J Electr Eng Technol Vol. 9, No. 2: 501-507, 2014
http://dx.doi.org/10.5370/JEET.2014.9.2.501

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

A High Efficiency DC-DC Boost Converter with Passive Regenerative Snubber

Radika P[†]

Abstract – This paper describes the improvement in converter efficiency by reducing the switching loss and by recovering the snubber stored energy. A capacitive based passive regenerative snubber circuit is modeled for a dc-dc boost converter. The proposed snubber is mainly used to reduce the turn-off loss of the main switch. The energy recovery process and the turn-off loss depends on the size of the snubber capacitance; therefore, the conventional and the proposed converters are designed for high and low input voltage conditions with different sizes of the snubber capacitance. Based on the results obtained, the snubber capacitors are classified as small, normal and large snubbers. The Matlab simulation results obtained are presented.

Keywords: Boost converter, Passive snubber, Regenerative snubber, Turn-off loss, Snubber capacitor, Boost inductance

1. Introduction

In general, soft-switching techniques have been used to reduce the switching losses and stress of a power switching devices. To reduce the stress and the switching conditions for the power switches can be improved by using snubber circuit also. During turn-on condition a series inductor called snubber inductor is used to limit the rate of rise of current (di/dt) through the device. A shunt capacitor called snubber capacitor is used to limit the rate of rise of voltage (dv/dt) across the device at turn-off instant.

During snubbing action energy is stored in the magnetic/ electric field of these components. The stored energy must be removed after each switching transition to assure repetitive snubbing action. The simple way is to discharge the stored energy into a resistor which results in dissipative snubbers [1, 2]. Therefore, dissipative passive snubbers are usually added to the power circuits so that dv/dt and di/dt of the switching devices can be reduced, and the switching losses and stress can be diverted to the snubber circuits.

The size of the snubber inductor/capacitor may be small, normal, or large according to the definition of McMurray [3, 4] as shown in Fig. 1. It shows that the switching loss in the switching device decreases with an increase in snubber. For good snubbing action at high power levels and switching frequencies, a relatively large snubber is, therefore, needed. This result in a large quantity of stored energy in the snubber element and at the same time causes more snubber energy loss. However, the power electronics products are in demand for their high efficiency in saving energy. To cope with the demand, the snubber energy losses of the converters are not negligible and should be improved [5]. In order to improve the efficiency of the system, the use of the regenerative or energy recovery or non-dissipative snubber is necessitated. This snubber is able to recover some of the stored energy, by feeding it back to the supply or load. This may be passive or active one [6].

In some of the passive snubber based converters incorporated a snubber circuit with energy recovery transformer [7-10]. This introduced additional losses. Whereas, the proposed snubber does not use recovery transformer. Also it was observed that generally the studies of dc-dc converter [6, 11-13] had been carried out for a particular value of snubber capacitance and the effect of the size of the snubber capacitance had not been discussed much. Therefore, for a proposed converter, the selection of

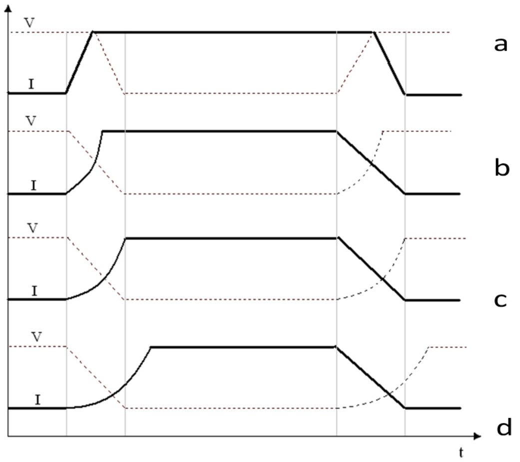


Fig. 1. Voltage and current waveforms of a transistor with different sizes of snubber: (a) No snubber; (b) Small snubber; (c) Normal snubber; (d) Large snubber

---

[†] Corresponding Author: Dept. of Electrical and Electronics Engineering, Adhiparasakthi Engineering College, Melmaruvathur, India. (radikasenthil@gmail.com)

Received: December 28, 2012; Accepted: October 22, 2013

the size of the snubber capacitance which is an important factor to obtain the better performance is analysed. The change in turn-off loss, output voltage and efficiency for different sizes of the snubber capacitance are discussed in the present work. Based on the results obtained, the snubber capacitors are classified as three groups: Group I as small snubber, Group II as normal snubber and Group III as large snubber.

