FPGA Based Single Phase Power Factor Correction Using Boost Converter

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Abstract: Most electronic equipment works on DC. So AC to DC converter is an important part of power supply. But during this AC to DC conversion not all the input power is delivered to load. Some amount of power is wasted during the conversion process. Thus extra power will be drawn from the supply to compensate this wasted power. Thus the power factor of the system will be very poor. To reduce this wastage and improve power factor we are going for power factor correction. A single phase AC-DC boost converter is addressed in this paper. This paper describes mainly on the control mechanism using hysteresis mode control using a half bridge converter with output LCL filter. Control signals are generated using Spartan 6 FPGA board with software implemented on Xilinx using Verilog code.

Keywords: - Single phase AC-DC boost converter, Power factor correction(PFC), Hysteresis mode control, Half bridge converter, LCL filter, Spartan 6 FPGA board.

I. INTRODUCTION

Nowadays there are numerous appliances where DC power supply is required. So in order to obtain DC power, there must be an interface between AC line and DC load. This conversion is carried out by diode rectifiers. Most of power electronics system which is getting connected to AC utility uses diode rectifier at input. So AC to DC converter is an important part of power supply. But during this AC to DC conversion not all the input power is delivered to load. Some amount of power is wasted during the conversion. Thus some extra power is drawn to compensate the wasted power. This leads to the need for the creation of efficient power converters. The main aim of power conversion is to provide a high quality power conversion. Two main goals are pursued in order to design the efficient ac/dc power converter. First one is to keep the power factor value as close as possible to unity and the second one is to achieve efficient load voltage regulation to a desired constant level.

The efficiently by which current is being converted into real work is specified by power factor. The ratio between the real power to the total apparent power consumed by a load is called power factor. If the power factor is less than unity, then extra power is needed to achieve the actual task at hand. Power factor value reflects the efficiency and quality of a power conversion process. A converter with a unity value power factor doesn't add any distortion and also improves the efficiency of the power conversion. Two main aspects have to be considered while designing a power converter. One is the hardware topology and another one is the control algorithm. Many schemes and solution are introduced for performing power factor correction. The two type of PFC are active and passive. A number of passive and active PFC correction methods are proposed. Passive PFC correction methods which use L and C components are used for linear loads. But for non-linear loads active PFC methods are used because of their improved performance. Topologies mainly used for PFC correction are buck, boost and buck-boost. Topology of boost is relatively simple and it gives low distorted currents with almost unity power factor employing different control techniques. The boost converter along with single phase diode rectifier is widely used in active PFC [1]. Control algorithm using current control methods include peak current control scheme, average current control scheme, borderline control scheme and hysteresis control scheme. Hysteresis current control is a simple method for PWM technique with comparatively better current loop response.

This project mainly focuses on the control part of the power factor correction. This is implemented using FPGA. Control method used here is hysteresis control scheme. It is demonstrated using half bridge converter with output LCL filter employing voltage mode control.

II. POWER FACTOR CORRECTION

The elimination of charges related to reactive power-consumption is the primary benefit of PFC [1]. Passive PFCs are used in low power application. Passive PFCs employ bulky and heavy components. Passive power factor correction or active power factor correction can improve the power factor. Passive power factor corrections involve

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the use of linear inductors and capacitors to filter or minimize the harmonic components and improve the power factor. But, they also have so many disadvantages: One is that they are relatively bulky. They are highly sensitive to line frequency. Their dynamic response is poor and also lack voltage regulation. Controlled switches are used by active PFCs to force the line current to follow the envelope of the line voltage and go in phase with it. Non-isolated switching power supply topologies, such as buck, boost and buck/boost are employed by active PFCs. The paper [3] proposes active power factor correction technique. This is based upon current wave shaping technique. In this technique the source current is made in phase with the input voltage. Current wave shaping is achieved by implementing by using two control loops. An outer voltage control loop and an inner current control loop. Work carried out by [4] shows the aspects regarding control strategies for Power Factor Correction (PFC) converters. It also describes the major control techniques to absorb sinusoidal input currents in boost PFC's.

