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High Efficiency DC/DC Boost Converters for Medium/High Power Applications

Furqan Zahoor*, Swastik Gupta and Vipan Kakkar

Department of Electronics and Communication Engineering, Shri Mata Vaishno Devi University, India
**14mmc011@smvdu.ac.in, swastik.gupta@smvdu.ac.in, vipan.kakar@smvdu.ac.in*

Abstract

Switching Converters commonly known as DC/DC Converters have gained tremendous popularity due to their use in variety of applications such as hybrid energy systems, hybrid vehicles, satellite applications and portable electronic devices to name a few. The main positives of using high step up converters include improving voltage gain, reduction of voltage stress and current ripple. But these converters seem to have some disadvantages like very high EMI due to reverse recovery of the boost diode and considerable amount of losses which occur due to hard switching of the boost switch. Many variations of the original boost schematic have been suggested to overcome these problems. The Zero Voltage Transition (ZVT) Boost converter and Zero Current Transition (ZCT) Boost converter are such solutions. These soft switching topologies employ an auxiliary resonant circuit which allows the boost switch to turn on and off under zero voltage and zero current conditions respectively thus reducing the switching losses. In addition, these boost converter circuits have major drawback of low power efficiency particularly at light loads due to the negative value of inductor current at light loads. In this research, a novel technique for designing a boost converter is proposed. The proposed converter employs an auxiliary circuit which allows switching of the main switch as well as the auxiliary switch under zero voltage/zero current conditions. In addition, the boost converter automatically senses the zero current across the resonant inductor, thus forcing the convertor to step automatically from Continuous Conduction Mode (CCM) to Discontinuous conduction mode (DCM) when the inductor current tries to go negative. This prevents the inductor current to go negative and hence improve convertor's power efficiency. A novel boost convertor which steps up 200V input voltage to 400V output is designed in PSIM software with a switching frequency of 100KHz. The simulation results show that the proposed convertor has an efficiency of about 99.3% at nominal output power.

Keywords*: Boost Converter, DC/DC convertor, Power efficiency of Boost convertor, Switching Mode Power Supply, Zero Current Switching (ZCS), Zero Voltage Switching (ZVS)*

1. Introduction

Switching converters commonly known as the DC/DC Converters with Pulse Width Modulation (PWM) are widely used circuits in many industrial applications. They convert a fixed-voltage dc source into a variable-voltage dc source. DC/DC Converters are usually used to obtain an output voltage which is: i) higher in magnitude (Boost) than the input voltage or ii) lower in magnitude (Buck) than the input voltage or iii) Both higher and lower (Buck Boost) than the input voltage. This literature is related only with the DC/DC Boost Convertors. When Boost, converters are operated at high frequencies, they suffer

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significant reverse recovery related losses which become more prominent when the converter is switched under hard switching conditions. Therefore, the Boost Converters need to be operated at low switching frequencies to achieve higher conversion efficiencies. Thus, by introducing the concept of soft switching, will significantly enhance the switching frequency and therefore the power density of the Boost Converters.

Till date, a significant number of soft switched boost converters have been proposed [1] – [11]. To control the turn-off di/dt rate of the rectifier, Soft switching converters employ various additional components such as inductor and capacitor thus forming a snubber circuit. By implementing various soft switching techniques, the switch will make a transition from its on-state to its off state and from its off state to its on state at the instant when the switch voltage or the switch current is zero. This will prevent the occurrence of the switching losses. Soft Switching techniques are mainly categorized as: i) Zero Voltage Switching (ZVS) and ii) Zero Current Switching (ZCS). During switching period when either voltage or current is zero, then the product of voltage and current becomes zero which in turn means that there is ideally no power loss in the device. Thus, Soft Switching results in enhanced system efficiency.

In [1], [2], [9], [10], [11] and [13] a concept of Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) is introduced which results in significant improvement in switching losses in the boost converter thus enhancing the efficiency. Zero Voltage Switching is presented to achieve a Zero Voltage Switching of active switches. This technique turns the power MOSFET switch in the Boost converter ON & OFF only when the drain to source voltage across it is zero. Thus, significantly reducing the power losses. On the other hand, zero current switching(ZCS) ensures that the switching takes place only at zero current.