2. Principle of Operation

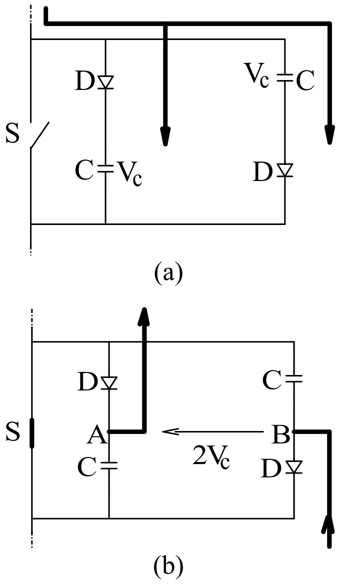
The principle of operation of the proposed snubber without energy recovery circuit (Fig. 2) is explained as follows [14]: When switch S turns-off, as in Fig. 2(a), the two capacitors are charged equally by the energy stored in the circuit, here Vc denotes the voltage of each capacitor. When the switch turns-on, as in Fig. 2(b), these two voltages are superimposed and 2Vc appears across the terminals A and B. If these two terminals are connected with the source or the load through an inductor, the capacitor voltages will discharge resonantly to zero, thus recovering the stored energy of the snubber capacitors. The switch turns-off softly at zero voltage by virtue of being in parallel with the capacitors.

2.1 Circuit configuration and modes of operation

Fig. 3 shows the proposed boost converter. It differs from a conventional PWM boost converter by adding a passive regenerative snubber network, which consists of snubber capacitors (Cs1, Cs2), snubber diodes (Ds1, Ds2) and the energy recovery circuit components of resonant inductors (Lr1, Lr2) and diodes (Dr1, Dr2). The proposed one has two modes of operation (Fig. 4) based on switch on and off conditions as explained below.

1) Mode 1 Operation: Assuming that, initially, the voltage across the snubber capacitors $C_{s1}=C_{s2}=C_s$ is zero.

In Fig. 4(a), the main switch S turns-off at zero voltage condition. The inductor current I_L is transferred to the snubber capacitors charging them equally up to the output voltage V_o ($V_o=V_{in}+V_L$). The diode D conducts exactly in the same manner as diode D of conventional boost converter. During this mode, the voltage across the each



(a)

(b)

Fig. 2. Proposed passive snubber (without energy recovery circuit) (a) Two snubber capacitors are charged in parallel when switch turns-off (b) Discharged in series when switch turns-on

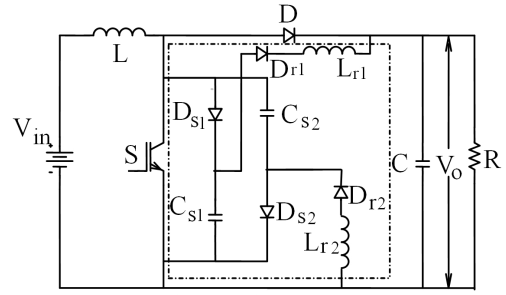
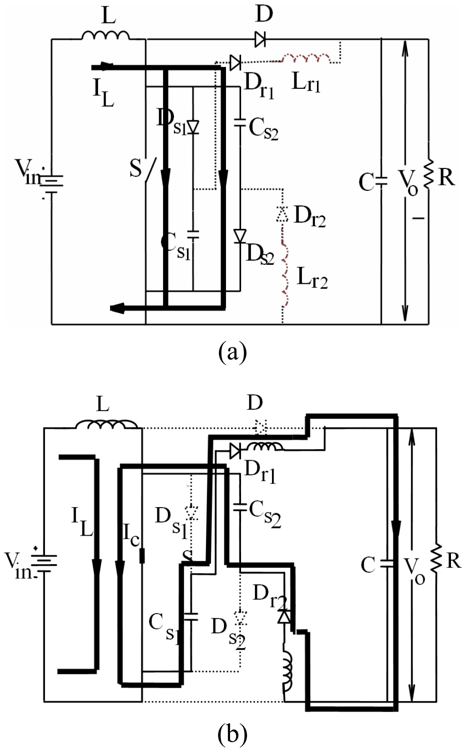


Fig. 3. Proposed boost converter with passive regenerative snubber



(a)

(b)

Fig. 4. Modes of operation of a proposed converter: (a) Mode 1 operation: Snubber capacitors to charge when main switch turns-off; (b) Mode 2 operation: Discharging the snubber voltages into the output side when main switch turns-on

snubber capacitor V_{Cs} is given as

$$V_{Cs}(t) = \frac{I_L t}{2C_s} \qquad (1)$$

Based on the design of turn-off snubber, if the snubber capacitor voltage $V_{Cs} = V_o$ is obtained during this interval, the snubber capacitor C_s is given as follows

$$C_s = \frac{I_L t}{2V_o} \qquad (2)$$

In general, this shunt snubber is named as normal snubber C_n.