III. METHODOLOGY

Power factor correction is done by making the input voltage and inductor current wave form in a boost converter in phase with each other and also achieving a constant output voltage [2]-[3]. Boost converter is shown in Fig.1.

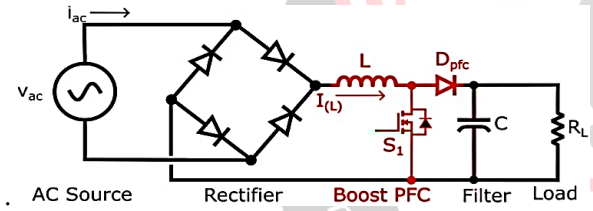

Fig.1 Boost converter section

Boost converter working can be divided into 2 modes.
Mode 1: When switch 'S' is closed, in this mode of operation the switch is in on state. The current flows through switch and inductor. Here the inductor stores the energy. At the same time, the capacitor discharges and supplies current to the load. Mode 1 is shown in Fig.2.

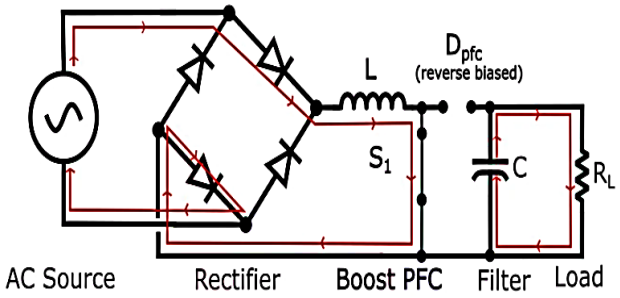

Fig.2 Boost converter with switch (S1) closed

Mode 2: When switch 'S' is open, in this mode of operation the switch is in off state. The current is flowing through the inductor, diode and the capacitor with the load and then return to main. Mode 2 is shown in Fig.3.

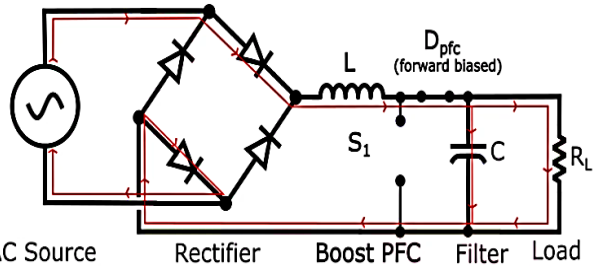

Fig.3 Boost converter with switch (S1) open

Thus from here we can see that the inductor current can be controlled by turning the MOSFET on and off. When we turn on the MOSFET, the inductor current goes on increasing and when we turn off the MOSFET, the inductor current decreases.

3.1 Control technique

The Fig.4 shows the boost converter employed with power factor correction. It consists of three sections: Rectifier, boost converter and a control circuit. In this control technique the inductor current is forced to follow the shape of the rectified ac line voltage.

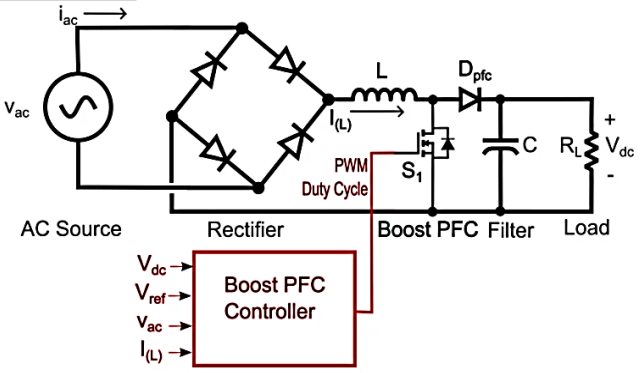

Fig.4 Boost converter with PFC

The boost PFC controller uses two control loops. These are used for maintaining the output voltage constant and also for making the power factor unity. The voltage regulator output is limited to a safe value. This is made as the amplitude of input reference current. The obtained reference amplitude is then multiplied with a scaled version of input voltage. This is done to synchronize the reference with input voltage. This is necessary for performing unity power factor operation. The inductor current is then made to follow its reference current using current controller. This generates corresponding gating signals for controlling the active devices.

