IJREAT International Journal of Research in Engineering & Advanced Technology, Volume 1, Issue 1, March, 2013
ISSN: 2320 - 8791
www.ijreat.org

A High Power Density Single Phase Pwm Rectifier with Active Ripple Energy Storage

A. Guruvendrakumar[1] and Y. Chiranjeevi[2]

[1] Student (Power Electronics), EEE Department, Sathyabama University, Chennai, India

[2] Assistant Professor, EEE Department, Sathyabama University, Chennai, India

Abstract

It is well known that there exist second-order harmonic current and corresponding ripple voltage on dc bus for single phase PWM rectifiers. The low frequency harmonic current is normally filtered using a bulk capacitor in the bus which results in low power density? This project proposed an active ripple energy storage method that can effectively reduce the energy storage capacitance. The feed- forward control method and design considerations are provided.

Keywords: *High power density converter, Single phase rectifier, Ripple energy, Active energy storage.*

1. Introduction

Fault-tolerant multi-phase converter systems have been extensively researched for aircraft application because of their inherent fault tolerance capability [1]. Accordingly high power density single phase converter modules are desirable for such systems. One of the Important characteristics of the single-phase system is the low-frequency ripple on the dc link when the ac input voltage and current are sinusoidal. To limit this low-frequency ripple, a bulk electrolytic dc-link capacitor is usually required, which results in large converter volume, low power density and poor life-time due to the electrolytic capacitors needed. To improve the power density of a single-phase converter, it is essential to reduce the dc-link capacitor required for filtering the low-frequency ripple energy [2]. Some active methods for ripple reduction are summarized and classified in a previously published work [3]. In addition, the previous work verified the feasibility of increasing the system power density by using active ripple energy storage method. In this paper, a high power density single phase PWM rectifier is proposed and a feed-forward control method is provided. This feed-forward method can help the auxiliary active energy storage circuit working as a parallel active power filter for filtering out the low frequency ripple current from the H-bridge rectifier. The detailed design considerations are provided. Finally, a 15W hardware prototype is developed and the experimental results are provided.

2. Proposed Single Phase PWM Rectifier

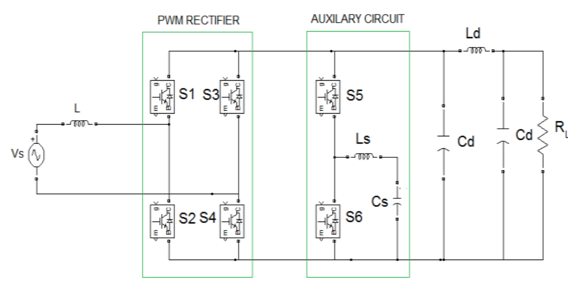


Fig 1: Proposed single phase pem rectifier

The proposed topology of the ripple energy storage method is depicted in Fig.1. A bidirectional buck-boost converter is connected as auxiliary circuit at the output of a typical single-phase bidirectional PWM rectifier. Since second-order harmonic current is generated from the single phase H-bridge rectifier, the auxiliary circuit is used as a parallel current filter. An auxiliary capacitor, with capacitance Cs, is used as an energy storage element; while the inductor Ls is used as an energy transfer component. A dc-link capacitor, with capacitance Cd, is still needed at the output of the PWM rectifier to filter the switching ripple energy and the residual second-order harmonic ripple energy not fully absorbed by the auxiliary capacitor Cs. S5 is controlled as a buck switch for charging and S6 is controlled as a boost switch for discharging. The current of switch S5 is discontinuous, so this auxiliary circuit can only be used as low frequency current filter which is typical for single phase. Meanwhile, there is no voltage higher than the dc bus existing in this system and the auxiliary circuit can be integrated together with the main circuit easily as one additional phase leg.

The single phase rectifier parameters for the sample system are summarized in TABLE.I.

