept in the off state during one third of a half cycle period and also the maximum current through the switch is only 0.866 times the peak value of per phase current. The current rating can be lowered in this case. The source current THD is only 2.77% as depicted in fig.11, which shows the harmonic spectrum of source current for a switching frequency of 20kHz. From the dynamic performance analysis of the system, it is observed that the adaptive hysteresis controller with reduced switching loss is able to provide excellent dc output voltage regulation with negligible ripple content (less than 0.05%). The controller also stabilizes the output voltage to the new command value within a short time (less than 0.03 sec) with minimum disturbance in input current and load current. The input power factor is maintained to near unity value (0.995) within the complete frequency range of operation.

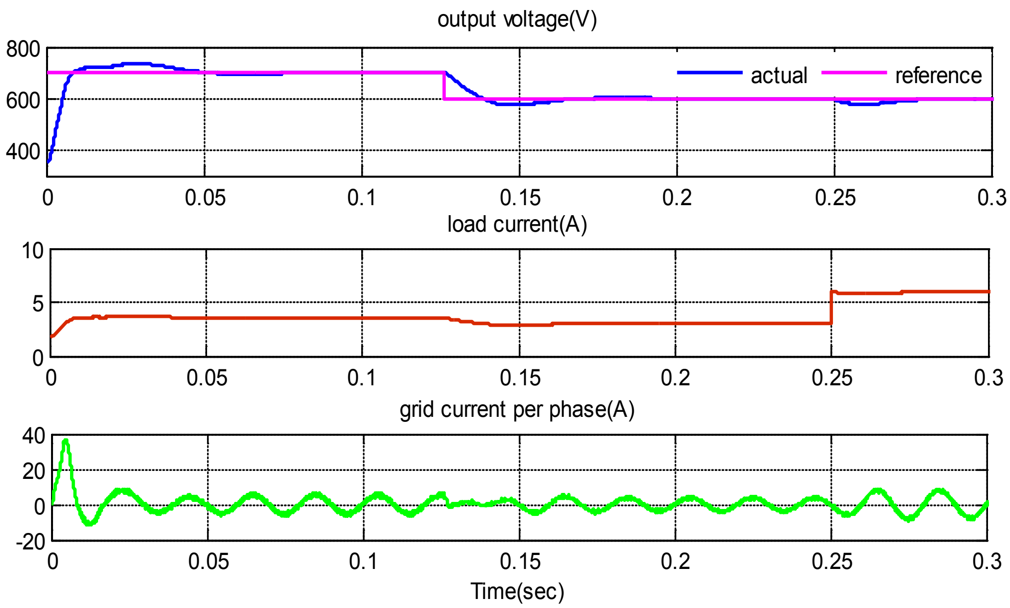

Figure 8: Dynamic Performance of the adaptive hysteresis Controller with reduced switching loss algorithm