3.2 Voltage Control Loop

To regulate the load, the variation between the output voltage and the fixed dc reference is obtained. The voltage control loop maintains the voltage of the capacitor at a set reference value. This is done using feedback action. The error generated at the output is regulated. This is done by incorporating a PI controller (voltage compensator or Integrator).The output of the PI controller is added to the current control loop. This will vary the duty ratio to maintain the DC output voltage constant.

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3.3 Current Control loop

In the current control loop PI controller output is multiplied with unit amplitude sensed rectifier line voltage. This is done to control the inductor current amplitude. Different current control includes hysteresis control, predictive control, linear control and timer controller with constant switching frequency [4]. Here hysteresis control method is used for current control loop.

The advantages for this type of control include no need of compensation ramp, converting a voltage source into a fast-acting current source. The inductor is easy to design, and operating switching frequency is high and low distorted input current waveforms with fixed load. Fig.5 shows hysteresis current control technique for generating the switching pulses required controlling the active devices.

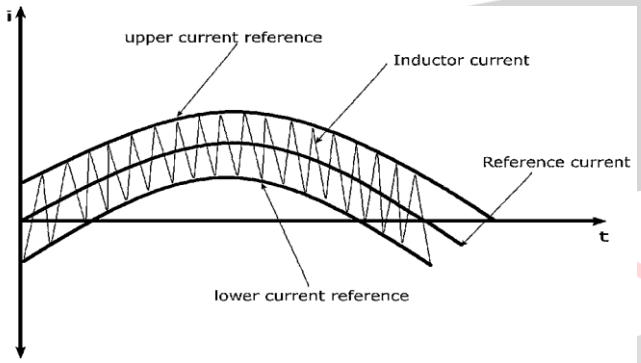

Fig.5 hysteresis current control

Hysteresis current control is adopted here. The upper and lower bands required for the control are generated by adding and subtracting a band to the reference signal respectively [5]. In this process the inductor current is forced to fall within the hysteresis band. Whenever the current goes above the upper hysteresis band, the pulse given is low. This forces the current to fall as the current will flow through the load. When the current goes below the lower hysteresis band, the pulse is high. This will cause the current to increase linearly [6]. In this way the switching of the power switch can be done to track the reference current command. The resultant current drawn by both the loads will be nearly sinusoidal with low harmonic content. Hence the power factor of the supply can be improved.

IV. PROPOSED SYSTEM

We are implementing a half bridge converter with a LCL filter at its output to demonstrate the method of hysteresis mode voltage control.

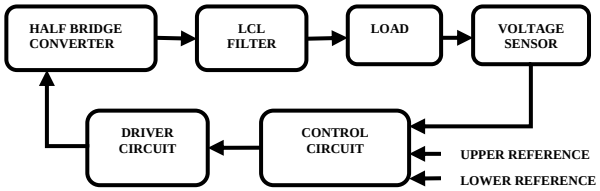

Fig.6 Block diagram of proposed system

Fig.6 shows the proposed block diagram for demonstrating hysteresis voltage mode control mode control. In this a dc voltage is given to a half bridge converter. The output voltage sensor is basically a resistor divider in order to scale the output voltage to a proper value for processing signals. Based on the PWM signals generated the driver circuit drives the MOSFETs to on and off state. The PWM signals are generated by the control circuit by taking the feedback from the converter and also the input reference bands. Control circuit consists of comparators and FPGA. The PWM signals generated by the control circuit should be amplified in order to drive the power MOSFETs.

