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A NEW ZCS-ZVS SINGLE PHASE PFC CONVERTER WITH A LCD SNUBBER FOR OUTPUT VOLTAGE REGULATION

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ABSTRACT

A single phase ac-dc soft switched PFC converter with a LCD snubber is presented for dc output voltage regulation. The LCD snubber cell provides zero current switching (ZCS) turn ON and zero voltage switching (ZVS) turn OFF for the converter switch without increasing current or voltage stress. In this study, steady state analysis of proposed PFC converter is presented in detail and the theoretical analysis with its operation stages is verified with simulation results. This converter has a total efficiency of 95% and 0.994 power factor with sinusoidal input line current. Moreover the proposed converter is compared with the hard switched PFC converter and it can be seen that the improvement of efficiency is significantly achieved.

Keywords: Power Factor Correction (PFC), snubber, alternating current – direct current power conversion (ac-dc), efficiency.

INTRODUCTION

All ac-dc power converters are operated at higher switching frequencies such that the size and weight of their filter and magnetic elements are reduced. The main drawback of high switching frequency operation is that the converter efficiency is reduced due to the increased switching losses. Electromagnetic interference (EMI) noise is also created which will affect the nearby electrical equipment and the own converter too. To overcome the drawbacks explained above, many types of snubber circuits for power converters has been presented in the literature (Adib *et al.* 2009), (Wu *et al.* 2008).

The snubbers are broadly classified into two categories active ones and passive ones. Active snubber helps to achieve soft switching with zero voltage turn ON and zero current turn OFF. They need an extra switch and additional control circuits. Passive snubbers help in reducing turn ON di/dt and turn OFF dv/dt with ZCS turn ON and ZVS turn OFF. Passive snubbers are found to be an alternative for active ones with advantages like low cost and good reliability without an additional switch and control circuitry. A simple auxillary resonant circuit is presented for a boost converter (Dhivya Devi *et al.* 2014) which provides ZCS turn ON and ZVS turn OFF. The active power factor correction, magnetic compensation and balancing of nonlinear loads are performed with current control technique. ZCS condition for the main switch is achieved (Aiswariya *et al.* 2013).

A PWM converter is proposed to reduce the circulating current with less amount of current and voltage stresses on the main switch (Ahmad Mousavi *et al.* 2012). A dc-dc converter is proposed to reduce the reverse recovery current of diodes with high voltage gain and reduced input current ripples. But the circuit needs the usage of coupled inductor (Do *et al.* 2010). The snubber circuit proposed (Aksoy I. *et al.* 2010) tries to enhance the circuit efficiency and reduces the electromagnetic interference problems. But significant amount of losses are seen in the switch. Synchronous rectifiers are introduced for a ZVTPWM converter (Adib *et al.* 2010). Even though switching losses are greatly reduced the reverse recovery current of diodes are not taken into account. For the main switch (Nihan Altintas *et al.* 2014) ZVT turn ON and ZCT turn OFF are achieved by the proposed active snubber circuit but with some resonant circuit losses.

In the proposed converter, the active snubber helps the main switch to be operated under soft switching whereas the snubber switch is hard switched (Sang-Hoon Park *et al.* 2010). To reduce the switching losses the snubber circuit as in (Li J *et al.* 2011) is proposed. The drawback is seen as that at light loads the efficiency of the converter reduces. In (Chen R. Y *et al.* 2005) - (Jalbrzykowski S *et al.* 2008) LC resonance schemes are used which helps to have soft switching of the main switches. But, its resonance energy is added to the conduction losses of the converter such that it cannot be transferred to the load. A snubber of RCD type is used in, where the resistor dissipates the energy of the snubber circuit (Zhu L *et al.* 2006). For a three phase boost PFC converter a passive clamping technique is proposed. The power transformer biases due to the passive clamping circuit (Wang D *et al.* 2010). The efficiency of the converter is reduced due to the passive snubber proposed (Meng T *et al.* 2009) since, a series diode is connected with the bridge leg switches. An another passive snubber is investigated for a three-phase single-stage PFC converter and between the two resonant circuits an unbalance of the voltage and current is seen due to the added passive snubber (Meng T *et al.* 2011).