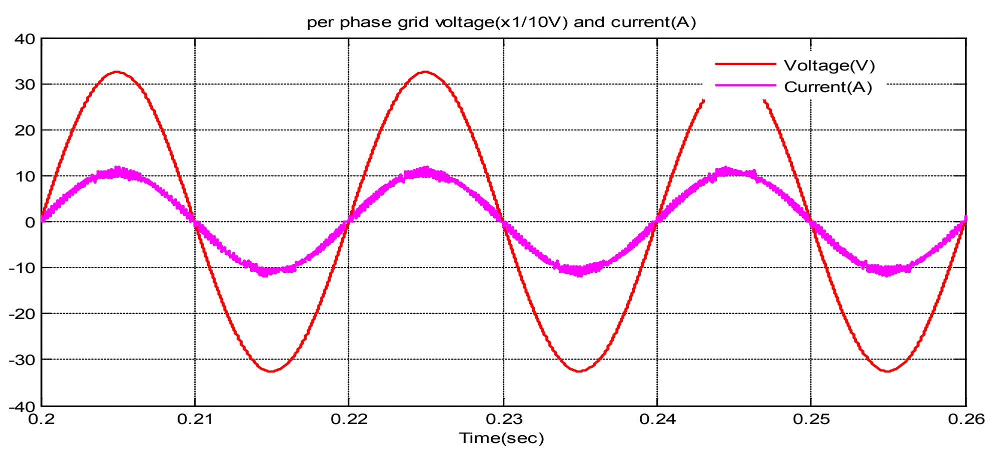

Figure 9: Source voltage and current/phase

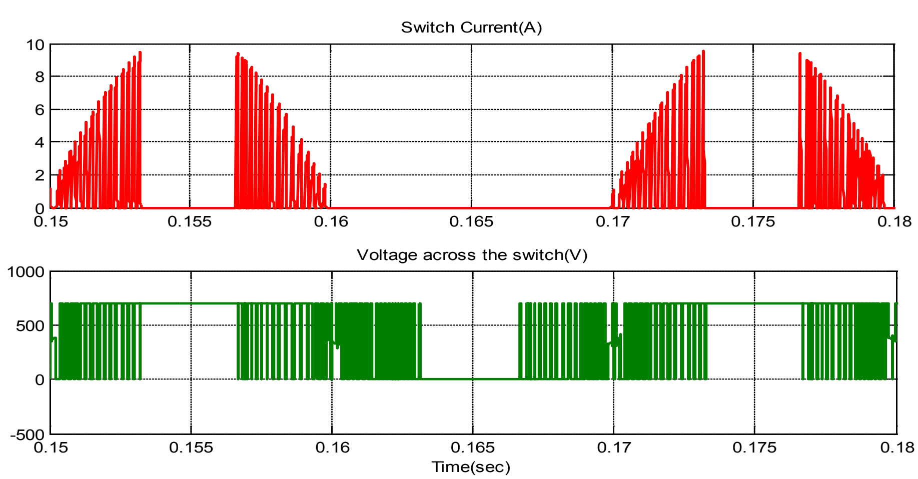

Figure 10: Switch current and voltage

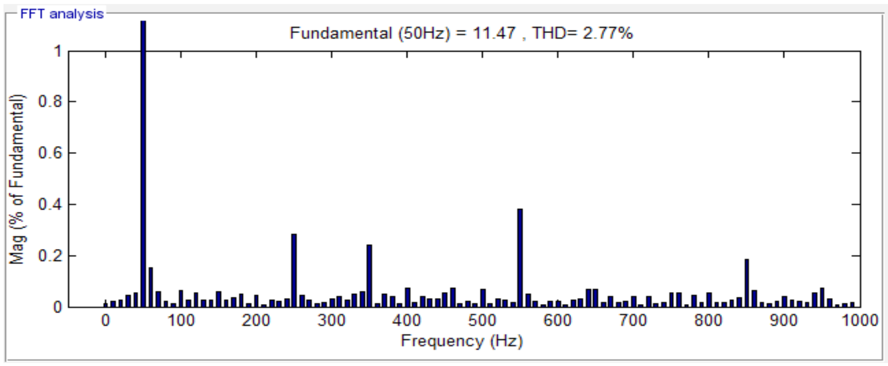

Figure 11: Harmonic Spectrum of grid current

3.2. Comparison of Performance of the Constant Bandwidth Controller with and Without Reduced Switching Loss Algorithm

Performance of the constant hysteresis band current controller with reduced switching loss algorithm has been compared with a conventional hysteresis controlled model.Various performance parameters such as the switching loss,overall efficiency and input current THD are compared for the two schemes with respect to the hysteresis bandwidth and the results are analyzed. Average reduction in switching loss per switch can be found as 30% and is shown in Fig.12,with the addition of reduced switching loss algorithm into the conventional controller.