In [8], [9], [10] a new class of Boost converters referred to as Novel ZVT-ZCT-PWM Boost converters were introduced with a new kind of an active snubber cell. This approach is effective in reducing the switching losses as it mainly focusses to modify the control technique used in the earlier ZCT-PWM converter [1]. In the novel ZVT-ZCT Boost converter [11], ZVT turn on and ZCT turn “off” of the main switch is ensured. The main devices are subjected to minimal voltage as well as minimal current stresses. In addition, the stresses on the auxiliary devices are very low in the proposed new converter. This novel ZVT-ZCT structure has an advantage of providing desirable results at light load conditions as well as at very high frequencies. The simplicity of the structure as well as minimum cost of the overall structure are the additional benefits of this soft switching topology.

In this paper, a novel technique for designing a boost converter is proposed. The proposed converter employs an auxiliary circuit which allows switching of the main switch as well as the auxiliary switch under zero voltage/zero current conditions. In addition, the boost converter automatically senses the zero current across the resonant inductor, thus forcing the convertor to step automatically from Continuous Conduction Mode (CCM) to Discontinuous conduction mode (DCM) when the inductor current tries to go negative. This prevents the inductor current to go negative and hence improve convertor’s power efficiency. By using this approach, the converter achieves high efficiency over a wide load range. The results obtained from the design confirm the superior performance of the proposed converter.

2. Proposed Architecture of Boost Converter

The block diagram of the proposed ZCT-PWM Boost Converter is shown in Figure (1). The proposed converter is a boost converter with an auxiliary circuit, that consists of a switch (S2), a diode (Daux) placed in series with the switch “S2”, a resonant capacitor (Cr) and a resonant inductor (Lr). The circuit consists of various additional blocks such as: i) an error amplifier. ii) Pulse Width Modulator)

Zero Current Detector and IV) logic block. The addition of series diode Daux in the auxiliary circuit of the ZCT PWM Boost converter has the advantage of preventing the conduction of body diode of the auxiliary switch “S2” which is a slow recovery diode. This also has the benefit of preventing the parasitic capacitance of the switch “S2” from resonating with the resonant inductor “Lr”.

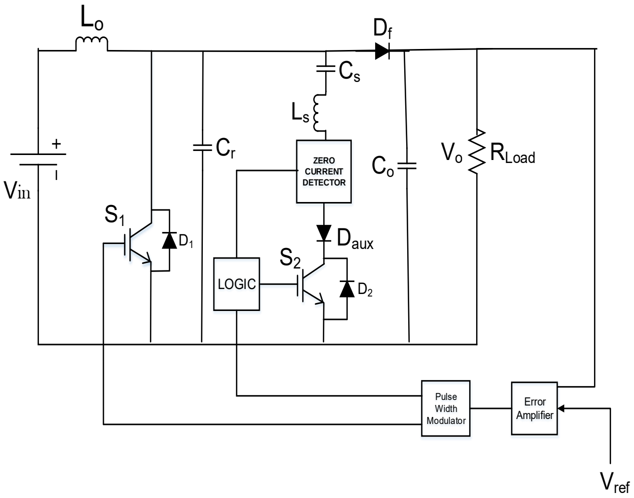

Figure 1. Block Diagram of Proposed Architecture of Boost Converter

The purpose of these various blocks in the design is mentioned as follows: The error amplifier block in the proposed ZCT-PWM boost converter is used to compare the actual output voltage obtained from the boost topology with the desired or reference output voltage. It then produces an error signal based on the difference between these two voltages. This error voltage from the error amplifier is then fed to the next block in the topology which is the Pulse Width Modulator block. The purpose of the PWM block is to produce a pulse width modulated signal. This PWM signal is applied as gate drive to the switch “S1” in the proposed ZCT-PWM Boost Topology. The zero-current detector circuit is incorporated into the design to overcome the effects of negative current flow through the resonant inductor. This negative current flows due to the resonant circuit formed by the inductor and total capacitance from auxiliary switch node to ground including the parasitic capacitance of the switch which leads to ringing’s (undesirable voltage spike), thus producing noise at the output. This undesirable noise reduces the efficiency of the boost converter circuits because of the increased conduction losses due to the negative inductor current flow in the circuit. Zero current detector circuit present in the design overcomes this negative current flow problem thus enhancing the efficiency. As the current through the inductor tries to go below zero, the zero-current detector produces a control signal indicating the inductor current is zero. At this instant, we need to turn the auxiliary switch “S2” off, thus preventing the flow of negative inductor current in the circuit. The switch “S2” will be turned “off” with the help of a suitable logic block which will also take into consideration the PWM signal driving the main switch “S1”.