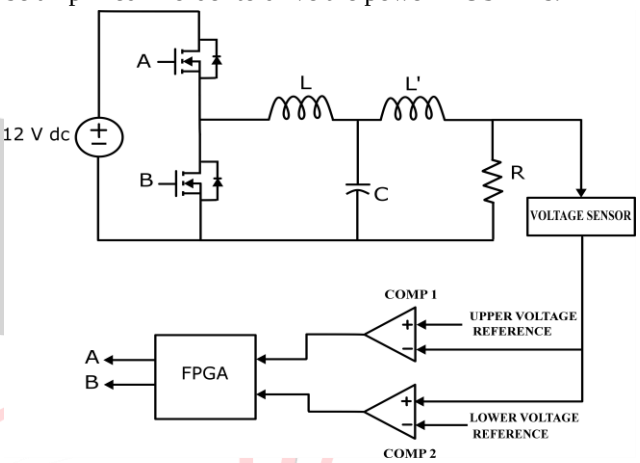

Fig.7 Block diagram of proposed system

Fig.7 shows the proposed circuit diagram for demonstrating hysteresis voltage mode control mode control. When signal A is high and B is low, current through L goes on increasing and capacitor C charges. Some current less than the current through L flows through L'. So current through L' increases slowly as compared to L. Here capacitor C used for filtering purpose that is by increasing time delay for charging the load.

When signal A is low and B is high, initially capacitor C goes on charging as there is still current through the inductor and then starts to discharge in opposite direction. The current through L' flows towards the load. From this we can analyze that there is bidirectional current flow through L and unidirectional current flow through L'. The voltage sensor is basically a resistor divider which is used to scale the output voltage to a desired value so as to give it to the comparator. The two comparators are used to compare the scaled output voltage with both the upper and lower voltage references separately.

The output of the comparator is given as the input to the FPGA through an optocoupler for providing isolation from the converter section. These signals are processed and corresponding PWM signals for controlling the half bridge converter module are generated using Spartan 6 FPGA board. Code is developed using Verilog.

Half bridge converter consists of MOSFETs as switching devices for which the gate pulses are given using a controller, FPGA. The pulses are generated by FPGA and

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then given to the switches. In order to make the reliable operation of the converter module to prevent the interference of the control circuit i.e., FPGA, the use of main (converter) and control circuit is isolated from each other. For this purpose an optocoupler is provided just before the converter.

MOSFET driver IC used to amplify and isolate the signal which is given to the switching devices. Due to the switching action of the switches and non-linear characteristics of the semiconductors devices, the output of converter consists of harmonics. Thus to eliminate harmonics filters are used.

V. HARDWARE SET UP

5.1 Half bridge converter with output LCL

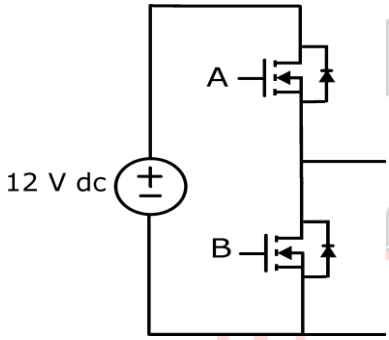

Fig.8 Half bridge converter section

The half bridge converter designed here consists of 2 power MOSFETs as shown in Fig.8. These MOSFETs should not be turned on simultaneously. It will result in a short circuit current across the dc link voltage supply. The converter moves from one state to another based on the comparison of the feedback with upper and lower reference signals. To reduce the harmonics in generated current caused by semiconductor switching an LCL filter is provided at the output. Here we designed the converter section to obtain a output voltage 5V and load current of 0.5 Amps. So the load resistance used has a value of 10 ohm.