HARD SWITCHEDPFC CONVERTER

The conventional boost topology used for PFC applications is shown in Figure-1. The circuit uses a diode bridge to convert input ac voltage to dc voltage. The diode bridge is then followed by a boost converter. The boost converter has circuit components like a boost inductor L_f, switch S, diode D_f and an output capacitor C_o connected to the output side resistive load R. The boost converter is a type of dc-dc converter that helps in increasing the dc

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output voltage more than the input dc voltage. The problem associated with the boost PFC circuit is that, at higher power levels, the losses across the circuit increases; thereby the efficiency is reduced. The output capacitor current has more ripples. Due to these drawbacks, more heat is dissipated for a smaller area. The output voltage is not in a regulated manner and the input current is not perfectly sinusoidal (Figures-2, 3).

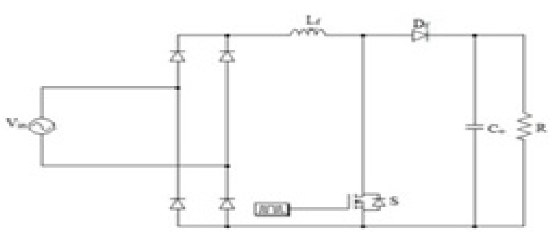


Figure-1. Hard switched boost PFC converter.

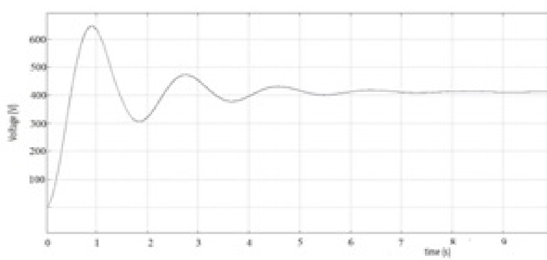


Figure-2. Output voltage of hard switched boost PFC converter.

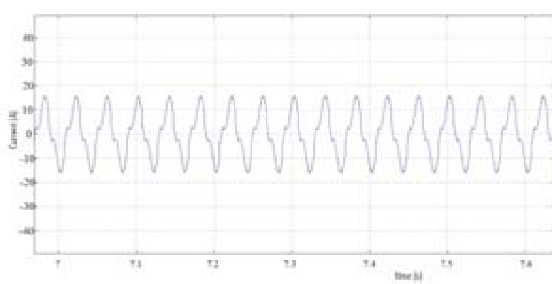


Figure-3. Input current of hard switched boost PFC converter.

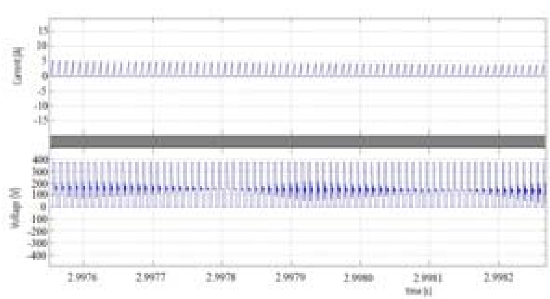


Figure-4. Main switch voltage and current of hard switched boost PFC converter.

The current at output diode is discontinuous, so an output capacitor is used to filter it. Due to these factors, the power factor at the input side is disturbed with a value of 0.96. The main switch has more voltage and current stresses due to the switching losses (Figure-4).

Circuit structure of proposed PFC converter

The proposed LCD snubber consists of snubber inductor L_S, snubber capacitors C_1 and C_2 and snubberdiodes D_1 and D_2. The LCD snubber is added to the conventional hard switched boost PFC converter circuit which comprises of input inductor L_m , output capacitor C_0 , main diode D_f and a switch S.