How we can detect the zero current and what kind of logic we need to use will be discussed once we step over to the design process.

3. Proposed Boost Converter Circuit Design

The circuit diagram of the proposed Boost convertor designed in PSIM software is shown in the figure (2). The convertor uses PWM technique for regulating the output voltage. In addition, As the ESR of output inductor and capacitor is very low, so it uses Type III compensation technique to ensure the stability of the feedback loop [16], it must be noted that in the proposed Boost converter topology both the main switch as well as the auxiliary switch are chosen as Insulated Gate Bipolar Transistor (IGBT). The IGBT is a minority carrier device with a voltage drop across its collector and emitter nearly independent of the current it conducts. This is totally in contrast to the MOSFET, which acts as an equivalent drain source resistance when it conducts current.

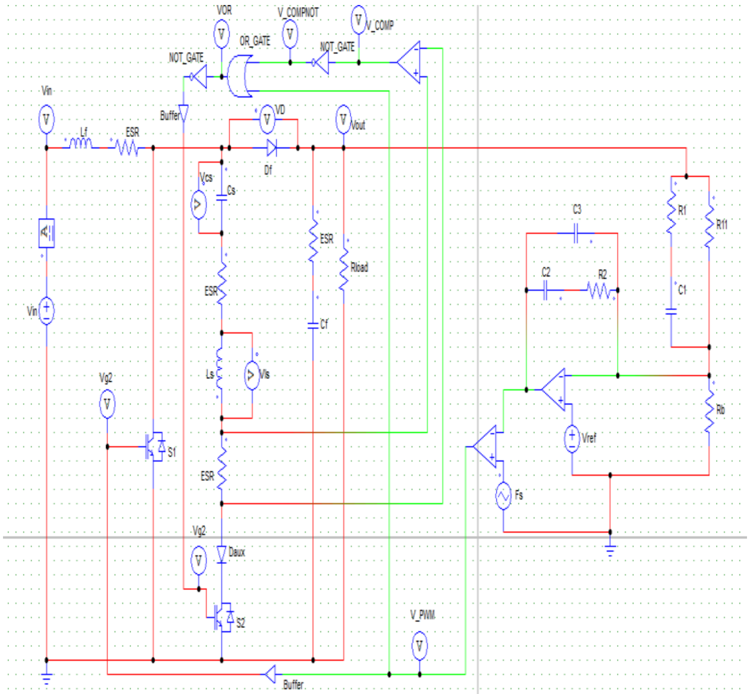

Figure 2. Circuit Diagram of Proposed Boost Converter

The nearly fixed voltage drop of the IGBT along with its higher voltage rating and power density makes it a device of choice in power applications where switches must conduct greater currents and conduction losses can be reduced. To simplify the analysis, all the semiconductor devices and resonant circuits are assumed ideal. The switching frequency here taken is 100 KHz to reduce the component size *i.e.* to reduce the size of output inductor and capacitor. The higher frequency results in on-chip integration of both inductor and capacitor however it also results in more switching losses in the switch transistors (IGBT). So, we take the optimum switching frequency value as 100 KHz. The design specifications of the boost convertor to be designed are given in Table I.

The boost inductor & boost capacitance value calculation is first step in the designing process of a boost convertor. The min. value of inductor is computed by using below equations. The minimum value of inductor which ensures operation in CCM is given by [17]

$$L_{min} = \frac{(1-D)^2 * D * R}{2f} \quad \ldots\ldots \quad \ldots \ (1)$$

Based on the specification given in Table (I), we get the value of $L_{min} = 6.25\ \mu H$

The minimum value of capacitor which ensures operation in CCM is given by [17]

$$C_{min} = \frac{D\ Vo}{Vr\ R\ f} \quad \ldots\ldots\ldots \quad \ldots.. \ (2)$$

Here Vo/Vr = 1% *i.e.* Vr=0.01*Vo and taking into consideration the specification given in Table (1), we get the value of $C_{min} = 50$ Mf

Thus, it is clear from the above equation that the capacitor size can be reduced by choosing higher switching frequency. The component values used in type III compensation network [16], in the feedback controller are given in Table II.