Fig. 13 shows the increased efficiency when the reduced switching loss algorithm is added to the conventional controller and it is found that there is an average 4% increase.The input current thd is almost within the allowable limits for both the schemes as in fig. 14. Indeed all these parameters depend on the set value of hysteresis bandwidth.It can be observed as the bandwidth increases, switching frequency decreases and hence the loss decreases. Even when the number of controlled switches is limited to two in this case, the switches operate with variable frequency and hence the reduction in loss is less. The dynamic performance, the dc voltage regulation and the input current quality of this constant bandwidth controller is as good as that of the adaptive counterpart. The input power factor for the entire range of hysteresis bandwidth is observed near to unity (0.999) and the total harmonic distortion profile of the converter is excellent and meets with IEEE 519-1992 standards.

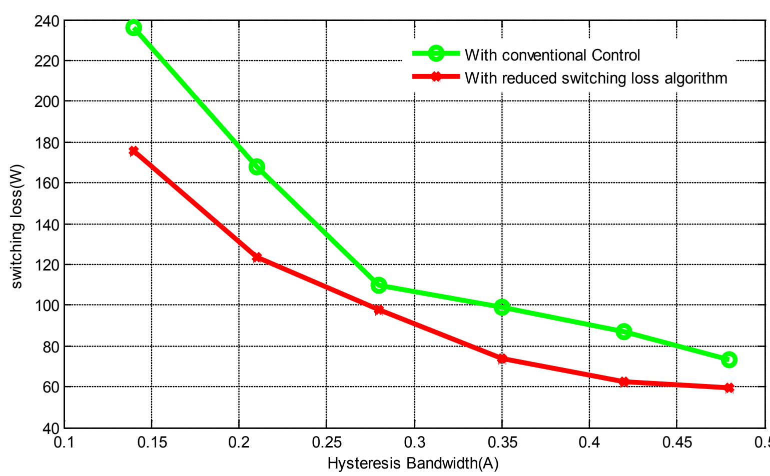

Figure 12: Variation of Switching loss with HB

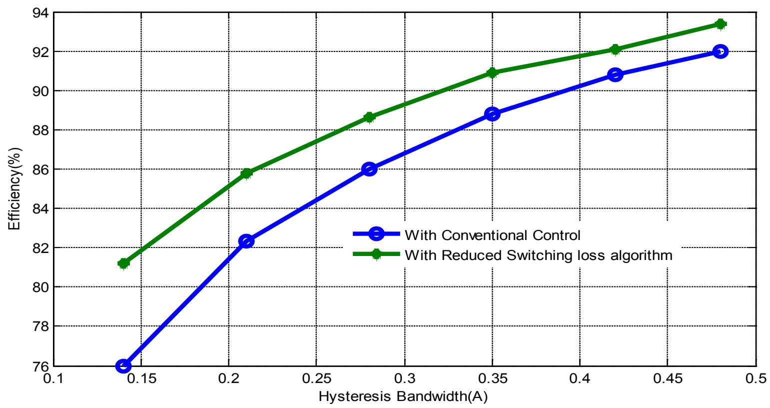

Figure 13 : Variation of efficiency with HB

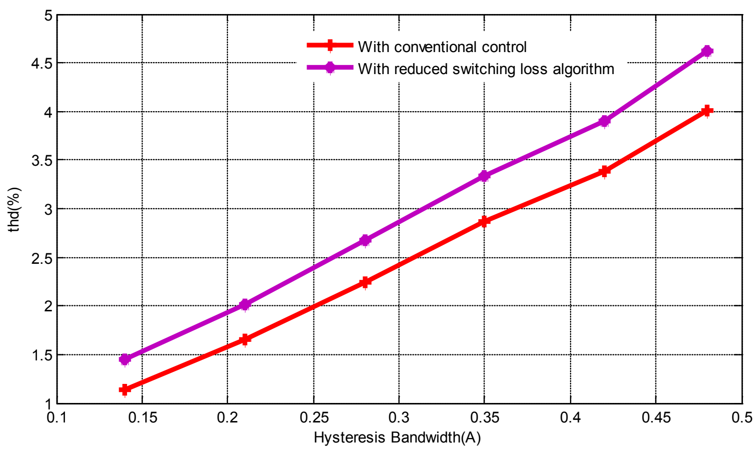

Figure 14: Variation of thd with HB

Table 2
Power System configuration

Parameters	*Value*
Phase Voltage (rms) and frequency	230V,50Hz
Line inductance	10mH
DC side Capacitance	500µF
Load Resistance	100Ω
Sampling frequency for simulation	1MHz