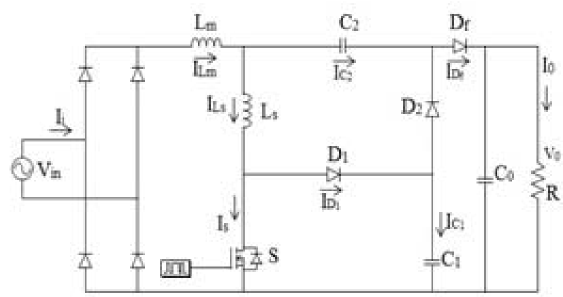
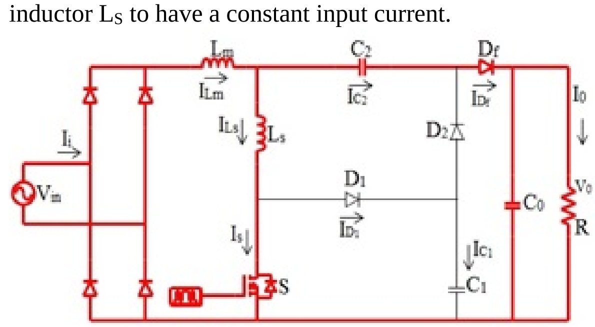


Figure-5. Proposed boost PFC converter.

Operating principle

One switching period of the proposed converter has six operating modes. These are explained by the equivalent circuit of proposed converter as in Figure-6.Some assumptions are made during the simulation of proposed converter.

a. All the semiconductor devices used in the proposed converter are ideal.
b. Reverse recovery of the boost converter diode is considered and taken into account.
c. The output capacitor C_o is assumed to be large to produce a constant output voltage.
d. The main inductor L_m is much greater than resonant inductor L_S to have a constant input current.



(a)

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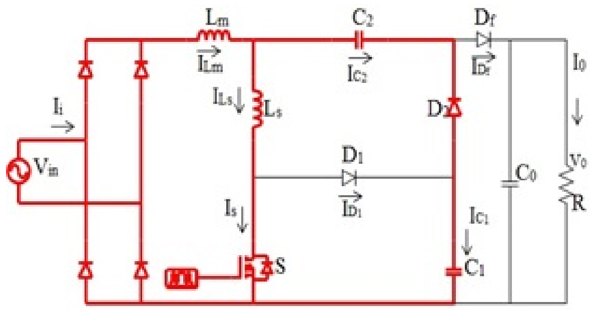
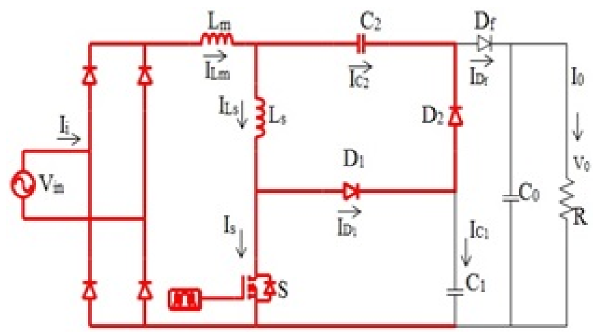


(b)



