

Simulation of a novel ZVT technique based boost PFC converter with EMI filter

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Abstract. A novel Zero Voltage Transition (ZVT) technique based closed loop control of Boost Power Factor Correction (PFC) converter with Electro Magnetic Interference (EMI) Filter is presented in this paper. It operates at a fixed frequency while achieving zero voltage turn-on of the main switch and zero current turn-off of the boost diode. This is accomplished by employing resonant operation only during switch transitions. During the rest of the cycle, the resonant network is essentially removed from the circuit and converter operation is identical to its non-resonant counterpart. The principle of operation and simulation results of proposed converter are presented in this paper. The power factor is improved to near 0.99 using the proposed converter.

Keywords: power factor correction, electro magnetic interference, zero voltage transition, common mode, differential mode

1 Introduction

The demand for power, which is increased tremendously over the last few decades, has forced the power engineers to establish reliable network in order to supply “quality” power to the consumers. Power factor, which is defined as the cosine of the phase angle between the voltage and current signals, plays a key role in delivering quality power to the consumers^[3].

Over the years lot of research has been carried out for the control of the power factor. This research got a tremendous boost with the strides made in the miniaturization of the electronic industry. The component of input current normal to voltage across the load resistance wastes power in the resistance of the source generator. In power supplies with a capacitor filter across the input bridge rectifier, the input line current consists of very narrow spikes with the fast rise and fall time.

These current spikes have a high rms value, waste power and give rise to RFI/EMI problems. Power supplies with such input line currents have poor “power factor”. Power Factor Correction seeks to eliminate such line current spikes and force input current to be sinusoidal, in phase with input voltage and to generate a fairly well regulated DC output voltage somewhat greater than the peak of the incoming sine wave^[2, 8].

Generally EMI problems arise due to the sudden changes in voltage (dv/dt) or current (di/dt) levels in a waveform. In diode rectifier, the line current can be pulse of short duration and the diode recovery current pulse can generate transient voltage spikes in the line inductance. A conductor carrying dv/dt wave acts like an antenna and sensitive signal circuit and appear as noise. The EMI problems create communication line interference with sensitive signal electronic circuits^[7].

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2 Basic boost power factor correction converter

Boost converters can be operated in either the discontinuous or continuous mode. But the continuous-mode boost topology is far better suited to yield relatively smooth, ripple-free half sinusoids of input line current in this application. This can be seen from Fig. 1, which shows a continuous-mode boost converter fed from a constant DC input voltage. The continuous-mode boost topology differs significantly from the discontinuous mode.

In the discontinuous mode, the inductor L_1 is made small to yield a steep ramp ($di/dt = V_{IN}/L_1$) of input current to Q_1 . When Q_1 turns off, all the current or energy stored in L_1 is transferred via D_1 to the load. Since L_1 is small, the downward ramp of current through D_1 [$di/dt = (V_0 - V_{IN})/L_1$] is also steep and D_1 current falls to zero before the next Q_1 turn-on. The input line current then, which is the sum of the Q_1 current when it is ON and the D_1 current when Q_1 is OFF, is not at all constant over one complete switching cycle. It consists of steep up and down ramps with zero current gaps between the end of a turnoff and the next turn-on.

But in the continuous-mode of Fig. 1, the inductor L_1 is made significantly larger. Then the Q_1 current (Fig. 1c) has the shape of a large step of current with a slow upward ramp on it, and the D_1 current has the shape of a large step with a slow downward ramp. And importantly, there is no gap of zero current between the end of a turnoff and the next turn-on. Input line current (Fig. 1e) is now the sum of the I_{Q1} and I_{D1} currents and if the ramps are made small by using a large L_1 , the line input current over one switching cycle is then a constant I_{av} with very small peak-to-peak ripple of ΔI . The input power is $V_{IN}I_{av}$.

Now for an AC input, such a continuous-mode boost converter is used after the input bridge rectifier output. At any point on the half sinusoid input voltage, the Q_1 ON time will be forced by a PWM control chip to boost that instantaneous voltage to the desired DC output voltage. A DC voltage error amplifier, a DC reference voltage, and a pulse with modulator in the control chip modulate the Q_1 ON time in a negative feedback loop, to yield a constant DC output voltage throughout the half sinusoidal input voltage. The instantaneous input line current will be sensed by a sensing resistor R_S and will be proportional to the instantaneous voltage throughout the half sinusoid.