3.3. Comparison of Performance of the Adaptive Hysteresis Controller with and Without Reduced Switching Loss Algorithm

The comparative analysis is now made on the performance of adaptive hysteresis controller with the reduced switching loss algorithm with that of the adaptive hysteresis controller. As the bandwidth of the adaptive controller depends on system parameters as given by (6), the switching frequency of operation is treated as the variable parameter for all the analysis. Fig.15 shows the average switching loss per switch for the converter with only adaptive control and the controller with the switching loss algorithm incorporated for various switching frequencies. As is clear, the loss increases directly with switching frequency, and an average 60% reduction in switching loss per switch can be achieved with the added algorithm. Overall efficiency of the converter is also compared for both the cases and is seen from fig.16 that the increase in efficiency is about 8% due to the reduction in switching loss. The input current THD is within the limits of 5% for switching frequencies higher than 10 kHz as depicted in fig.17.

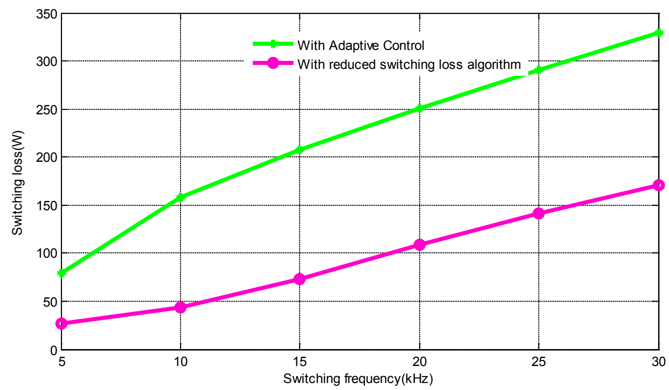

Figure 15: Variation of Switching loss with switching frequency

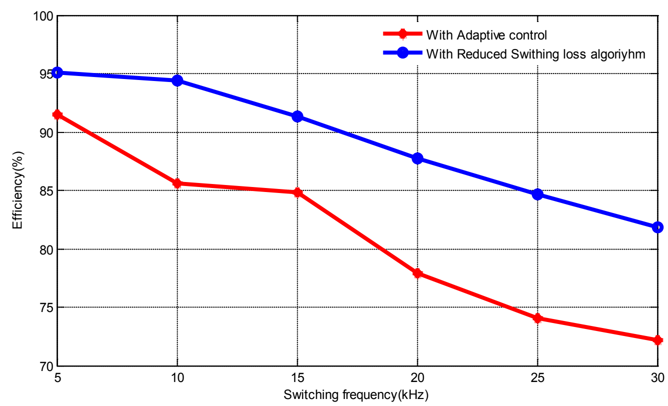

Figure 16: Variation of Efficiency with switching frequency

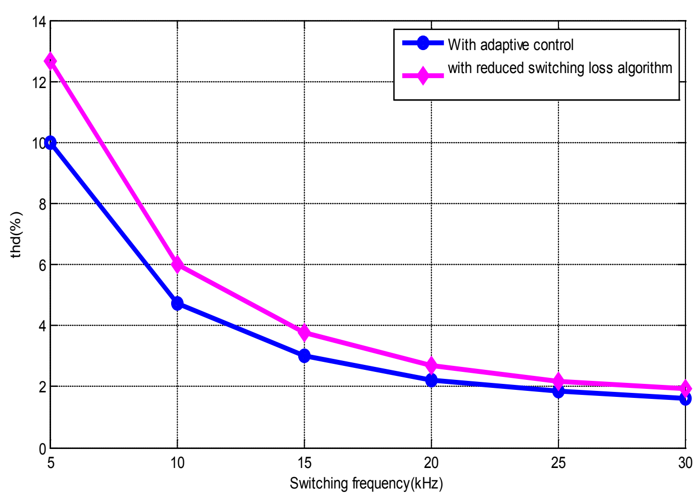

Figure 17: Variation of THD with switching frequency

4. CONCLUSION

A comprehensive analysis of the three phase PWM rectifier with constant and adaptive hysteresis band current controllers has been done. Performance of the controllers with and without reduced switching loss algorithm have been explained and compared. Among the various performance indices, the switching loss, efficiency and the THD factor of input currents are observed for all the control schemes and is found that the reduced switching loss algorithm based adaptive hysteresis controller gives the best performance among all the schemes. Constant hysteresis bandwidth controller also performs good except that the switching frequency is variable and as a result the switching loss is higher. It can be concluded that the reduced switching loss algorithm incorporated into the adaptive hysteresis current controller reduces the switching loss considerably. Since the switching loss contributes to a major factor in the overall efficiency of the rectifier, the operating cost of the system can be reduced. The heat sink requirements of the switches, device ratings, manufacturing cost of the rectifier and the physical size of the rectifier system can also be rduced with the introduction of the reduced switching loss algorithm.