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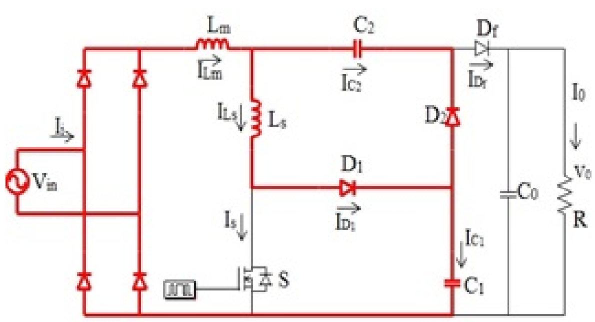
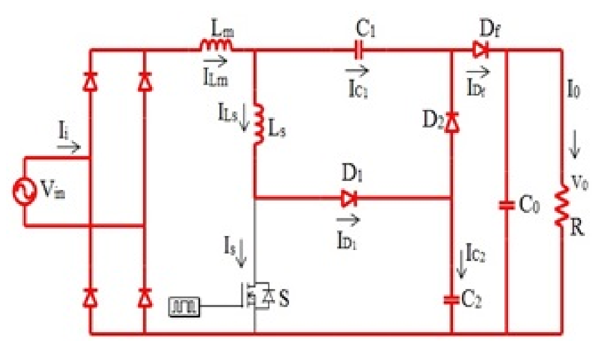
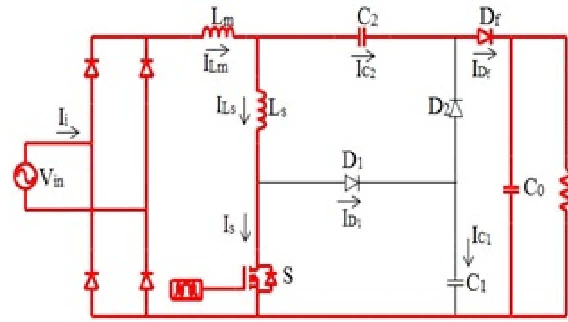


(d)



(e)



(f)

Figure-6. Operation modes of the proposed converter in a switching cycle: (a) mode 1; (b) mode 2; (c) mode 3; (d) mode 4; (e) mode 5; (f) mode 6.

Mode 1[$t_0<t<t_1$]

Switch S turns ON at $t=t_0$. Diode D_1 and D_2 are in the OFF state. The main diode D_f remains ON. The voltage across the snubber capacitor C_1 reaches the output voltage level. During this mode the current through L_m and switch S is given by

$$I_{L_m}(t) = I_{L_m}(t_0) - \frac{(V_0 - V_{in} - V_{C_2})}{L_m}(t - t_0) \tag{1}$$

$$I_s(t) = \frac{(V_0 - V_{C_2})}{L_s}(t - t_0) \tag{2}$$

Switch is turned ON at a ZCS condition due to the diode current condition

$$I_{D_f} = I_{L_m} - I_s \tag{3}$$

$$I_{D_f}(t) = I_{L_m}(t_0) - \left(\frac{L_S(V_0 - V_{in} - V_{C_2}) + L_m(V_0 - V_{C_2})}{L_m L_S}\right)(t - t_0) \tag{4}$$

When the current through the diode D_f decreases to zero

$$I_s(t_1) = I_{L_m}(t_1) \tag{5}$$

Mode 2[$t_1<t<t_2$]

During the beginning of this mode snubber diode D_2 gets turned ON, D_1 is in the OFF state with the main diode Df turn OFF, and switch S remains ON. Resonance starts between C_1, D_2, C_2, L_s and the switch. The voltage across the snubber capacitor C_1 is given by

$$V_{C_1}(t) = \left(V_0 - V_{C_2} - \frac{L_S V_{in}}{L_m + L_S}\right)\cos\omega_r(t - t_1) + \left(V_{C_2} + \frac{L_S V_{in}}{L_m + L_S}\right) \tag{6}$$

$$\omega_r \cong \sqrt{(L_m + L_S)/L_m L_S C_1} \tag{7}$$

$$I_{D_2}(t) = \omega_r C_1\left(V_0 - V_{C_2} - \frac{L_S V_{in}}{L_m + L_S}\right)\sin\omega_r(t - t_1) \quad (8)$$

The input current through the main inductor L_m is given by

$$I_{L_m}(t) = I_{L_m}(t_0) + \frac{V_{in}}{L_m + L_S}(t - t_1) - \frac{1}{\omega_r L_m}\left(V_0 - V_{C_2} - \frac{L_S V_{in}}{L_m + L_S}\right)\sin\omega_r(t - t_1) \quad (9)$$

$$I_s(t) = I_{L_s}(t) = I_{L_m}(t) + I_{D_2}(t) \quad (10)$$

At the end of the mode the voltage across the snubber capacitor C_1 reaches zero.