During any one ON time, current flows through L_1 , Q_1 and R_S back to the negative end of the bridge and during the following OFF time it flows through L_1 , D_1 , R_0 and C_0 in parallel and R_S back to the negative end of the bridge. By making L_1 large, the peak-to-peak ripple current throughout each switching cycle is kept small. Depending on switching speed of Q_1 , there may be very narrow spikes on the half sinusoids of current monitored in R_S . If present, these may cause an RFI problem. But a very small capacitor (in the vicinity of 1.0mF) across R_S easily eliminates them.

3 Zero voltage transition (ZVT) technique

In order to increase the switching frequency while maintaining acceptable efficiency, several soft switching techniques have been developed. Most of these resonant techniques increase the semiconductor current and/or voltage stress, leading to larger devices and increased conduction losses due to greater circulating current^[1].

The Zero Voltage Transition (ZVT) technique allows the increase in switching frequency without the associated increase in switching losses, while overcoming most of the disadvantages of the resonant techniques. ZVT converters operate at a fixed frequency while achieving zero voltage turn-on of the main switch and zero current turn-off of the boost diode. This is accomplished by employing resonant operation only during switch transitions. During the rest of the cycle, the resonant network is essentially removed from the circuit and converter operation is identical to its non-resonant counterpart^[4-6].

This technique allows an improvement in converter efficiency over the traditional boost converter, as well as operating the boost diode with reduced stress due to controlled di/dt at turn-off. This technique programs the input current of the converter to follow the line voltage so that the power factor is improved to 0.99.

The power stage of proposed Boost PFC converter with ZVT technique is shown in Fig. 2. The diode rectifier, inductor L , switch Q_{MAIN} , diode D_1 , capacitor C_0 and the load forms the basic boost converter. The