5.2 LCL filter

The attenuation of LCL filter is 60dB/decade. This happens for frequencies that are above the resonant frequency. Therefore we can go for lower switching frequency for the converter. This will also ensure better decoupling between the filter and the grid impedance. It also ensures lower current ripple across the grid inductor. Therefore LCL-filter is best suitable for our application. The LCL filter can provide good current ripple attenuation even with small inductance values [7]. However it can also bring resonances and unstable states into the system. Thus it is necessary that the filter must be designed precisely according to the parameters of the specific converter. In the technical literature there are many articles on the design of the LCL filters. The most important parameter of the filter is its cut-off frequency [8]. The cut-off frequency of the filter should be minimally one half of the switching frequency of the converter. This is because the filter must have enough attenuation in the range of the converter's switching frequency. The cut-off frequency must have a sufficient distance from the grid frequency, too. The equation for cut-off frequency of the LCL filter is,

Resonant angular frequency,

$$w_r = \sqrt{\frac{L+L'}{L*L'*C_f}}$$

Cut off frequency,

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{L+L'}{L*L'*C_f}}$$

Assuming w_r constant, for minimum capacitance, $L = L' = L_t$

$$w_r^{\,2} = \frac{4}{L_t C}$$

The inductor value used here is 800µH each for L and L'. The capacitor value for obtaining 100 KHz switching frequency can be calculated as

$$(2\pi * 100 * 10^3)^2 = \frac{4}{800 * 10^{-6} * 800 * 10^{-6} * C}$$

$$C = 16\ \mu F$$

5.3 Inductor

The inductor used here is a yellow and white toroid type shown in Fig.9. The core is made of powdered iron. It has permeability µ=75. It is a hydrogen reduced material. A yellow and white toroid inductor has highest permeability of all of the iron powder materials. They are mainly used for EMI filters and DC chokes. It can provide and extended frequency range.

Fig.9 Yellow and white core

The yellow and white toroid type inductor used here has a dimension of 27mm x 14mm x 10mm (D x d x T). The number of turns for an inductance L is calculated as

$$N = 100 * \sqrt{\frac{L}{A_L}}$$

Where, L = inductance in μH

$$A_L = \ \mu H\ per\ 100\ turns$$

$$N = number\ of\ full\ turns$$

$$L = A_L * \frac{N^2}{10^4}$$

Here A_L=350 $\mu H\ per\ 100\ turns$

$$800 = 350 * \frac{N^2}{10^4}$$

$$N = 151\ turns$$

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VI. EXPERIMENT RESULTS

6.1 Generation of upper and lower references

The upper and lower reference bands used for performing hysteresis mode voltage control are generated from the 230 ac voltage after stepping down using a 9V transformer followed by rectification and then giving it to reference band generation circuit. The peak to peak voltage of both the reference signal is 3V. There is an offset difference of .3V between the two reference bands. The yellow colored one shown in the Fig.10 forms the upper reference signal and the green colored one is the lower reference signal.

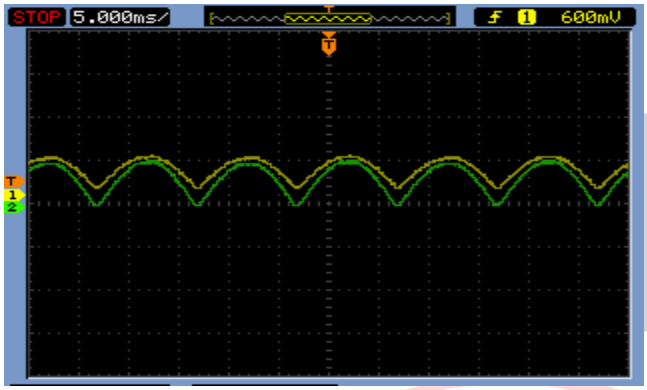

Fig.10 Upper and lower reference bands

6.2 Designed LCL filter

Fig.11 shows designed yellow and white color powdered iron core type inductor. It has a value of 800µH each. The dimension of the core used is 27mm x 14mm x 10mm (D x d x T). The no of turns in order for obtaining the desired value of 800µH is 151. The inductance value is tested and confirmed using LC meter.