Mode 3[$t_2<t<t_3$]

At $t=t_2$ the snubber diode D_1 turns ON and the snubber diode D_2 and switch S remain in OFF state. Snubber capacitor C_1 gets discharged fully

The current through the snubber inductor and the main inductor becomes

$$I_{L_s}(t) = I_{L_s}(t_1') - \frac{V_{C_2}}{L_S}(t - t_1') \quad (11)$$

$$I_{L_m}(t) = I_{L_m}(t_1') - \frac{V_{in} + V_{C_2}}{L_m}(t - t_1') \quad (12)$$

Current freewheels through D_1, D_2, C_2 and L_s. At $t=t_3$ switch is turned OFF with ZVS condition.

Mode 4[$t_3<t<t4$]

At $t=t_3$, switch is turned OFF with D_1 and D_2 remains in ON state and main diode is in the OFF state. Snubber capacitor C_1 gets charged by the current through main inductor L_m through the diode D_1. D_1 current is given as

$$I_{D_1}(t) = I_{L_s}(t) = I_{L_s}(t_2) - \frac{V_{C_2}}{L_S}(t - t_2) \quad (13)$$

Resonance starts between C_1, D_2, C_2, L_S and source.

$$I_{D_2}(t) = I_{D_1}(t) - I_{L_m}(t) \quad (14)$$

At $t=t_4$ voltage across C_1 reaches near the output voltage.

Mode 5[$t_4<t<t_5$]

Main diode is turned OFF; switch S will be in OFF state and diode D_1 and D_2 are in ON state.

$$V_S(t) = V_{C_1}(t) = V_0 \quad (15)$$

$$V_{L_s}(t) = -V_{C_2} \quad (16)$$

$$V_{L_m}(t) = V_{in} + V_{C_2} - V_0 \quad (17)$$

$$I_{L_m} = I_{D_f} \quad (18)$$

At $t=t_5$ current through D_1 and D_2 reduces linearly to zero.

Mode 6[$t_5<t<t_6$]

At the beginning, main diode is ON, switch is OFF and snubber diode D_1 and D_2 are turned OFF as the currents through it reduces to zero.

$$I_{L_m} = I_{D_f} \quad (19)$$

$$V_{L_s}(t) = 0 \quad (20)$$

$$V_{L_m}(t) = V_{in} + V_{C_2} - V_0 \quad (21)$$

$$V_S(t) = V_0 - V_{C_2} \quad (22)$$

A resonance is created by L_s and the parasitic capacitance of the switch. Due to this the voltage across the switch starts to decrease from the output voltage value. At the end of this mode switch is turned ON again and the switching period is over too.

DESIGN OF PROPOSED LCD SNUBBER

Main inductor L_m

The main inductor value is chosen such that the current through it should be less than the maximum allowable current. This maximum allowable current should always be less than twice as that of maximum value of the input current.

$$\Delta I_{L_m} \cong \frac{(V_0 - V_{in} - V_{C_2})(1 - D_C)}{L_m f_S} \quad (23)$$

Thus when switching frequency increases the value of main inductor gets decreased when compared to the conventional converter.

$$\Delta I_{L_m} = \frac{(V_0 - V_{in})(1 - D_C)}{L_m f_S} \quad (24)$$

Resonant inductor L_s

For achieving ZCS turn ON of the switch the required value of resonant inductor is determined from the following equation

$$L_S > L_{S,min} = \frac{(V_0 - V_{C_2})t_r}{I_i} \quad (25)$$

wheret_r is the rise time of the switch current

When the switch gets turned ON at $t=t_1$ reverse recovery current of main diode D_f flows through resonant inductor. $(V_0 - V_{C_2})$ is the voltage which will have to be absorbed by L_s to avail the ZCS condition to have switch turn ON. When L_s increases it will decrease the turn ON

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losses of the switch. Maximum inductance value of L_s is given as from

$$L_S \leq L_{S,max} = \frac{(1-D_C)T_S V_{C_2}}{I_{L_S}(t_2)} \tag{26}$$

Resonant capacitors C_1 and C_2

To control the dv/dt of switch at turn OFF a snubber capacitor C_1 is connected in parallel to the switch with a diode D_1.The minimum value of C_1 depends on the output voltage as it will appear across C_1 during the switch turn OFF.

$$C_1 > C_{1,min} = \frac{I_S(t_2)t_f}{2V_0} \tag{27}$$

Where t_f is the switch current fall time

When C_1 increases the turn OFF losses of the switch decreases as the voltage across the switch decreases.