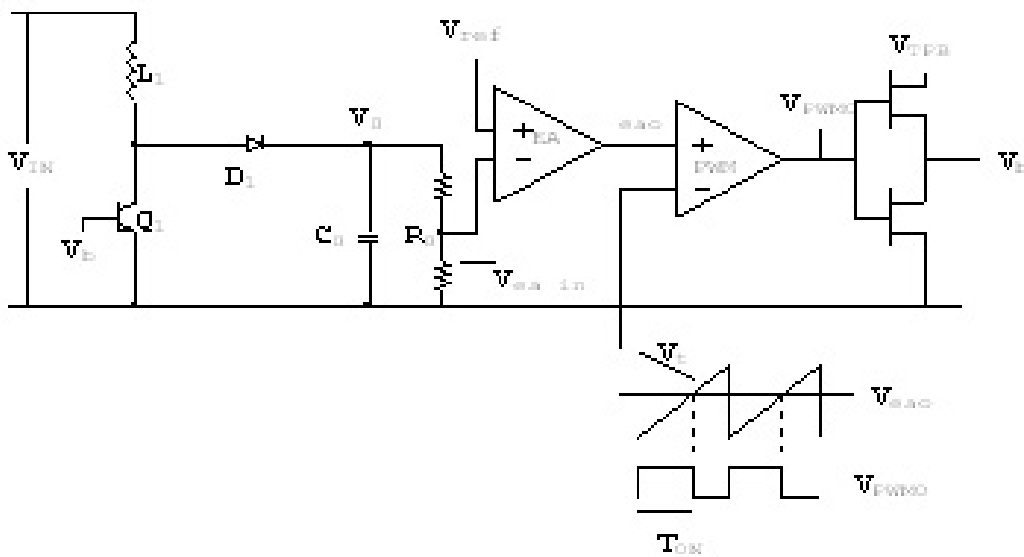


Fig 1a

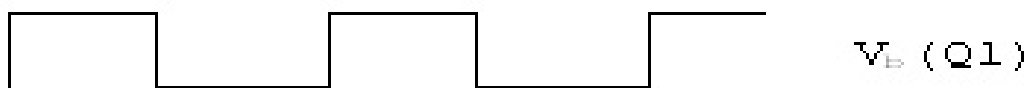


Fig 1b

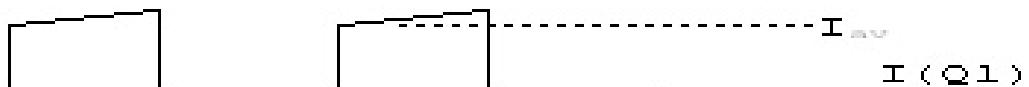


Fig 1c

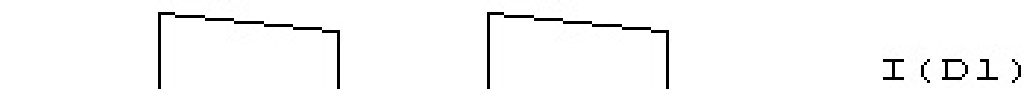


Fig 1d

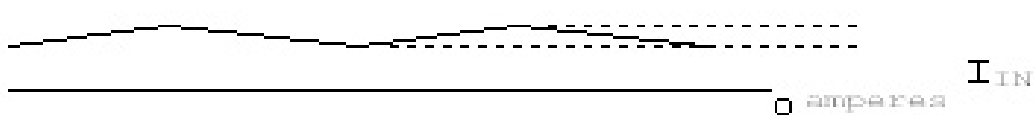


Fig 1e



Fig 1f

Fig. 1. Continuous conduction mode boost converter and wave forms of q_1 and d_1 for various DC load currents at a fixed DC input voltage

switch Q_{ZVT} , diode D_2 , diode D_3 , inductor L_r and capacitor C_r forms the ZVT circuit. This ZVT circuit provides active snubbing of the diode and main switch of the basic boost converter.

The ZVT switch is turned on before turning on the main switch. This initiates a resonant process, which creates zero voltage switching conditions for the main switch. The time intervals where the ZVT circuit is

active are very short when compared to the switching period. Hence, except for the commutation intervals, the waveforms of the ZVT technique based boost PFC converter are the same as traditional boost converter.

The timing diagram of ZVT technique is shown in Fig. 3. This figure shows the gate pulses for main switch Q_{MAIN} , ZVT switch Q_{ZVT} , drain to source voltage and drain current of main switch, current through resonant inductor L_r , voltage across diode D_1 and the current through diode D_1 .