Fig.11 Yellow and white toroid

The total LCL filter section with load is shown in Fig.12. The capacitor used here is 10µF. Here in order to obtain an output voltage of 5V and 0.5A current, a resistor value of 10 ohms is used. A voltage divider is provided in order to scale the output voltage to a lower value to be given as the input to comparators.

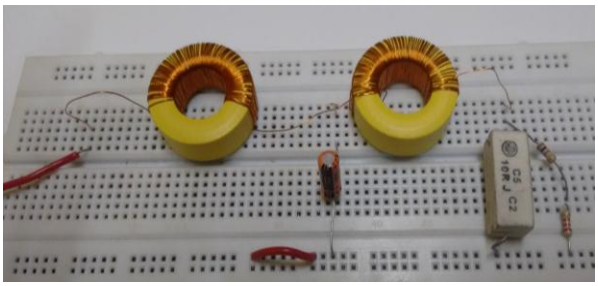

Fig.12 LCL filter with load

6.3 Final setup

Overall experimental set up is shown in Fig.13. It consists of the designed half bridge converter with feedback control using FPGA to maintain the output voltage at a constant value by the method of hysteresis control.

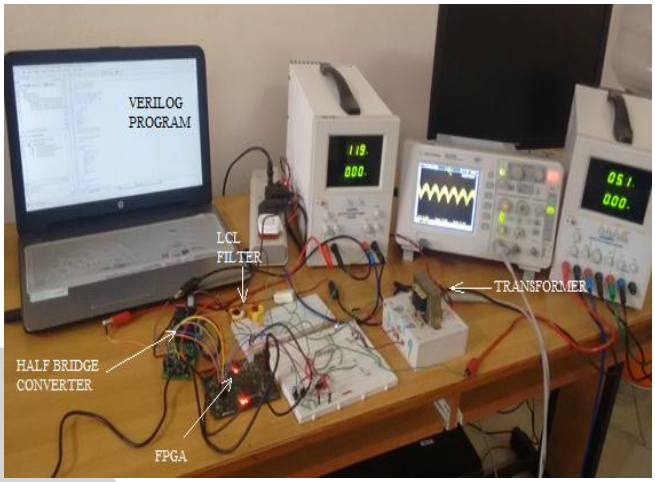

Fig.13 Final setup

Fig.14 shows the half bridge converter output. The output is a dc signal of 5V amplitude. The generated PWM signal by comparing the feedback signal and the upper and lower references using FPGA is given into the corresponding MOSFET for obtaining the hysteresis band structure. Thus the output voltage is made to fall within the created reference bands keeping it at the required level. A better hysteresis is band is obtained as the output. The switching frequency is 100 KHz.

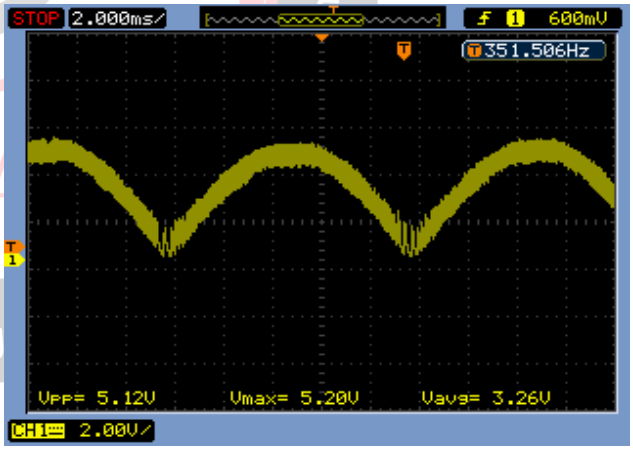

Fig.14 Half bridge converter output

VII. PERFORMANCE ANALYSIS

Fig.15 shows the converter output along with one of the reference bands i.e upper reference band. Here we can clearly see that the converter output follows the shape of the reference band as required. Both the converter output and the upper reference signals are in phase with each other. Fig.16 shows the zoomed view of the output.

