

DSP Based Voltage Controlled Single Stage PFC Converter with Synchronous Rectification

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Abstract - Synchronous switching power converters give better performance than non-synchronous converters in low output voltage, high output current systems applications. This work presents a single stage PFC synchronous rectifier, which has low switch voltage stress with high efficiency implementing a constant output voltage and bus voltage. A single stage isolated AC/DC PFC converter with synchronous rectification for high DC-link voltage low-power applications, achieved through an effective integration of AC/DC and DC/DC stages, where all of the switches are shared between two operations. With the converter and switching scheme, input current shaping and output voltage regulation can be achieved simultaneously without introducing additional switches or switching actions. Due to the flexible DC-link voltage structure, high power factor can be achieved at high line voltage. Proposed system provide high power factor with controlled output and bus voltage. The performance of the single stage PFC converter is simulated in the MATLAB/SIMULINK environment. C2000 Piccolo Launchpad DSP processor is used to generate the control pulses and setup a prototype model of voltage controlled single stage PFC with synchronous rectification.

Key Words: DC-link voltage, Single stage PFC converter, Synchronous rectification, Zero voltage switching, High power factor

1. INTRODUCTION

AC/DC power converters are required to operate with high power factor (PF) and low total harmonic distortion (THD) for improved grid quality and full capacity utilization of the transmission lines. Passive PF correction (PFC) circuits consist of inductive and capacitive filters followed by a diode bridge provide the simplest way of achieving high PF with high efficiency; however, they require low line frequency filters which are bulky and heavy. In order to operate at high frequency and reduce the size of the circuit, high frequency two-stage active PFC converters have been used [1]. In this architecture, a front-end AC/DC PFC converter is operated with a switching frequency in the order of tenths to several hundred kHz for converters with Si semiconductor devices, and from several hundreds of kHz to tenths of MHz with wide band gap devices, to shape the input current close to sinusoidal waveform in phase with the grid voltage . The

second stage DC/DC converter provides the galvanic isolation and output voltage regulation. The controllers of the two stages are completely independent. The flexibility in control allows optimizing power stages, fast output voltage regulation and operating with high PF and low THD. However, this method comes with the expense of more components and larger size. Moreover, the constant switching losses such as parasitic capacitance losses associated with power switches reduce the efficiency of the converter at light load condition. This study proposes a new SSTL isolated AC/DC PFC converter for high DC link voltage and low power applications, achieved with complete integration of two stages, where all of the switches are shared between input current shaping and output voltage regulation stage[1]. In comparison with the existing three level single stage topologies, the converter offers minimum number of components as of three level AC/DC converter, and does not require any auxiliary circuit other than a diode bridge and an inductor. The topology can serve as a low cost power electronic interface intended for applications requiring high-voltage DC link. Two independent control algorithms, embedded in a single microcontroller, are used to achieve PFC and output voltage regulation[1]-[4] .This feature allows having lower output current ripple and less distorted input current even at light load condition. In addition switches are turned on under zero voltage, which increases the efficiency of the converter in comparison to hard-switched AC/DC single stage converter. Furthermore, higher PF can be achieved at high line voltage due to the flexible DC link voltage structure. But the system has more power loss thus it has less efficiency. In order to increase efficiency synchronous rectification method is used [8]. Synchronous Rectification (SR) the use of MOSFETs to achieve the rectification function typically performed by diodes. SR improves efficiency, thermal performance, power density, manufacturability, and reliability, and decreases the overall system cost of power supply systems .

2. SINGLE STAGE PFC SYNCHRONOUS RECTIFIER

The PFC converter is essentially an integrated version of a boost PFC circuit and three-level isolated DC/DC converter. Basically, a diode bridge and an inductor are added to the three level isolated DC/DC converter topology as shown in fig.1.