Table 1. Design Specifications of Boost Converter

Input Voltage	200V
Output Voltage	400V
Switching Frequency	100Khz
Inductor ESR	1 nΩ
Capacitor ESR	1 nΩ

Table 2. Component Values in Type III Compensator

R11	930 kΩ
R1	734 kΩ
C1	0.884 nF
R2	50 kΩ
C2	17 nF
C3	20.161 nF
Rb	150 kΩ

In the proposed boost converter circuit, the diode “Daux” is used to block the slow body diode of the switch “S2” from conduction. The value of resonant inductor “Lr” and resonant capacitor “Cr” are selected as 8 μF and 8.2 nf respectively. In addition, the reference voltage of the error amplifier V_{ref} has been assigned a fixed value of 400V whereas the switching frequency of the PWM block has been assigned a value of 100 KHz.

The converter operation can be described as follows: Initially prior to the time t=T0, the input current Iin is flowing through the diode Df as both the switches (S1 and S2) are in the “OFF” state.

At **t = T0 (Mode 1)**, the auxiliary switch (S2) turns “ON”, due to which a resonance starts between the inductor(Ls) and capacitor(Cs). Therefore, the current through the auxiliary circuit increases whereas the current through diode (Df) falls simultaneously. As a result, the diode (Df) turns off with Zero Current Switching (ZCS) conditions.

At **t = T1(Mode 2)**, the capacitor “Cr” discharges due to the previously started resonance, this forces the body diode “D1” to turn on with ZVS.

At **t=T2 (Mode 3)**, the main switch (S1) is turned “ON” with ZVS and as such the current through the main switch “S1” continues to increases.

At **t=T3 (Mode 4)**, the current through the switch “S2” becomes zero and as such switch “S2” is turned “OFF” with ZCS.

At **t=T4 (Mode 5)**, as the current through the switch “S2” goes zero, the diode “Daux” connected in series with auxiliary switch(S2) prevents the conduction of the body diode (D2) of the switch “S2” which is a slow recovery diode.

At t=T5 (Mode 6), the main switch “S1” continues to conduct the input current. The switch “S1” can be turned “OFF” at some time when the current flowing through it reaches its peak value and at that instant the switch “S2” can be turned ON. Thus, the current which flows through the main switch(S1) reduces.

At t = T6 (Mode7), the current through the main transistor falls to zero and this turns “ON” the body diode of the main switch(S1) with ZCS. Also, the control signal of the auxiliary switch(S2) is removed.

At t = T7 (Mode8), the capacitor “Cr” is charged linearly under the input current. The main diode (Df) turns “ON” with ZVS and this mode finishes. This completes one switching cycle and another switching cycle starts.

Now let us understand how this converter works. Consider the waveforms shown in the Figure (3).

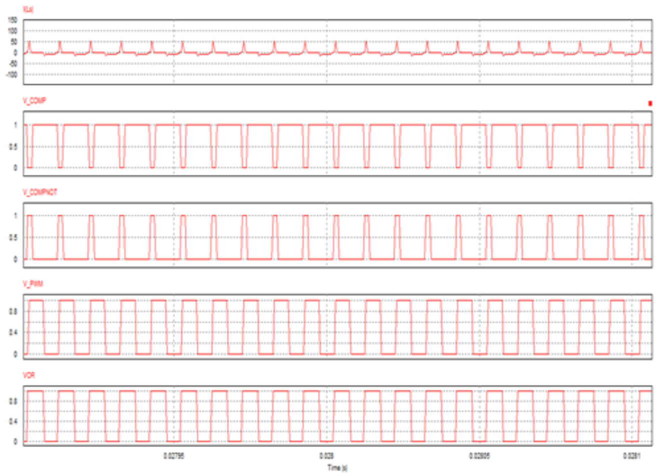

Figure 3. Various Waveforms for Understanding Operation of Converter.