2) Mode 2 Operation**:** At the turn-on of the switch as shown in Fig. 4(b), the superimposed capacitor voltage $2V_o$ discharges resonantly into the output side. The switch carries both the main current I_L and the capacitor discharging current I_c. At the end of this mode of operation, the voltage across the capacitors becomes zero. Therefore, at ZVS condition the switch is turned-off again. If the voltage across each snubber capacitor, at the end of the charging condition, is V_{Cso}, then, the Eqs. (3) and (4) give the capacitor current I_c and voltage V_{Cs} respectively during the discharging period.

$$I_c(t) = \frac{2V_{Cso} - V_o}{2Z} \sin \omega t \qquad (3)$$

$$V_{Cs}(t) = \frac{2V_{Cso} \cos \omega t + V_o (1 - \cos \omega t)}{2} \qquad (4)$$

where, $C_{s1} = C_{s2} = C_s$, $L_{r1} = L_{r2} = L_r$ and

Resonant impedance $$Z = \sqrt{\frac{L_r}{C_s}} \qquad (5)$$

Resonant frequency $$\omega = \frac{1}{\sqrt{L_r C_s}} \qquad (6)$$

3. Simulation Analysis

In simulation the performance of the converter is analyzed at both high (200 V) and low input (15 V) voltage conditions. The boost inductor of the converter is designed using the conventional method as follows:

$$L = V_{in} \frac{dt_{on}}{dI} \qquad (7)$$

It shows that the design of inductance depends on its inductor current ripple. Based on some design examples [15-19] two values of current ripple is assumed for analysis rather than the optimal design values [20, 21]. This leads to four cases. The circuit parameters for each case are shown in Table 1 and Table 2.

Table 1. Reference parameters

Parameters	Values			
	Case I	Case II	Case III	Case IV
Input voltage, V_{in}	200 V		15 V	
Duty cycle, d	0.5			
Switching frequency, f_s	25 kHz			
Load resistance, R	500 Ω			
Input current ripple, ΔI_{in}	2.5 %	1 A	2.5 %	1 A
Output voltage ripple, ΔV_o	0.0125			

Table 2. Calculated parameters

Parameters	Values			
	Case I	Case II	Case III	Case IV
Output volta			30 V (conventional)	
Input boost i	100 mH f	L=15 m	100 mH f	1mH for
Output filter	1280 μF		100 μF	

3.1 Case I. Input voltage, V_{in}: 200 V and input boost inductance, L: 100 mH

The obtained result of the conventional boost converter is shown in Table 3.

Table 3. Results of conventional boost converter

V_{in} (V)	V_o (V)	Theoretical V_o (V)	Efficiency (%)
200	397.8	400	80.68

The selection of the size of the snubber capacitor is an important factor to obtain the better performance of the proposed converter. Since, the main switch turn-off loss can only be reduced by snubber capacitor, it is necessary to select a snubber capacitor so that further increments of capacitor value will not significantly reduce the turn-off loss. Therefore, using the same reference parameters (Table 1), the proposed converter is simulated for different values of snubber capacitance ($C_s = \frac{I_L t}{2V_o}$). The obtained output voltage and efficiency are plotted in Fig. 5. Based on the results obtained, the snubber capacitors can be classified as three groups:

- Group I (0.01 - 0.069 μF) as small snubber
- Group II (0.07 - 0.14 μF) as normal snubber
- Group III (0.15 - 0.3 and > 0.3 – 5 μF) as large snubber.