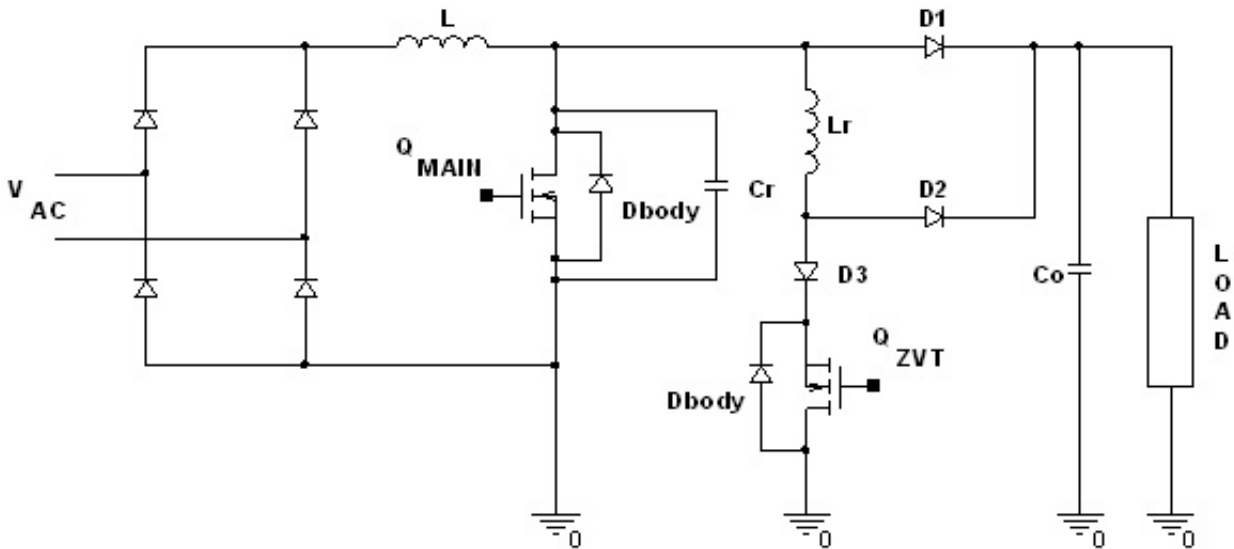


Fig. 2. Power circuit of zvt based boost pfc converter

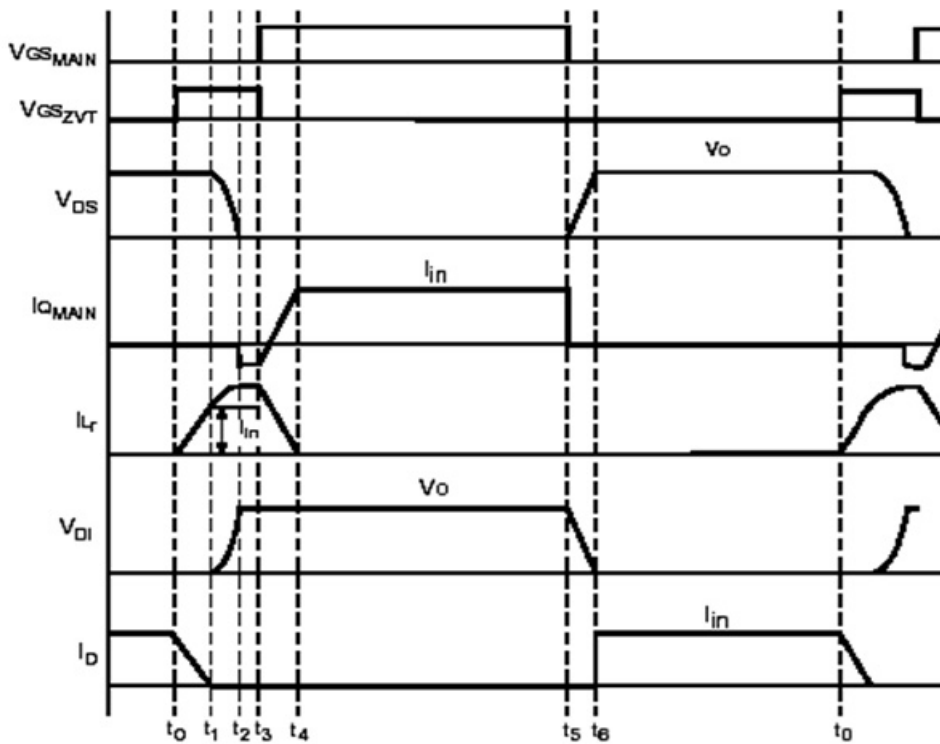


Fig. 3. Timing diagram of zvt technique

4 Modes of operation

4.1 Mode1 ($t_0 - t_1$):

During the time prior to t_0 , the main switch Q_{MAIN} is off and diode D_1 is conducting the full load current. At t_0 , the ZVT switch Q_{ZVT} is turned on. Then the current through the resonant inductor L_r i.e. I_{Lr} ramps up linearly to the value I_{in} i.e. the input current. During this time the current through diode D_1 i.e. I_D ramps down. When the diode current reaches zero, the diode D_1 turns off (i.e. soft switching of D_1). In the practical circuit some reverse recovery of the diode will occur since the diode needs time to remove the junction charge. During this interval, the voltage across the resonant inductor L_r is V_0 .

4.2 Mode2 ($t_1 - t_2$):

At the instant t_1 , the current I_{Lr} reaches I_{in} . Now, the resonant inductor L_r and resonant capacitor C_r will begin to resonate.

This resonant cycle discharges C_r until its voltage equals to zero. The dv/dt of the drain to source voltage of the main switch i.e. V_{DS} is controlled by C_r . The current I_{Lr} continues to increase while C_r discharges. At the end of this period, the body diode of the main switch turns on and hence the voltage V_{DS} reaches zero. The time required for the voltage V_{DS} to reach zero is 1/4 of the resonant period.

4.3 Mode3 ($t_2 - t_3$):

At the instant t_2 , the body diode of the main switch turns on and the voltage V_{DS} reaches zero. Now, the main switch Q_{ZVT} can be turned on since the voltage across it i.e. V_{DS} is zero. The current through the body diode is being driven by the resonant inductor L_r and it freewheels through body diode and L_r during this interval.

4.4 Mode4 ($t_3 - t_4$):

At the instant t_3 Q_{MAIN} is turned on and the Q_{ZVT} is turned off. After Q_{ZVT} is turned off, the energy in L_r is discharged linearly through diode D_2 to the load.