The comparator used in circuit diagram shown in Figure (2) produces the positive pulse when the current through the resonant inductor becomes zero and it gives an output of zero when the current flowing through the resonant inductor is non-zero as clearly shown in the simulated waveforms in Figure (3). From Figure 3, if the inductor current is non-zero (positive), the output of the comparator is zero. Once the inductor current goes zero, the comparator produces a positive pulse at the output as shown in Figure 3. The output of the comparator is represented by V_COMP whereas V_COMPNOT represents the inverted output of the comparator as shown in figure (3). When the COMP_NOT and PWM waveforms are ORed, we get the waveform presented by OR in the Figure 3. This OR waveform is again fed to the not gate to obtain a suitable logic. This signal which is obtained is fed to the auxiliary switch ”S2” of the boost converter through a switch controller whereas the PWM signal is fed to main switch “S1” of the convertor. It is evident from Figure 3, as the PWM goes low, the switch “S1” of the converter is turned OFF however at this time switch “S2” of the proposed converter is turned ON as the OR waveform also is low. When PWM is high, the switch “S1” is ON. At the same time OR waveform also is high, so the switch “S2” is OFF during this period. So, the inductor current decreases linearly. Thus, as the current which flows through the resonant inductor falls to zero and, the output of the OR gate goes high, thus turning the switch "S2" OFF. This turning OFF the switch "S2" makes the resonant inductor current zero and prevents the flow of negative inductor current in the circuit. Thus, by making use of the PWM controller and with the help of a suitable zero current detector we obtain the control of both the auxiliary and the main switch of the proposed converter.

4. Results of the Proposed Boost Converter

Figure (4) shows the input and output voltage waveform of the proposed boost convertor. It is clear from the figure that the convertor steps UP the input voltage of 200V to the output of 400V.Figure (5) shows the output current waveform under steady state for the proposed boost convertor. The output current is drawn at a load of 40 A *i.e*. when the convertor is being operated under heavy load conditions. Figure (6) shows the steady state output current waveform at a load of 0.80 A for the proposed boost convertor. It must be noted that there is always flow of power from source to the load both under heavy load as well as the light load conditions. So, the efficiency of the proposed boost converter in both the cases is improved which is confirmed once we see the efficiency results at various loads. Figure (7) shows the gate control signals G1 and G2 of the switches S1 and S2 respectively.

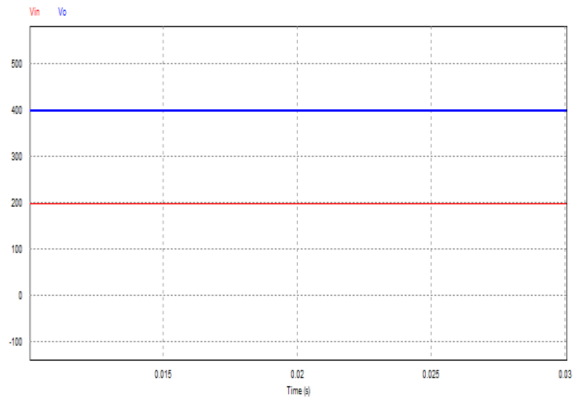

Figure 4. Input and Output Voltage Waveforms of Proposed Converter

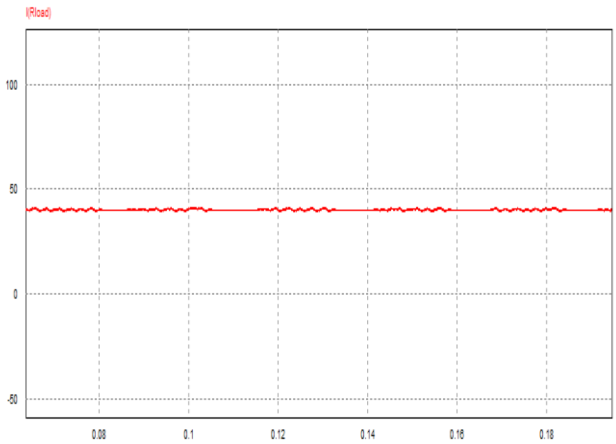

Figure 5. Output Current Waveform under Heavy Load (Io = 40A)