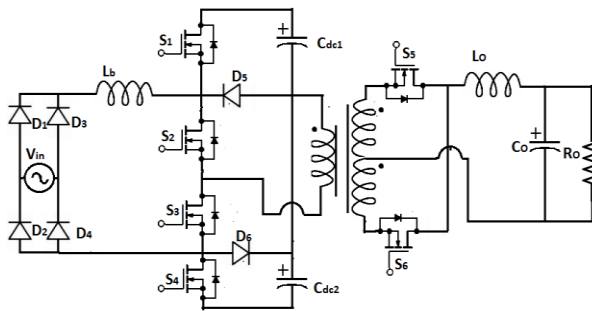


Fig -1: Single stage PFC synchronous rectifier

Here, the inductor is charged when S_2 and S_3 are turned on simultaneously. Body diodes of S_1 and S_4 serve as the boost diode of the PFC boost converter. At the same time, S_1 to S_4 are switched to apply $V_{dc}/2, -V_{dc}/2$, and zero voltage across the primary side of the transformer. Thus, all of the switches are shared between the two stages, which makes it fully integrated single-stage converter without any additional auxiliary switches. When a boost inductor and a diode bridge is added to the nodes the overlap of gate signals of S_2 and S_3 enables applying input voltage across the boost inductor[1]. The steady state wave form of the converter is given in fig.2. The switches S_2 - S_3 and S_1 - S_4 have 180 degree phase shift with respect to each other. The duty ratios of S_2 - S_3 should be greater than 0.5 such that two signals overlap. Here, the circuit is explained considering that input inductor current is discontinuous and the switching scheme is as follows; S_1 is turned on right after S_3 is turned OFF, and similarly, S_4 is turned on when S_2 is turned OFF. A dead-time should be inserted in between the turning ON instant of S_1 and turning OFF instant of S_3 and likewise between switching of S_2 and S_4 to avoid short-circuit. Synchronous switching power converters give better performance than non synchronous converters in low output voltage, high output current systems applications. Synchronous Rectification (SR) the use of MOSFETs to achieve the rectification function typically performed by diodes. Proposed system provide high power factor with controlled output and bus voltage. The conduction loss of diode rectifier contributes significantly to the overall power loss in a power supply, especially in low output voltage applications. Schottky diodes were an improvement over the standard diode because their forward voltage is lower. But Schottky diodes also start from a fixed forward voltage. Higher efficiencies can be achieved by synchronously switching MOSFET devices to emulate diodes, taking advantage of the FET's low conduction losses.

3. OPERATING MODES

3.1. Mode 1

In this mode, both S_2 and S_3 are on. The upper capacitor, C_{dc1} , discharges to the load by applying $-V_{dc}/2$ to the primary side of the transformer. The primary side current increases linearly under constant voltage. S_5 turn ON at the secondary

side of the transformer. In this mode, the boost inductor, L_b , does not interfere to the operation of the circuit.