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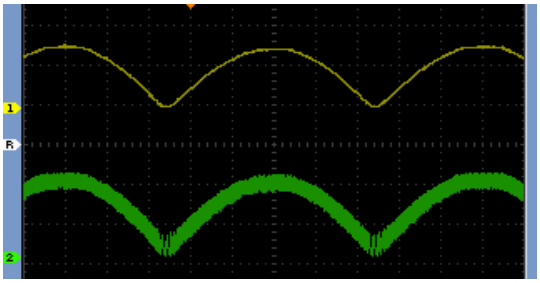
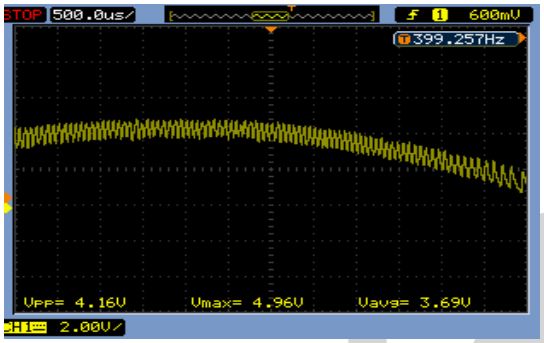
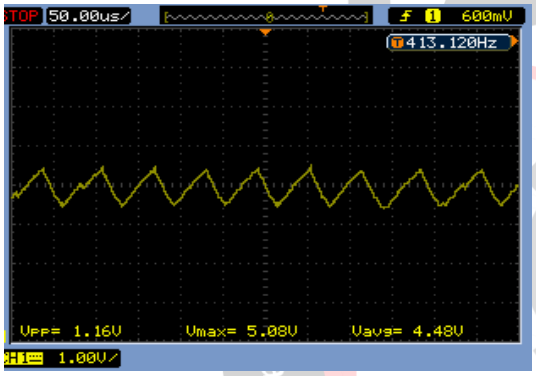


Fig.15 Converter output (green) with upper reference band (yellow)



(a)



(b)

Fig.16 Half bridge converter output zoomed view

Here we can see that the LCL filter is designed properly. When the capacitor value is increased while keeping other parameters fixed, the switching frequency decreases as it takes more time for charging and discharging. When capacitor value is decreased switching frequency increases. When the inductor value is increased while keeping other parameters fixed, switching frequency decreases and vice versa. As we increase the load the slew of the rising wave decreases and slew of falling wave increases. If we decrease the load the slew of the rising wave increases and slew of falling wave decreases. As switching frequency increases efficiency of the system decreases.

VIII. CONCLUSION

In this work a single phase PWM boost rectifier has been studied which is using MOSFET as a power switch. The PFC using boost converter employing hysteresis mode control is useful and better one for reducing the harmonics in the line current. In this paper, mainly the hysteresis control part is concentrated. To illustrate this half bridge converter with output LCL based on hysteresis voltage mode control is designed and implemented. FPGA is used as the controller here. The required PWM waves are synthesized using Xilinx ISE software. Verilog programming is used here. PWM generator architecture is downloaded onto FPGA and is used to control the MOSFETs of half bridge converter. By this way we are able to control ON and OFF time of converter. The converter is provided with an output LCL filter for filtering action. Here we have controlled the output of the converter by making it fall within the designed reference bands. The dc load voltage is regulated against load disturbance and variation. Thus hysteresis method can be extended for the current mode control by using appropriate current sensors. The experiment results illustrate that by providing some additional hardware the same method can be used for power factor correction using a boost converter.

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