4.5 Mode5 ($t_4 - t_5$):

At the instant t_4 , the current in diode D_2 reaches zero. When this occurs, the circuit is operated like a conventional boost converter.

4.6 Mode6 ($t_5 - t_6$):

This mode operation is also exactly similar to a conventional boost converter. At the instant t_5 , the main switch Q_{MAIN} is turned off. The voltage V_{DS} ramps up to V_0 . The diode D_1 begins to supply the current to the load.

From the modes of operation, it is clear that the main switch is turned on when the voltage across it is zero and the boost diode is turned off when the current through it is zero. Hence, the phenomenon is named as Zero Voltage Transition (ZVT) technique.

The main power stage components of the above converter experience no more voltage or current stress than normal boost converter. The main switch and boost diode both experience soft switching transitions. Having significantly reduced the switching losses, the operating frequency can be increased without an efficiency penalty. The diode also operates with much lower losses and hence the reliability increases.

The design specifications for the proposed ZVT based Boost PFC Converter are

AC input Voltage = $V_S = 170 - 250\text{Volts}$, DC output Voltage = $V_0 = 400\text{V}$
 Output Power = $P_{out} = 1000\text{W}$, Switching Frequency = $F_s = 250\text{KHz}$,
 Efficiency = $\eta = 95\%$

The designed values of different components in the converter circuit are

$$L = 200\mu\text{H}; C_0 = 1600\mu\text{F}; L_r = 8\mu\text{H}; C_r = 0.47\text{nF}$$

5 Electro magnetic interference (EMI) filter

The Electro Magnetic Interference can be transmitted in two forms: radiation and conduction. The switching converters supplied by the power lines generate conducted noise into the power lines that is usually several orders of magnitude higher than the radiated noise into free space. Metal cabinets used for housing power converters reduce the radiated component of the electromagnetic interference. Conducted noise consists of two categories commonly known as the differential mode and the common mode.

The differential mode noise is a current or a voltage measured between the lines of the source that is line-to-line voltage. The common mode noise is a voltage or a current measured between the power lines and ground that is line-to-ground voltage. An EMI filter is needed to reduce the differential mode and common mode noises. The EMI Filter for Boost PFC converter is shown in Fig. 4.

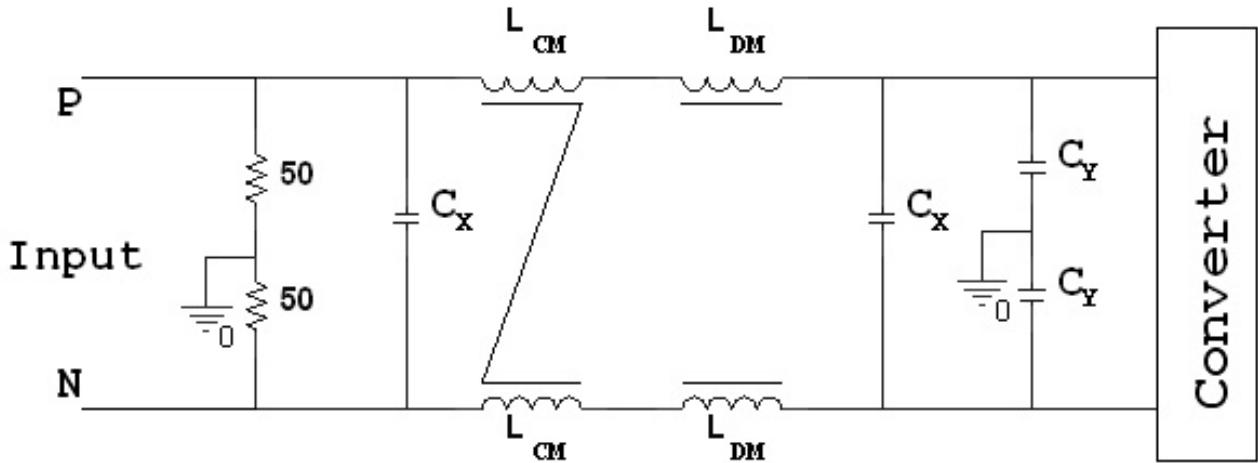


Fig. 4. EMI filter for boost PFC converter

For CM Noise,

$$f_{R,CM} = 1/(2\pi \sqrt{(2C_Y * L_{CM})}) \quad (1)$$

$$L_{leakage} = 0.5\% \text{ to } 2\% \text{ of } L_{CM} \quad (2)$$

For DM Noise,

$$f_{R,DM} = 1/(2\pi \sqrt{(2L_D C_X)}) \quad (3)$$

$$L_{DM} = (L_D - L_{leakage})/2 \quad (4)$$

The PFC converter has the predicted noise level and EMI which includes total noise, common mode and differential mode noises. In general, the corner frequencies of EMI noises in the PFC circuits are 28 KHz for CM noise and 20.5 KHz for DM noise. The designed values are L_{CM} is 4.9mH and LDM is 40μH.