In small snubber the capacitor voltage reaches quickly to the input voltage level during its charging condition. Therefore, it is not sufficient for turn-off protection. The normal snubber provides sufficient turn-off protection. With large snubber the voltage rises slowly to reach the input voltage, and thereby provides good turn-off protection with minimum turn-off energy loss. The obtained turn-off energy loss of the main switch for three

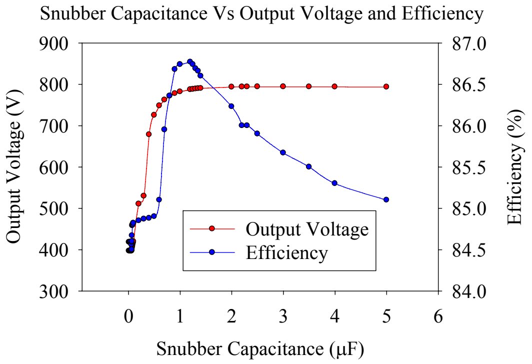


Fig. 5. Snubber capacitance Vs output voltage and efficiency of a proposed converter

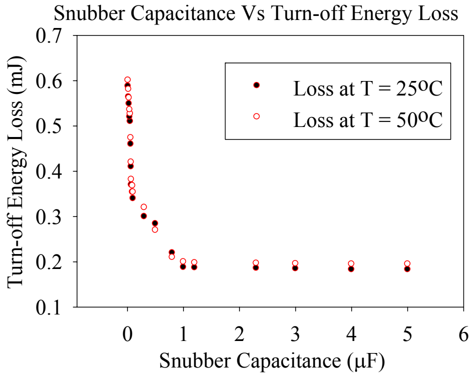


Fig. 6. Snubber capacitance Vs turn-off energy loss of a proposed converter at $V_{in} = 200$ V

Table 4. Comparison of conventional and proposed converters with case II parameters

	Convention		Proposed		Difference i	Difference i	Difference i
V_{in}	V_o	η	V_o	η			
100	19	89.0	385.5	91.36	66.67	48.64	2.58
200	39	89.2	776.4	91.7	66.67	48.76	2.73

groups of snubber capacitance, using MATLAB/PLECS, is shown in Fig. 6. It shows that an increase in snubber capacitance causes a reduction of turn-off loss. The minimum loss is obtained with snubber capacitors in the range of > 0.8 μF (Group III large snubber).

3.2 Case II. Input voltage, V_{in}: 200 V and input boost inductance, L: 15 mH for conventional converter and 5 mH for proposed converter

An increase in efficiency of both the converters is obtained under this case. The proposed converter with one-third of the inductance of the conventional model has good results. Table 4 compares the results of conventional and proposed converters with case II parameters. The results obtained clearly shows that both the converters have better performance under this condition. The proposed converter with regenerative snubber circuit has an increase in output voltage and efficiency than the conventional converter.

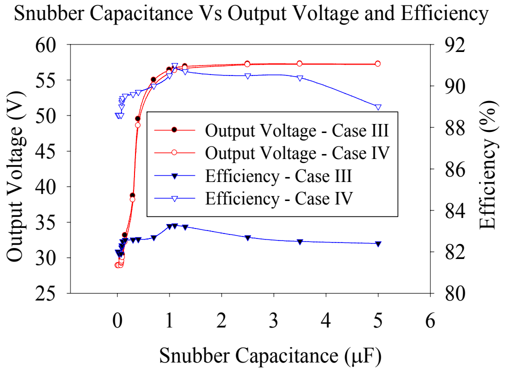


Fig. 7. Snubber capacitance Vs output voltage and efficiency of a proposed converter with case III and case IV parameters

3.3 Case III. Input voltage, V_{in}: 15 V and input boost inductance, L: 100 mH

The converters are designed for low voltage level similar to case I. The results of case III are similar to case I. The range of the three groups of the snubber capacitors are as follows: Group I (0.01-0.088 μF) is taken as small snubber which provides complete energy recovery. Group II is taken as normal snubber. The range (0.089–0.12 μF) is an ideal normal snubber and provides complete energy recovery. But the range (0.13–0.32 μF) provides partial recovery only. Group III (0.33–0.4 and 0.5–μF) is large snubber which provides partial energy recovery; and, here, voltage doubling also exists. Also, Group I provide, the output which is almost the same as conventional one and Group II is with slight increase of output than the conventional one. Group III has almost twice the output voltage of conventional one.

3.4 Case IV. Input voltage, V_{in}: 15 V and input boost inductance, L: 1mH

When compared with case III for all ranges of snubber capacitance a small reduction in the output voltage with an increase in efficiency is obtained as shown in Fig. 7.