TABLE 1. Parameters of the single phase pwm rectifier

PARAMETERS	VALUE
VOLTAGESOURCE(PEAK)	15 V
AC SUPPLY FREQUENCY	233 HZ
INPUT INDUCTOR	350 MH
OUTPUT VOLTAGE	28V
OUTPUT POWER	15W

3. Control Analysis

As mentioned above, there exists second-order ripple power in the single phase system. The ripple power after the H-bridge can be expressed as:

$$P_r = P_{r\_peak}\sin(2\omega t) \qquad (1)$$

where ω is the supply frequency.

Assume all the ripple energy is stored in the auxiliary capacitor.

$$\frac{dU^2_{cs}}{dt} = \frac{2\cdot P_{r\_peak}}{C_s}\sin 2\omega t \qquad (2)$$

With this, the low frequency ripple current and ripple voltage in the capacitor are shown in (3), (4) and Fig.2.

$$U_{cs} = \sqrt{Const - \frac{P_{r\_peak}}{C_s\omega}\cos 2\omega t} \qquad (3)$$

$$i_{cs} = \frac{P_{r\_peak}\sin 2\omega t}{\sqrt{Const - \frac{P_{r\_peak}}{C_s\omega}\cos 2\omega t}} \qquad (4)$$

$$Const = k\times\frac{P_{r\_peak}}{C_s\omega} \quad (k \geq 1).$$

If we consider total charge and discharge,

$$Const = \frac{P_{r\_peak}}{C_s\omega}$$ is desired.

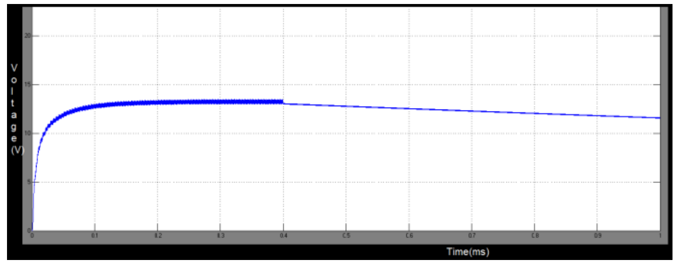
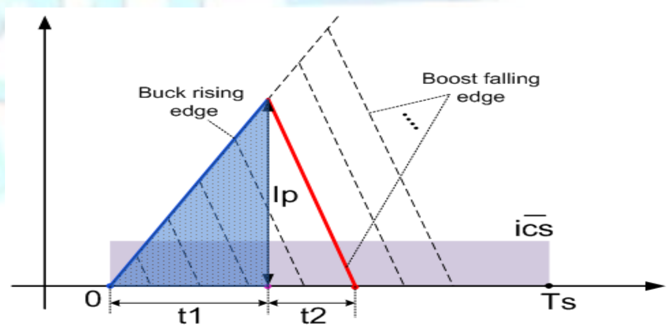
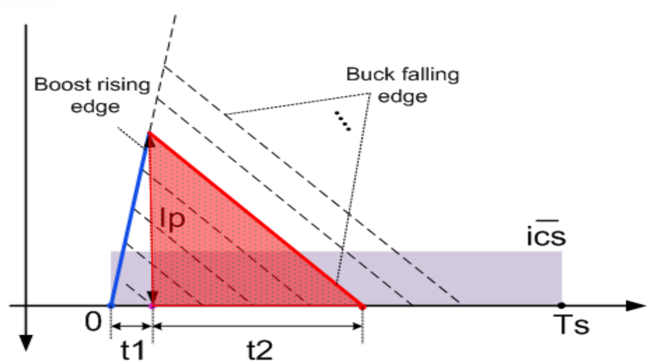


Fig 2: Low-frequency capacitive voltage

The energy storage capacitor Cs is selected as 140μF to meet the minimum requirement and the energy transfer inductor Ls is designed as 40μH according to (15) and (16) in the design consideration section. Due to that, the switching frequency 20 kHz is much higher than the Ls and Cs resonant frequency. At each switching period, the dc-link voltage and auxiliary capacitor voltage can be considered as quasi-static. This means the inductor charging slope and discharging slope can each be considered as a fixed value within each switching period.