6 Results

The proposed ZVT based Boost PFC converter is simulated using the software ORCAD-PSPICE software of version 9.2.

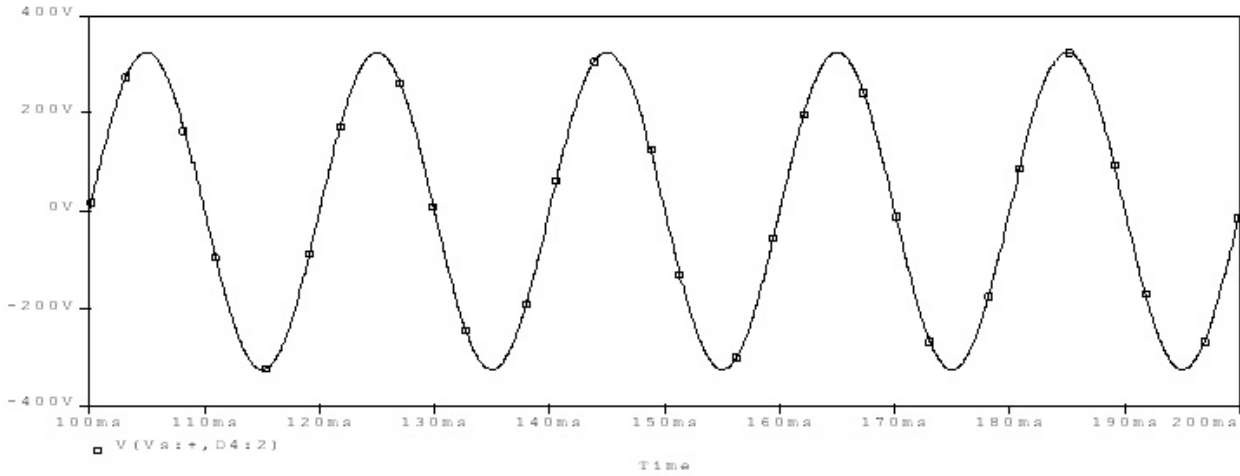


Fig. 5. Input voltage waveform without EMI filter

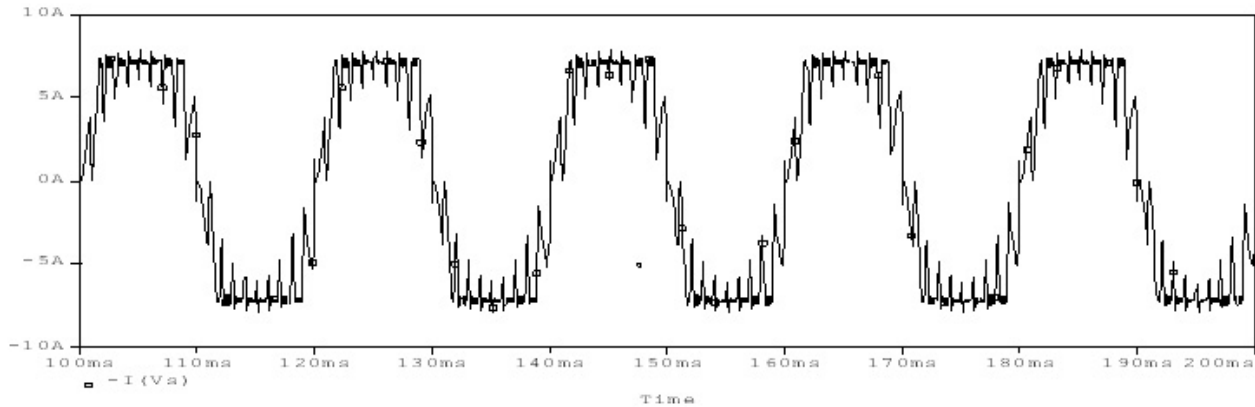


Fig. 6. Input current waveform without EMI filter

Fig. 5 shows the input voltage waveform without EMI Filter. Fig. 6 shows the input current waveform without EMI Filter. In this figure, there is more noise and more spikes. Fig. 7 shows the input voltage waveform with EMI Filter. Fig. 8 shows the input current waveform with EMI filter. Here, the noise and spikes are reduced because of Filter. Here, the power factor is around 0.99 and the noise and spikes are also reduced.