References

[1] C. Y. Lee, D. Boroyevich, and S. Hiti, "Review of high-performance three-phase power-factor correction circuits," *IEEE Trans. Ind. Electron*., vol. 44, no. 4, pp. 437–446, 1997.

[2] H. Rodriguez-Cortes, R. Alvarez-Salas, M. Flota-Banuelos, and M. F. Escalante, "Power factor compensation and DC-link voltage regulation for a single-phase PWM multilevel rectifier," *IET Power Electron*., vol. 5, no. 8, p. 1456, 2012.

[3] Y. Tang, P. C. Loh, P. Wang, and F. H. Choo, "One-Cycle-Controlled Three-Phase PWM Rectifiers With Improved Regulation Under Unbalanced and Distorted Input-Voltage Conditions," *IEEE Trans. Power Electron*., vol. 25, no. 11, pp. 2786–2796, Nov. 2010.

[4] M. Malinowski, M. P. Kazmierkowski, and a. Trzynadlowski, "Review and comparative study of control techniques for three-phase PWM rectifiers," *Mathematical Computer Simulation*, vol. 63, no. 3-5, pp. 349-361, Nov. 2003.

[5] A. M. Razali and M. A. Rahman, "Performance Analysis of Three-Phase PWM Rectifier Using Direct Power Control," *Electric machines and drives conference*, pp. 1603-1608, 2011.

[6] M. Malinowski, M. Jasin, and M. P. Kazmierkowski, "Simple Direct Power Control of Three-Phase PWM Rectifier Using Space-Vector," vol. 51, no. 2, pp. 447-454, 2004.

[7] M. Malinowski, S. Member, M. P. Kazmierkowski, and S. Hansen,"Virtual-Flux-Based Direct Power Control of three-phase PWM rectifiers" vol. 37, no. 4, pp. 1019-1027, 2001.

[8] Fujita H,Tominaga, Akagi H, "A practical approach to switching-loss reduction in a large-capacity static VAr compensator based on voltage-source inverters", Industry Applications, IEEE Transactions on, Volume: 36, Issue: 5, 2000.

[9] Kaku B, Miyashita IN one, S., "Switching loss minimised space vector PWM method for IGBT three-level inverter", *Electric Power Applications, IEE Proceedings*, Volume: 144, Issue: 3, 2002.

[10] E. M. Suhara, M. Nandakumar, "Analysis of Hysteresis Current Control Techniques for Three Phase PWM Rectifiers." *Signal Processing, Informatics, Communication and Energy Systems (SPICES),* 2015 pp. 1-5.

[11] M N Kumar, K Vasudevan, "Bi-directional real and reactive power control using constant frequency hysteresis control with reduced losses", *Electric Power Systems Research*, Elsevier 2005.