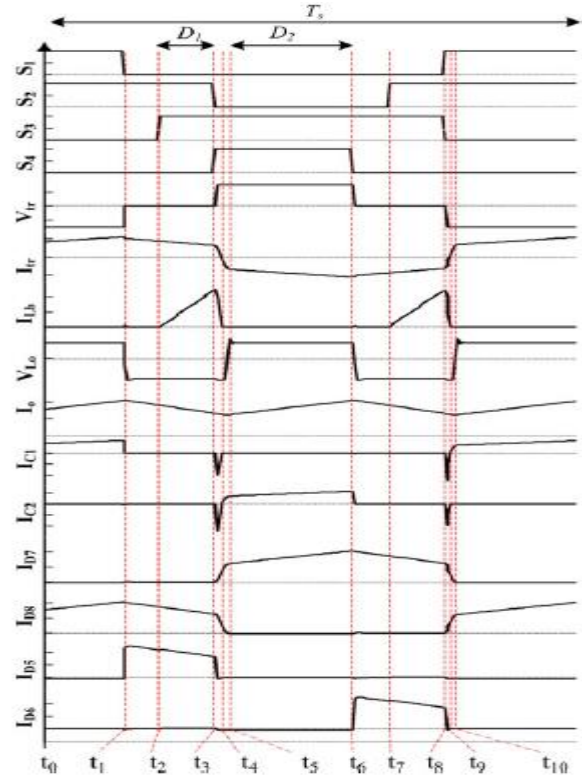


Fig -2: Steady state waveforms

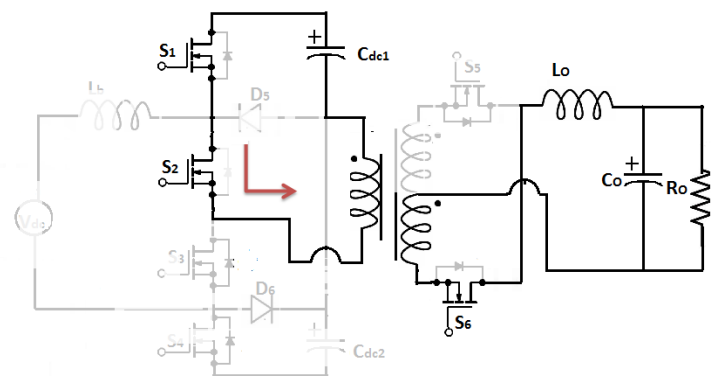


Fig -3: Equivalent circuit of mode 1

3.2. Mode 2

At $t = t_1$, S_1 is turned OFF and S_2 is kept on. The current in the leakage inductance conducts D_5 and the primary side current freewheels; hence, zero voltage is applied across the primary side of the transformer. The output inductor voltage is equal to $-V_0$. The output inductor current decreases linearly.

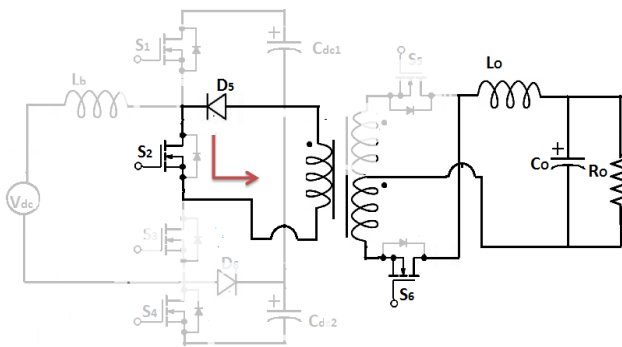


Fig -4: Equivalent circuit of mode 2

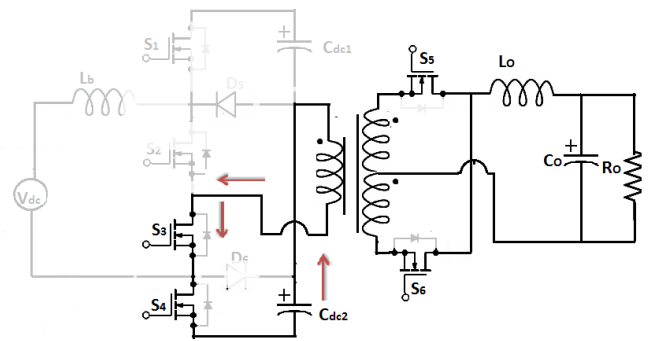


Fig -6: Equivalent circuit of mode 4

3.3. Mode 3

At $t = t_2$, S_3 is turned on, while S_2 still remains on. The primary current continues to freewheel and zero voltage is applied across the primary side; hence, the output inductor current continues to decrease under output voltage. Meantime, V_{in} is applied across L_b and input current increases linearly storing energy in the inductor.

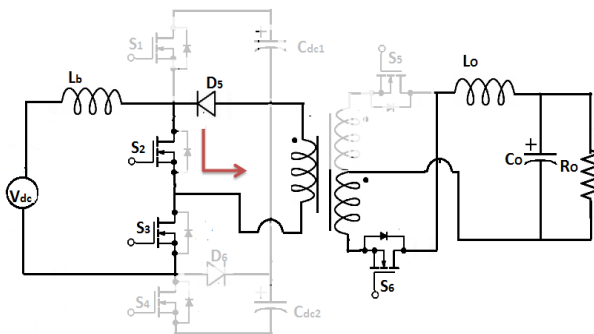


Fig -5: Equivalent circuit of mode 3

3.4. Mode 4

In the beginning of this mode, S_2 is turned OFF, S_4 is turned ON, while S_3 is kept on. Within this time interval, the following two operations are completed. The energy stored in the input inductor is transferred to the DC-link capacitors. The inductor current decreases linearly under $V_{in} - V_{dc}$. Meantime, $V_{dc}/2$ is applied across the primary side of the transformer. The current in the leakage inductance is transferred to C_{dc2} . This causes the output current to turn OFF from S_5 to S_6 . At the end of this time interval, the energy in the input inductor is completely transferred to the DC link capacitors and turning OFF of the switches S_5 and S_6 is completed. Depending on the DC bus voltage, and input current, one of these operations ends earlier than the other one. In this case, the energy stored in L_b is transferred to the DC link at $t = t_5$.