(a) Charging phase



(b) Discharging phase

Fig.3. Charging and discharging phases duty-cycle generation strategy

The inductor current in Fig.3 (a) shows the charging phase for one switching period, and Fig.3 (b) shows the discharging phase for one switching period. The aim is to control the average inductor current (the inductor and capacitor currents are same) to match the reference which is derived in (4). Defining the boost and buck slopes as (5) and (6):

$$Boost\_slope = \frac{U_{cs}}{L} \tag{5}$$

$$Buck\_slope = \frac{U_d - U_{cs}}{L} \tag{6}$$

For the charging phase, the time interval relationship between t1 and t2 can be expressed as:

$$t2 = \frac{Buck\_slope}{Boost\_slope} \times t1 \tag{7}$$

According to the control objective, the average current within one switching cycle should be equal to the current reference, that is:

$$\frac{1}{2}(t1 + \frac{Buck\_slope \cdot t1}{Boost\_slope}) \cdot Buck\_slope \cdot t1 = \bar{i}_{cs} \cdot T_s \tag{8}$$

Then, the duty cycle for the charging and discharging phases can be derived as (9) and (10). By using these equations, the second-order ripple energy can be accurately filtered out from the H-bridge.

$$D1 = \sqrt{\frac{2 \cdot \bar{i}_{cs} \cdot f_s}{(1 + \frac{Buck\_slope}{Boost\_slope}) \cdot Buck\_slope}} \tag{9}$$

$$D1 = \sqrt{\frac{2 \cdot \bar{i}_{cs} \cdot f_s}{(1 + \frac{Boost\_slope}{Buck\_slope}) \cdot Boost\_slope}} \tag{10}$$

Equations (9) and (10) determine the duty cycle control laws for the charging and discharging operating modes. For a practical implementation, it is not easy to determine the auxiliary capacitor current reference in (4). A more straightforward, but similar current filter method, is shown in Fig.4. The compensation current is used to regulate the low frequency ripple current. In Fig.3, the triangular shaded area is the current waveform of the compensation current. Using the previous method, the average compensation current within one switching period should be equal to the low frequency ripple current, then the duty cycle for the charging and discharging phases are derived as (11) and (12).

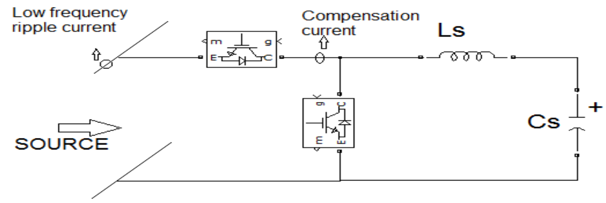


Fig.4. Auxiliary circuit working as a parallel active ripple current filters

$$D1 = \sqrt{\frac{2 \cdot \bar{i}_{comp} \cdot f_s}{Buck\_slope}} \tag{11}$$

$$D1 = \sqrt{\frac{2 \cdot \bar{i}_{comp} \cdot f_s \cdot Buck\_slope}{Boost\_slope^2}} \tag{12}$$

The control schematic of the system is shown in Fig.4. The rectifier duty cycle and the measured ac-side current are used to generate the ripple current reference for the auxiliary circuit. The dc link voltage and auxiliary capacitor voltage are sensed to generate the duty cycle for both charging and discharging phases. Within the duty cycle generation block, if the compensation current is positive, the auxiliary circuit is controlled in buck mode to assimilate the ripple power from the dc link charging the auxiliary energy storage capacitor. Similarly, when the compensation current is negative, the auxiliary circuit is controlled in boost mode to release the ripple energy stored back into the dc link. The auxiliary capacitor mean voltage control loop is required to prevent the Cs from over charging or undercharging. The PLL block is designed as shown in fig.