For ZVS turn OFF $V_{C_1}(t_2) = 0$

From this maximum value of C_1 determined

$$C_1 < C_{1,max} = \frac{1}{L_S}\left[\frac{t_2 - t_1}{\cos^{-1}(-V_{C_2}(V_0 - V_{C_2}))}\right]^2 \tag{28}$$

The value of C_2 must be chosen such that voltage across it is greater than the ripple voltage

$$\Delta V_{C_2} \ll V_{C_2} \tag{29}$$

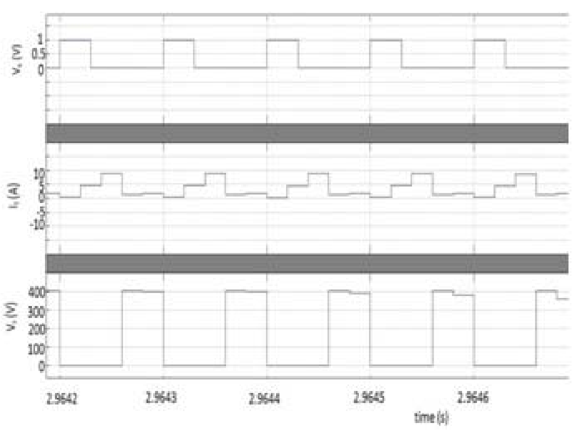

Figure-7.V_s, I_s and V_G for the proposed PFC converter.

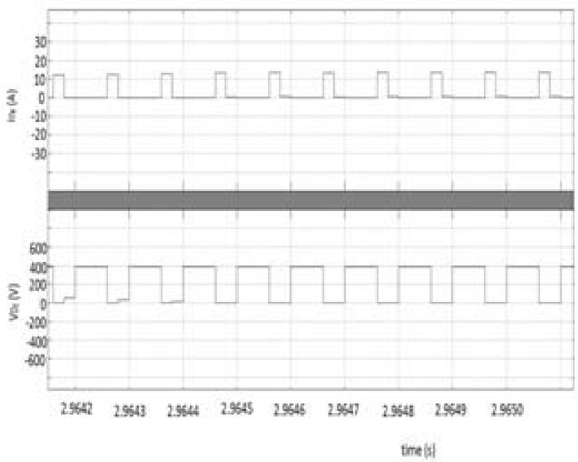

Figure-8.V_{Df} and I_{Df} for the proposed PFC converter.

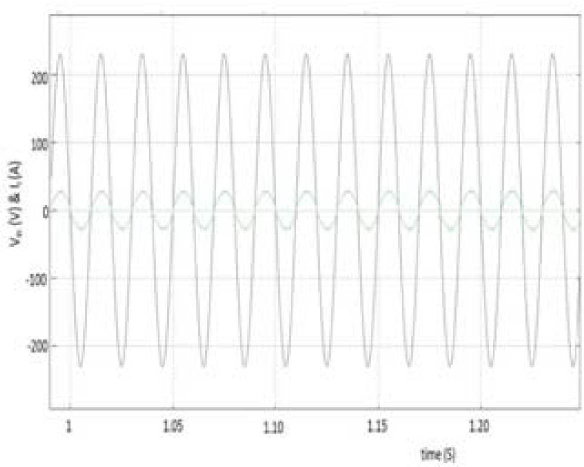

Figure-9.V_{in} and I_i of input ac line.