3.5. Mode 5

C_{dc2} discharges over to the load and $V_{dc}/2$ is applied across the primary side of the transformer. The voltage across the output inductor is $V_{L0} = (V_{dc}/2N) - V_0$. The input current remains at zero in DCM mode.

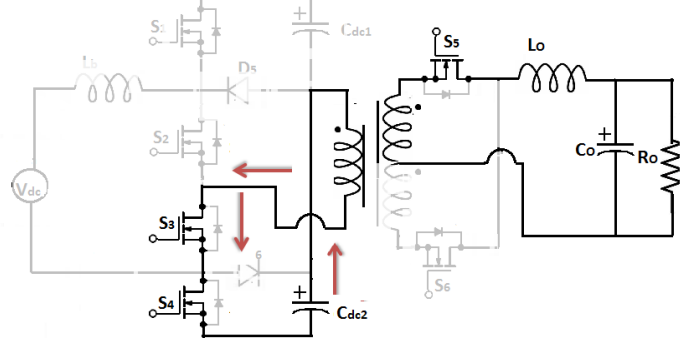


Fig -7: Equivalent circuit of mode 5

3.6. Mode 6

At $t = t_6$, S_4 is turned OFF, and only S_3 is on. This allows leakage current to freewheel through D_6 , and zero voltage is applied to the primary side. The output current decreases linearly under $-V_0$.

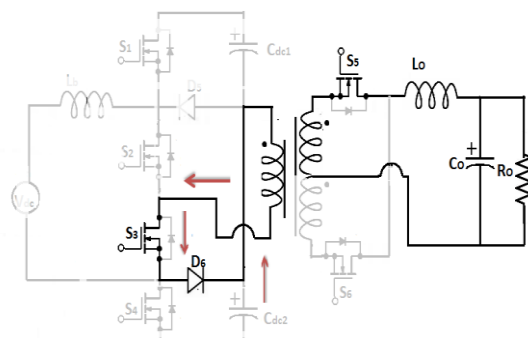


Fig -8: Equivalent circuit of mode 6

3.7. Mode 7

At $t = t_7$, S_2 is turned ON. The energy from the input is stored in the inductor. This is similar to mode 3, except that this time the primary side current is opposite to that in mode 3 and freewheels through D_6 .

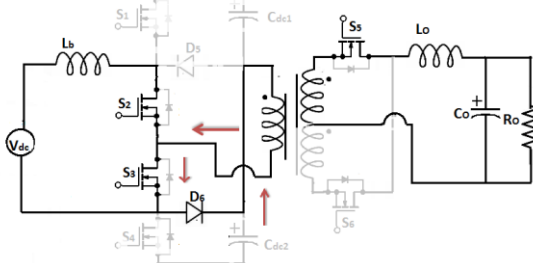


Fig -9: Equivalent circuit of mode 7

3.8. Mode 8

At the beginning of this interval, S_3 is turned OFF, S_1 is turned ON, and S_2 remains ON. This mode is similar to mode 4, where the stored energy in the inductor is transferred to the DC bus capacitors, and $-V_{dc}/2$ is applied to the primary windings.

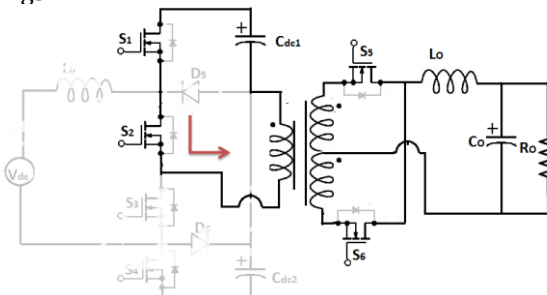


Fig -10: Equivalent circuit of mode 8

4. RESULTS AND DISCUSSION

4.1. Simulation Models and Results

The simulation and experimental results are shown in this section. The proposed PFC synchronous rectifier is simulated in MATLAB. The simulink model of single stage PFC synchronous rectifier is shown in fig.12. Table 1 shows the specification of different parameters used. MOSFET is used as the switch. Switching pulses are applied to the MOSFET, interleaved at 180 degree phase shift. A repeating sequence of required frequency is compared with constants 0.6 and 0.4, the duty ratio to generate pulses with 60% ON and 40% ON time. Whenever repeating sequence is less than the constant, it will output a high value and if constant is smaller, it will output a low value. The converter exhibits high PF