Table 5 shows the turn-off energy loss of the converters. The results obtained shows that the turn-off loss is reduced in the proposed converter. With increase in snubber capacitance the loss is reduced. With Cs = 1.1 μF, the obtained loss is shown.

4. Experimental Results

From the simulation observation, the converter at low voltage condition (case III) as it provides, better results is considered for experimental analysis. Therefore, a laboratory model of the converters is developed with an

Table 5. Turn-off energy loss of the converters

Converter	Turn-off energy loss (μJ) at V_{in} = 15 V
Conventional	51.0
Proposed	11.6

Table 6. Results of conventional boost converter

Input voltage (V)	Output voltage (V)	Efficiency (%)
15	30.14	83.48

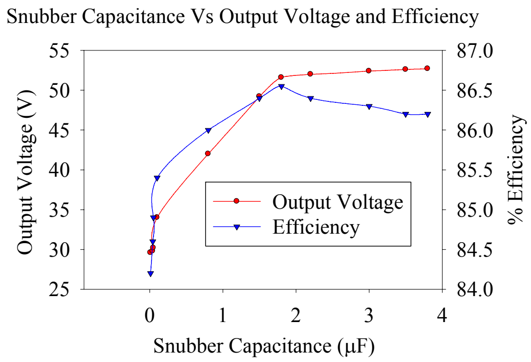


Fig. 8. Snubber capacitance Vs output voltage and efficiency

input voltage of 15 V. The observation of the conventional converter is shown in Table 6.

The results of the proposed converter are shown in Fig. 8. Based on the results obtained the snubber capacitors can be taken as follows.

- Small snubbers: 0.01 μF and 0.04 μF
- Normal snubbers: 0.05 μF (Ideal) and 0.1μF
- Large snubbers: 0.8 μF, 1.5 μF, 1.8 μF, 2.2 μF, 3 μF, 3.5 μF, 3.8 μF.

Compared with the conventional converter the changes are,

- Small snubbers provides decrease in output voltage with an increase in efficiency
- Normal snubbers provides increase in output voltage with an increase in efficiency
- Large snubbers as increase in output voltage with an increase in efficiency.
- The maximum efficiency of 86.55 % is obtained from the large snubber capacitance (1.8 μF).

Fig. 9 shows the comparison of simulation result with the experimental result of a proposed converter with V_{in} = 15 V. The simulated output voltage for higher range of snubber capacitance and the simulated efficiency for all range of snubber capacitance show a close conformity with the experimental result. Since the proposed snubber is mainly used to reduce the turn-off switching loss the switching voltage and current of the converters at turn-off condition is shown in Fig. 10. This clearly shows that the turn-off loss is considerably reduced in the proposed converter.

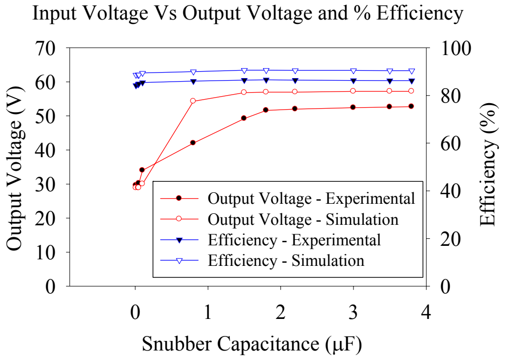


Fig. 9. Comparison of simulation and experimental results of a proposed converter

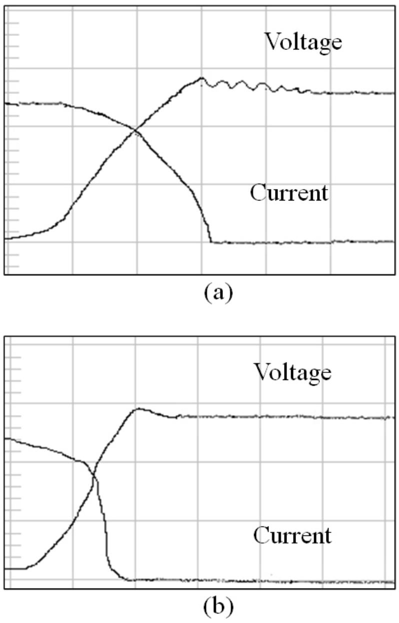


Fig. 10. Main switch voltage and current at turn-off condition: (a) Conventional converter; (b) Proposed converter -V/div = 20V, I/div = 0.5A, Time/div = 500ns

The voltage and current waveforms of the snubber capacitor is shown in Fig. 11. It satisfies the concept of the proposed snubber as shown in Fig. 1. At turn-off condition of the switch, each capacitor charged to its output voltage and discharged in series into the output side at turn-on condition.