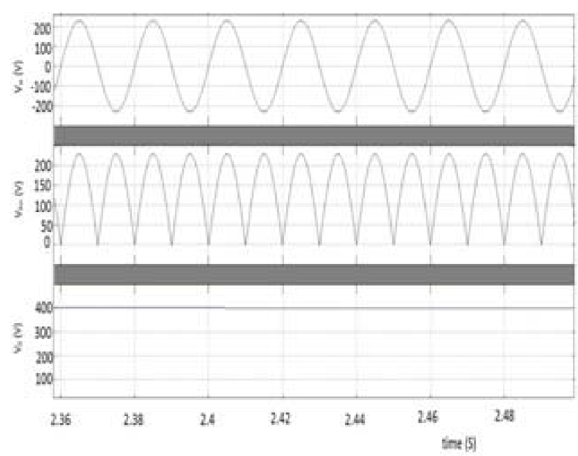

Figure-10.V_{in}, V_{rin} and V_o of the proposed PFC converter.

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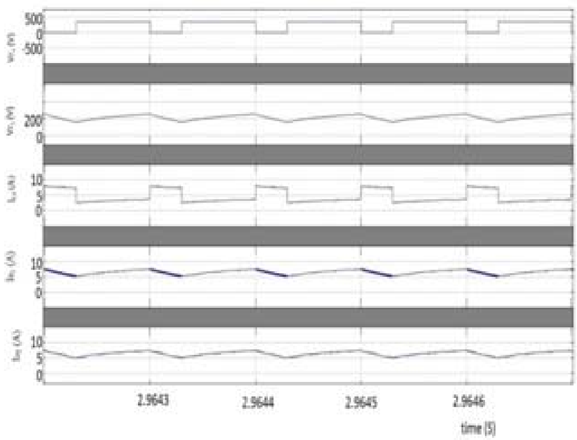

Figure-11. Vc_1, Vc_2, IL_s, ID_1 and ID_2 of the proposed PFC converter.

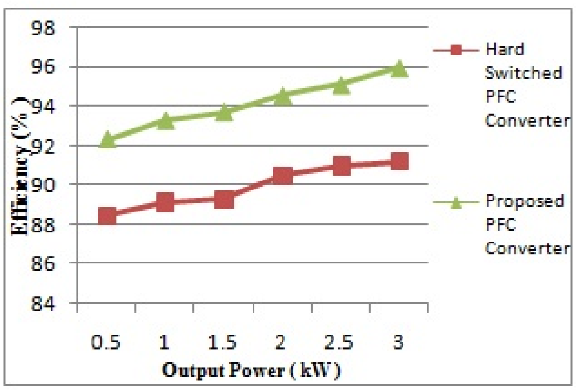

Figure-12. Output power and efficiency.

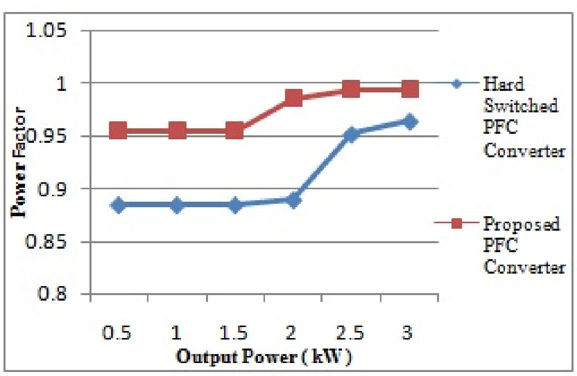

Figure-13. Output power and power factor.

CONCLUSIONS

The proposed LCD passive snubber cell helps the boost converter switch to have ZCS turn ON and ZCS turn OFF. This result in reduced turn ON and turn OFF switching losses. The proposed converter has a efficiency that is 4% higher than hard switched PFC converter. This converter has a total efficiency of 95% and 0.994 power factor with sinusoidal input line current. Conventional and proposed PFC converters are operated at 200 kHz switching frequency at 3.2 kW output power. Also the LCD snubber cell does not increase the cost and complexity as it is having only less number of components. Another advantage is that all the semiconductor components of the proposed PFC converter are operated under soft switching.

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