4. Design Considerations

For single phase H-bridge rectifier, the modulation method is specified to achieve both the minimum loss and balanced temperature distribution. For the auxiliary circuit, the auxiliary capacitor is selected according to the ripple energy requirements and the auxiliary inductor is designed as below.

4.1 Modulation method

Fig.6 shows the single phase discontinuous PWM modulation method [5]. One phase leg will not switch within half of the supply frequency. It can lead to the minimum switching loss.

IJREAT International Journal of Research in Engineering & Advanced Technology, Volume 1, Issue 1, March, 2013
ISSN: 2320 - 8791
www.ijreat.org

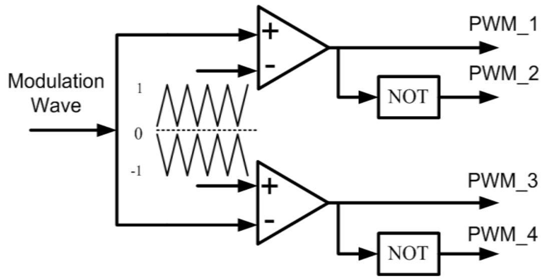


Fig.5. *Single phase discontinuous PWM modulation method*

4.2 Auxiliary inductance selection

There are two criteria for selecting the auxiliary inductance: Peak current boundary and the Discontinuous Current Mode (DCM) boundary. The maximum current in the auxiliary circuit must be smaller than the peak current requirement of the selected power semiconductor:

$$Buck\_slope \times D1 \times T_s \le I_{peak} \quad (13)$$

$$Boost\_slope \times D1 \times T_s \le I_{peak} \quad (14)$$

Then, the auxiliary inductance selection based on the peak current requirement is calculated as:

$$L_s \ge \frac{2 \cdot \overline{i}_{cs} \cdot T_s}{I_{peak}^2} \cdot \frac{U_d U_{cs} - U_{cs}^2}{U_d} \quad (15)$$

Meanwhile, as shown in Fig.3, in order to maintain DCM operation, subinterval t1 plus subinterval t2 should smaller than switching period Ts. Then, the auxiliary inductance selection based on the DCM requirement is calculated as:

$$L_s \le \frac{T_s}{2 \cdot \overline{i}_{cs}} \cdot \frac{U_d U_{cs} - U_{cs}^2}{U_d} \quad (16)$$

5. Simulation and Experimental Results

The High power density single phase PWM rectifier is simulated using Mat lab and the results are presented.

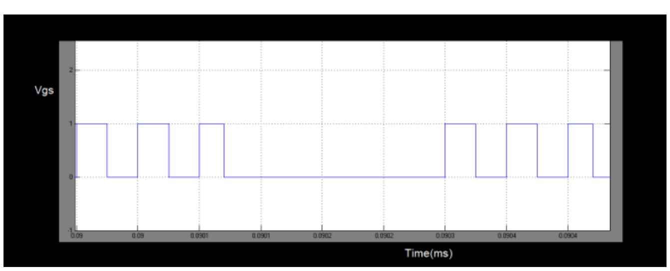


Fig 6. Gate pulses

5.1 Single phase pwm rectifier with c filter

The circuit consists of AC input source, PWM rectifier, Auxiliary circuit, filter and load. The AC input voltage is converted into DC voltage. DC voltage is given to auxiliary circuit and auxiliary output is given to c filter.