The voltage and current waveforms of the snubber capacitor is shown in Fig. 11. It satisfies the concept of the proposed snubber as shown in Fig. 1. At turn-off condition of the switch, each capacitor charged to its output voltage and discharged in series into the output side at turn-on condition.

Fig. 12 is the EMI noises of the converters. The peak condition is obtained around 26 kHz (switching frequency is 25 kHz) for both the converters. It can be seen that the noise at the switching frequency of the proposed converter

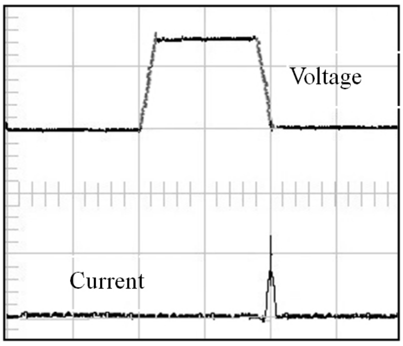
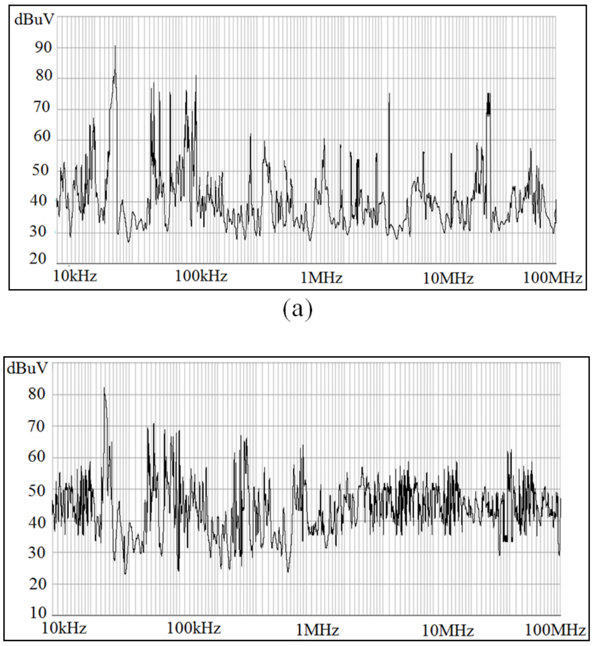


Fig. 11. Snubber capacitor voltage and current waveforms - V/div = 20V, I/div = 1A, Time/div = 20 µs



(a)

(b)

Fig. 12. Measured EMI signals of the converters conventional (b) Proposed

is approximately 6 dB lower than that of the conventional converter.

5. Conclusion

In this paper, a passive regenerative snubber circuit is presented. It has been developed for a dc-dc boost converter. The proposed snubber reduces the turn-off switching loss and the snubber stored energy is fed back to the output side. Thus the converter efficiency has been improved. At low input voltage condition the improvement is found to be 3 %. The switching voltage and current of the converters at turn-off condition is shown. The proposed converter with approximately 6 dB lower EMI than that of the conventional converter at switching frequency condition is also shown.

References

[1] C.G Steyn, "Optimum Size of Dissipative Nonlinear Turn- off Snubber", *IEE Electric Power Applications*, vol.135, no.4, pp.165-171, 1988.

[2] C.G Steyn and J.D Van Wyk, "Optimum Nonlinear Turn- off Snubbers: Design and Applications", *IEEE Transactions on Industry Applications*, vol.25, no. 2, pp. 298-304, 1989.

[3] W. McMurray, "Selection of Snubbers and Clamps to Optimize the Design of Transistor Switching Converters", *IEEE Transactions on Industry Applications*, vol. IA-16, no.4, pp. 513-523, 1980.

[4] P.C Sen, *Modern Power Electronics*, *Ist ed*., Wheeler Publishing, 1998

[5] M.Yatsu and N. Eguchi, "An Active Snubber-Energy-Recovery Unit at PWM Converters to Achieve High Efficiency", *IEEE Industrial Electronics Society*, vol. 1, pp. 2138- 2143, 2006.