0.9173 with less number of switches/diodes. The single stage PFC converter has an output voltage of 49 V and DC-link voltage of 625 V. In order to get constant output voltage

Table -1: Simulation parameters

Parameters	Specification
Input Voltage V_{in}	230 V
Resistor	1.5 Ω
Capacitor C_{dc1}, C_{dc2}	47 μF
Inductor L_o, L_b	500 μH
Output Voltage	12 V

and bus voltage at all load conditions introducing closed loop control for output voltage and bus voltage. For closed loop control of output voltage, output voltage is compared with a constant voltage 48(Reference voltage) and the error signal is given to a PI controller and the tuned signal from PI controller is used as new constant for pulse generation. Similarly for closed loop control of bus voltage, bus voltage is compared with a constant voltage 600(Reference voltage) and the error signal is given to a PI controller and the tuned signal from PI controller is used as new constant for pulse generation.

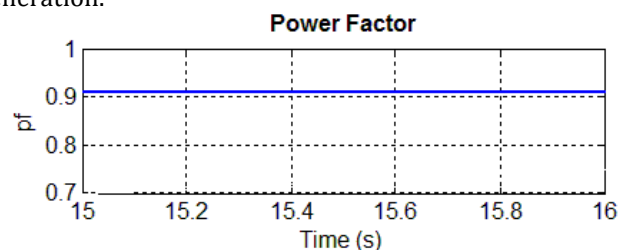


Fig -11: Power factor

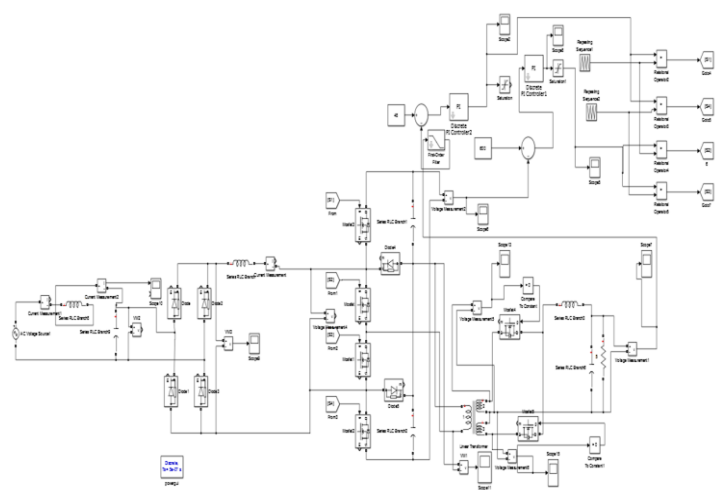


Fig -12: Simulink model of PFC synchronous rectifier

Fig. 13 shows the switching pulses for the PFC converter.

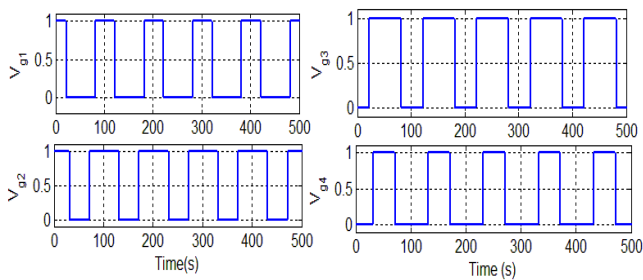


Fig -13: Switching pulses

The single stage PFC synchronous rectifier has less power losses compared to single stage PFC converter, which improves the efficiency of the system. Fig.14 shows power loss (7.5 W) and output voltage (10 V) of the system when diode is used instead of switch S_5 and S_6 .