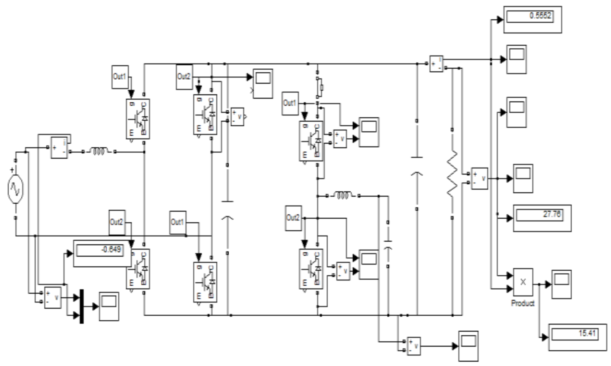


Fig 7. Open loop single phase pwm rectifier with c filter

C filter is used to reduce the ripple from output voltage. C filter having capacitor it will reduce the ripple from output voltage. Scopes are connected in the circuit to measure the pulses and output voltage, output current, etc.

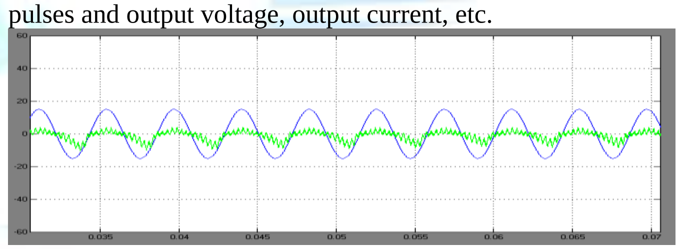


Fig 7. Input voltage and current

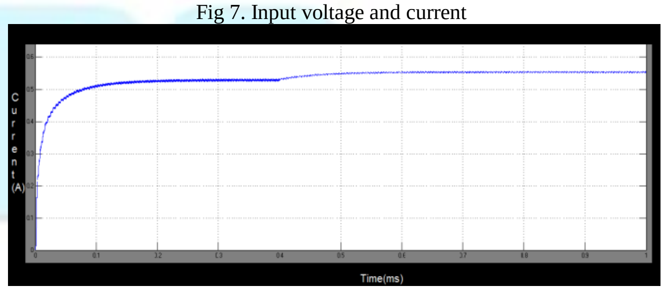


Fig 8. Output voltage

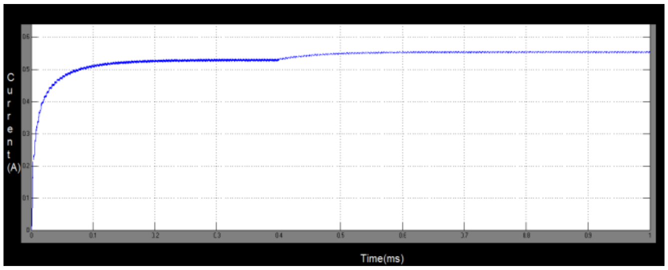


Fig 9. Output current

5.2 Single phase pwm rectifier with PI filter

The single phase pwm rectifier with PI filter which can be formed by using inductance and single capacitance

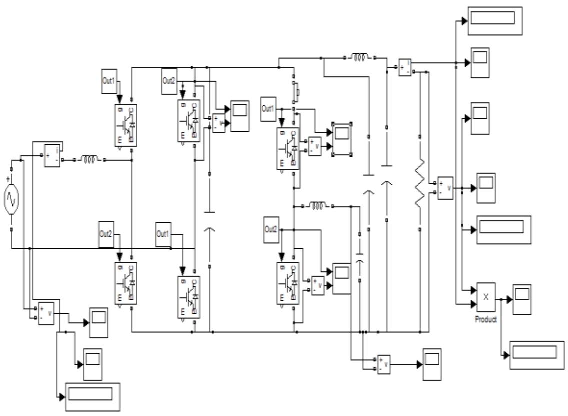


Fig 10**.** Open loop single phase pwm rectifier with PI filter

Compare to the C filter, PI filter has smooth and ripple free output waveforms. But PI filter has very less ripple than the C filter. Normally ripple is removed from the voltage but in this method ripple is removed and that removal ripple is stored in the capacitor and peak condition ripple is given to the output.