7 Conclusion

A Boost Power Factor Correction (PFC) Converter with EMI Filter employing Zero Voltage Transition (ZVT) technique is proposed. The proposed converter is simulated and the simulation results are presented in this paper. Power factor is improved upto 0.99 (lag) without compromising the efficiency because of the active snubbing.

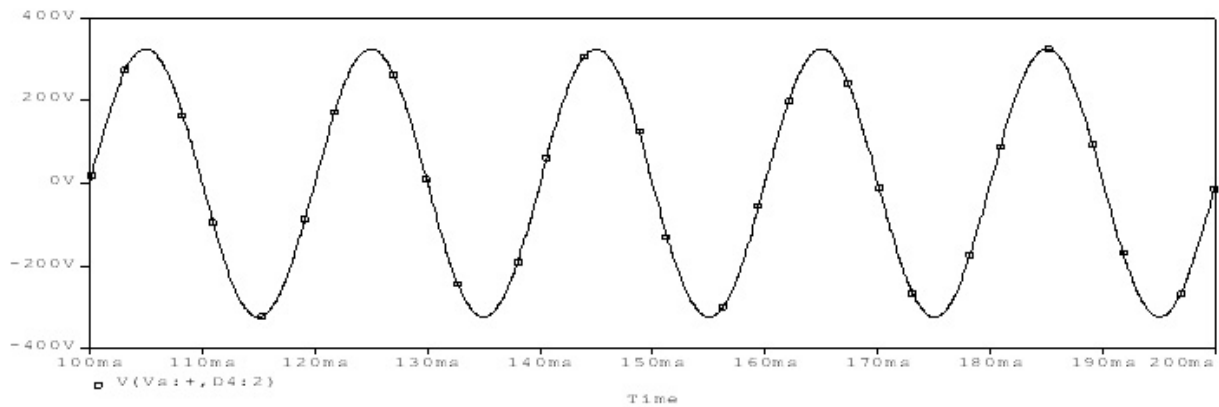


Fig. 7. Input voltage waveform with EMI filter

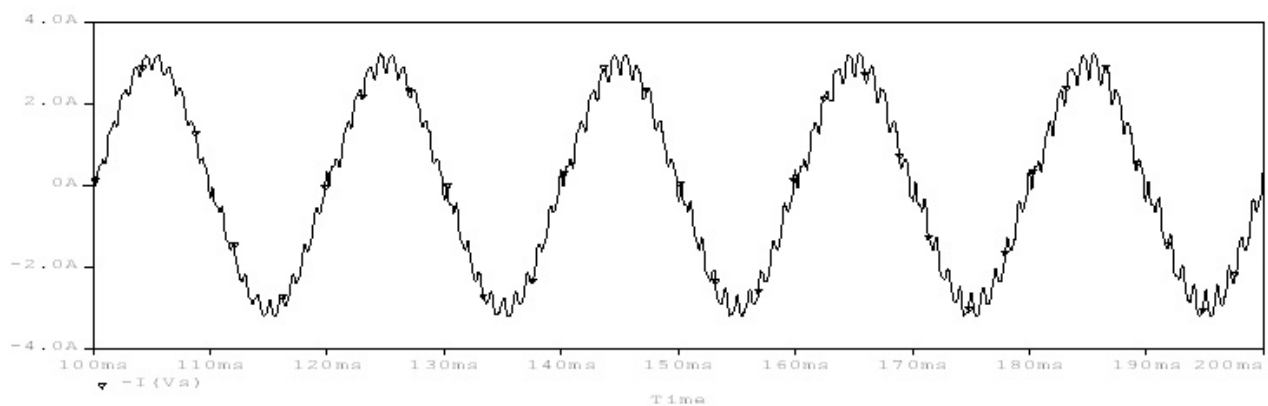


Fig. 8. Input current waveform with EMI filter

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