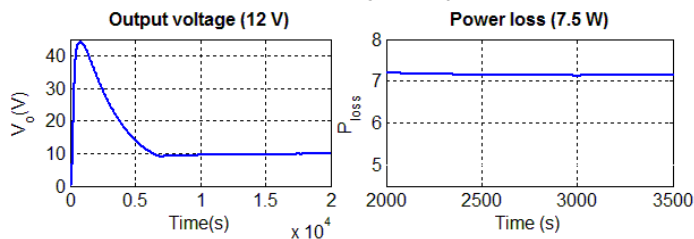


Fig -14: Output voltage and power loss

Fig. 15 shows power loss (0.25 W) and output voltage (10 V) of the system when switch is used. SR improves efficiency, thermal performance, power density, manufacturability, and reliability, and decreases the overall cost of power supply systems.

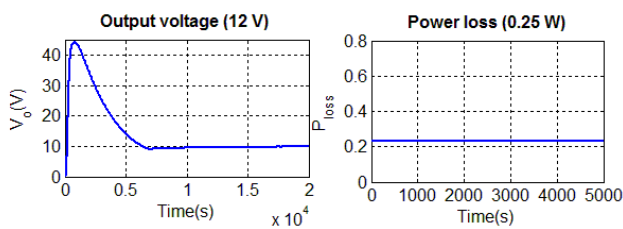


Fig -15: Output voltage and power loss

Efficiency curve for single stage PFC converter and PFC synchronous rectifier is plotted by varying load. Single stage PFC converter has an efficiency of 80% and PFC synchronous rectifier has 85%.

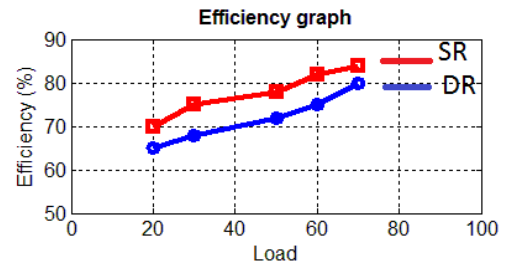


Chart -1: Efficiency curve

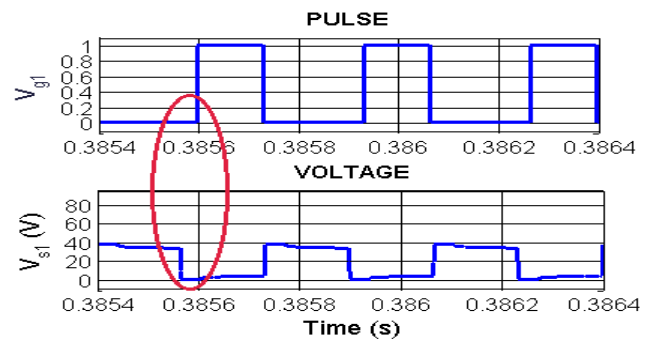


Fig -16: Zero voltage switching of switch 1

Soft switching of switches reduce the switching losses and increase efficiency. The switch S_1 is turn on at zero voltage (ZVS) as shown in fig.16

4.1. Experimental Setup and Results

Hardware setup is done in a Printed Circuit Board(PCB). Control circuit and power circuit are implemented in one PCB. A DSP controller TMS320C2000 which provides a high level of computational performance and programming flexibility is used as control circuit. Prototype is designed for an input voltage of 230 V, output voltage 24 V and bus voltage 300 V.

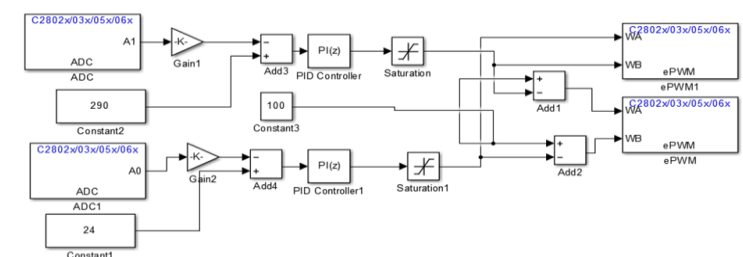


Fig -17: Control strategy

Simulink control logic for the closed loop control of single stage PFC synchronous rectifier is shown in figure 17. Analog pin is given to the gain block which is corresponding to the 12 bit resolution of ADC. Upper and lower limit of the duty cycle is specified in the saturation block. Reference value of voltage is given as a constant(24, 290). By proper tuning of PI controller the output voltage and bus voltage can be controlled.