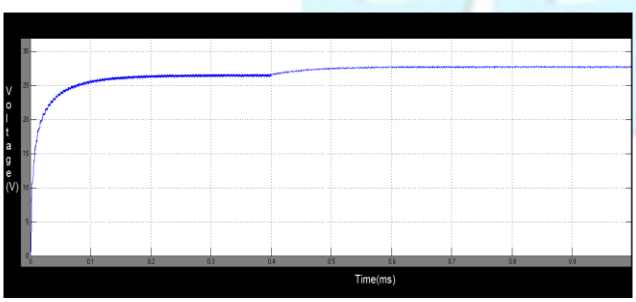


Fig 11. Output voltage

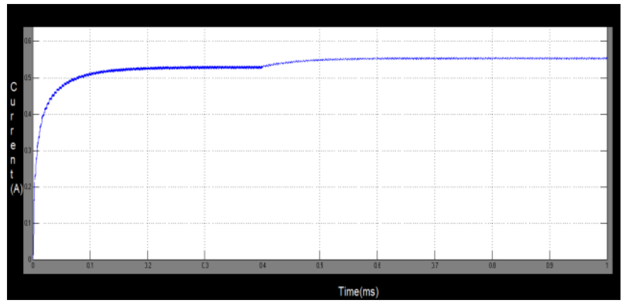


Fig 12. Output current

4. Conclusions

This project has presented an active ripple energy storage method is proposed to increase the single phase PWM rectifier's power density. Based on simulation and experiment, the following conclusions can be drawn: Firstly, the proposed auxiliary circuits will bring no voltage higher than the dc bus in the system and it can be easily integrated together with the H-bridge rectifier as an additional phase leg. Different from the traditional parallel active power filter, the auxiliary circuit compensation current is in discontinuous current mode so that it can only filter out the low frequency ripple current that dominates in single phase rectifier system. Secondly, the proposed feed-forward control method can generate the compensation current reference as fast as one switching period and can effectively filter out the low frequency ripple current from the H-bridge rectifier. Thirdly, although the total capacitance will decrease dramatically compared with traditional method, the total ripple current in capacitors will increase by using the active method. Finally, simulation and hardware prototype experimental results were provided for verification purposes.

The Basic circuit and modified circuit elements are designed using relevant equations. The simulation circuits are developed using elements of simulink library. The Simulation is successfully done and open loop / closed loop simulation results are presented. The Simulation results coincide with the theoretical results.

References

[1] Jack .G, B. C. Mecrow, and J. A. Haylock (1996), "A comparative study of permanent magnet and switched reluctance motor for high-performance fault-tolerance", IEEE Trans on Ind. Appl., vol. 32

[2] Kolar .J .W, U. Drofenik, J. Biela, M . L. Heldwein, H. Ertl, T. Friedli, and S. D.Round (2007), "PWM Converter Power Density Barriers". Power Conversion Conference Nagoya,. PCC '07.

[3] Rudi Wang, Fred Wang, Puqi Ning, Rixin Lai, Rolando Burgos, Dushan Boroyevich (1996), "Study of Energy Storage Capacitor Reduction for Single Phase PWM Rectifier" . IEEE Applied Power Electronics Conference.
[4] Timothy Thacker, Ruxi Wang, Dong Dong, Rolando Burgos, Fred Wang, Dushan Boroyevich (2008), "Phase-Locked Loops using State Variable Feedback for Single-Phase Converter Systems". IEEE Applied Power Electronics Conference.
[5] Thomas A, D.Grahame Holmes. Lipo (2003) "Pulse Width Modulation for Power Converters: Principles and Practice". A John Wiley & Sons, INC. Publication.
[6] Venkatachalam, K. Sullivan, C.R. Abdallah, T. Tacca (2002), H."Accurate prediction of ferrite core loss with nonsinusoidal waveforms using only Steinmetz parameters" . Computers in Power Electronics,. IEEE Workshop on. 1383.