[6] T.F Wu, Y.D Chang, C.H Chang, H.X Lee, K.Y Lee and J.G Yang, "A 5 kW Boost Converter with Various Passive/Active Snubbers for Reducing Component Stress and Achieving High Efficiency", *in Proceedings of IEEE Power Electronics and Drive Systems PEDS 2007 Conference*, Taipei, pp. 187-192, 2009.

[7] J. Finney and B.W Williams, "High Power GTO Thyristor Chopper Applications with Passive Snubber Energy Recovery", *IEE Proceedings on Electronics Power Appliances*, vol.144, no.6, pp. 381-388, 1997.

[8] F.Z Peng, G. Su and L.M Tolbert, "A Passive Soft-Switching Snubber for PWM Inverters", *IEEE Transactions on Power Electronics,* vol.19, no.2, pp. 363-370, 2004.

[9] B.W Williams and S. J Finny, "Passive Snubber Energy Recovery for a GTO Thyristor Inverter Bridge Leg", *IEEE Transactions on Industrial Electronics*, vol.47, no.1, pp.2-8, 2000.

[10] A. Isurin and A. Cook, "Passive Soft-switching Snubber Circuit with Energy Recovery", *in Proceedings of IEEE Applied Power Electronics and Exposition Conference APEC 2008*, Austin, pp. 465-468, 2008.

[11] R.T.H Li and H.S.h Chung, "A Passive Lossless Snubber Cell with Minimum Stress and Wide Soft-Switching Range", *IEEE Transactions on Power Electronics*, vol. 25, no.7, pp. 1725-1738, 2011.

[12] J. Bauman and M. Kazerani, "A Novel Capacitor-Switched Regenerative Snubber for DC/DC Boost Converters", *IEEE Transactions on Industrial Electronics*, vol.58, no.2, pp. 514-523, 2011.

[13] C.A Gallo, F.L Tofoli and J.A.C Pinto, "A Passive Lossless Snubber Applied to the AC–DC Interleaved Boost Converter", *IEEE Transactions on Power Electronics*, vol. 25, no.3, pp. 775-785, 2010.

[14] K. Fujiwara and H. Nomura, "A Novel Lossless Passive Snubber for Soft-Switching Boost Type Converters", *IEEE Transactions on Power Electro-*

nics, vol.14, no.6, pp. 1065-1069, 1999.

[15] G. Moschopoulos, P. Jain and G. Joos, "A Novel Zero-Voltage Switched PWM Boost Converter", *in Proceedings of IEEE Power Electronics Specialist Conference PESC 1995*, Atlanda, pp. 694-700, 1995.

[16] A. Kirubakaran, Shailendra Jain and R.K. Nema, "The PEM Fuel Cell System with DC/DC Boost Converter: Design, Modeling and Simulation", *ACEEE-International Journal of Recent Trends in Engineering*, vol.1, no.3, pp. 157-161, 2009.

[17] Cooper Bussmann, "Inductor Selection for Switching Regulators", *Coiltronics*, 2008.

[18] V.A. Bonfa, P.J.M. Menegaz and J.L.F. Vieira, "DC/DC PWM Converters Using Magnetically Coupled Regenerative Snubbers", *in Proceedings of IEEE Power Electronics Drive Systems PEDC 2001 International Conference*, pp. 822-828, 2001.

[19] P.J.M. Menegaz, J.L.F. Vieira and D.S.L. Simonetti, "A Magnetically Coupled Regenerative Turn-On and Turn-off Snubber Configuration", *IEEE Transactions on Industrial Electronics*, vol.47, no.4, pp. 722-728. 2000.

[20] Gyu-Yeong Choe, Jong-Soo Kim, Hyun-Soo Kang and Byoung-Kuk Lee, "An Optimal Design Methodology of an Interleaved Boost Converter for Fuel Cell Applications", *Journal of Electrical Engineering & Technology*, vol.5, no.2, pp. 319-328, 2010.

[21] Liu Shulin and Ma Yibo, "Optimization Design of the Inductance of Boost Converters", *in Proceedings of IEEE Electrical and Control Engineering ICECE 2010 International Conference*, pp. 3949-3952, 2010.

Radika P received B.E degree from PSG College of Technology, Coimbatore in 1990 and received M.E and Ph.D. degree from Sathyabama University, Chennai in 2006 and 2012 respectively. She is working in Adhiparasakthi Engineering College, Melmaruvathur from 1998. Her research interests are microprocessor and micro controllers, power electronics and renewable energy systems.