Output voltage is controlled to 24 V and DC-link voltage is controlled to 350 V. Fig. 18 shows the experimental setup for voltage controlled single stage PFC Synchronous Rectifier 180 degree phase shifted pulse output from the controller TMS320C2000 is shown in fig.19 and output pulse from driver IC which is of 12 V. Both voltage across switch and pulse of switch 1 is shown in fig. 20, in order to verify the ZVS operation.

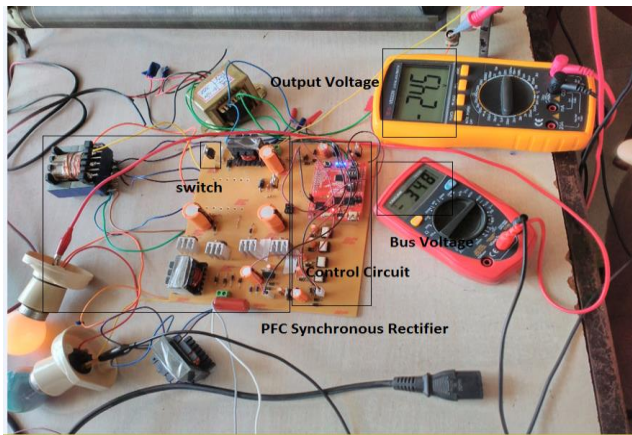


Fig -18: Experimental setup

180 degree phase shifted pulse output from the controller TMS320C2000 is shown in below and output pulse from driver IC which is of 12 V. The 12 V output is given to the gate of the switch.

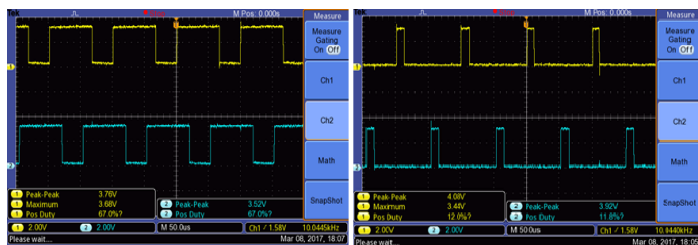


Fig -19: PWM output

Soft switching of switches reduce the switching losses and increase efficiency. The switch S_1 is turn on at zero voltage (ZVS). Thus efficiency can be increased.

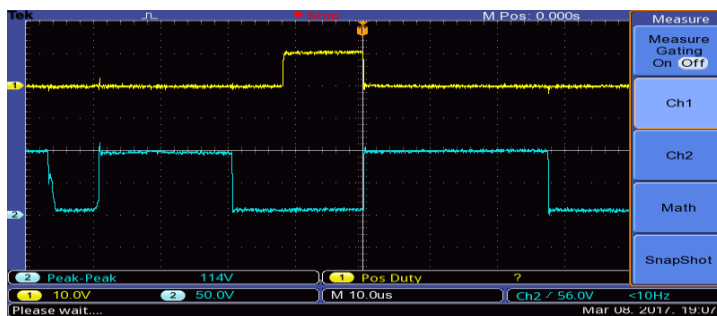


Fig -20: Zero voltage switching of switch 1

5. CONCLUSIONS

In this work a prototype model of voltage controlled single stage PFC with synchronous rectification is implemented. Synchronous switching power converters give better performance than non-synchronous converters in low output voltage, high output current systems applications. Single stage PFC synchronous rectifier, has been designed with low power loss, high efficiency, constant output voltage and bus voltage. Output voltage is controlled to 24 V and DC-link voltage is controlled to 350 V. The performance of the single stage PFC converter is simulated in the MATLAB/SIMULINK environment. C2000 Piccolo Launchpad DSP processor is used to generate the control pulses. PFC synchronous rectifier has high efficiency of 85% and get better power factor near to unity.

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