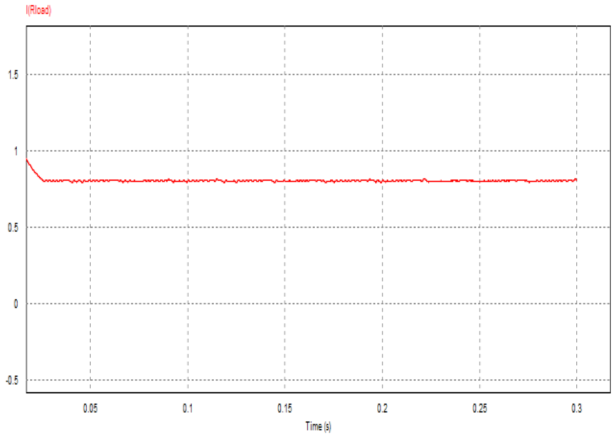

Figure 6. Output Current Waveform under Light Load (Io = 0.8A)

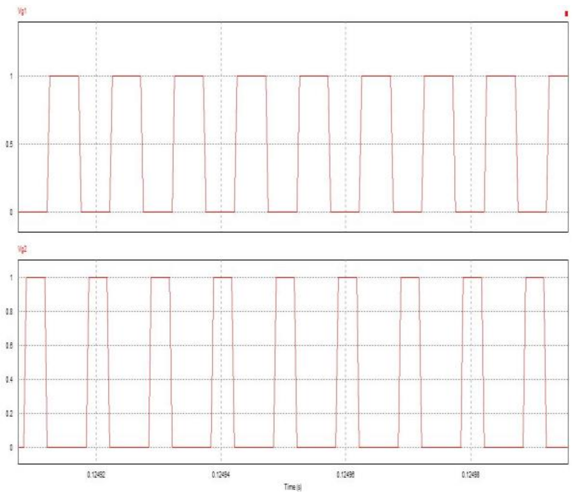

Figure 7. Gate Control Waveform of the switches S1 and S2

Table 1. Efficiency at Various Loads for Proposed Boost Converter

I_o	I_{in}	$P_{in}=V_{in}.I_{in}$	$P_{out}=V_{out}.I_o$	$\eta=P_{out}/P_{in}$
40A	80.53A	4.23mW	1MW	99.3%
20A	40.33A	4.86mW	2MW	99.22%
8A	16.134A	11.55mW	10MW	99.15%
4A	8.0767A	21.22mW	20MW	99%
2A	4.0467A	105.62mW	100MW	98.8%
1.33A	2.699A	223.30mW	200MW	98.5%
0.80 A	1.632A	430.83mW	333MW	98%

Table III gives value of efficiency for the proposed convertor at various loads. From Figure (8), it is seen that the overall efficiency of the new converter reaches a value of 99.3%. It must be noted that this efficiency is greater than the converter presented in [11] although the circuit operates at similar frequency (100 KHZ). It is also worthwhile to mention that the efficiencies at low output powers of the proposed converter are relatively higher than most of the other soft switching converters.

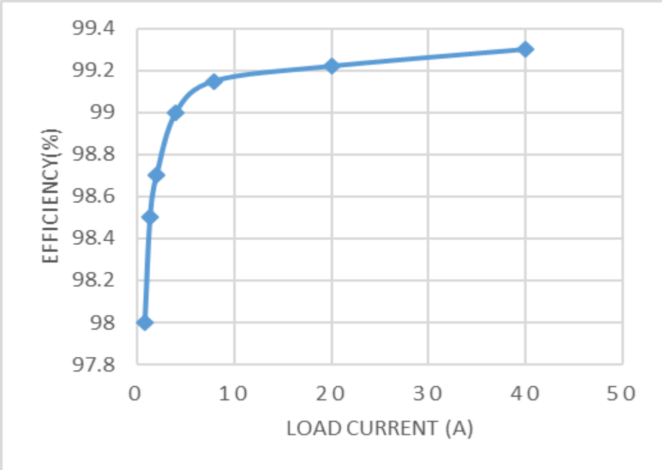

Figure 8. Plot between Load Current (A) and Efficiency of Boost Converter

In Figure 9 is shown the plot between the efficiency (%) and the output power (%) for the ZVT ZCT Boost Converter [11] and the proposed boost converter. It is clear from the above plot that the efficiency of the proposed boost converter is higher than the ZVT ZCT Boost Converter [11] both at heavy as well as light loads. This proves that our proposed converter design is better as it offers high efficiency performance over a wide load range.

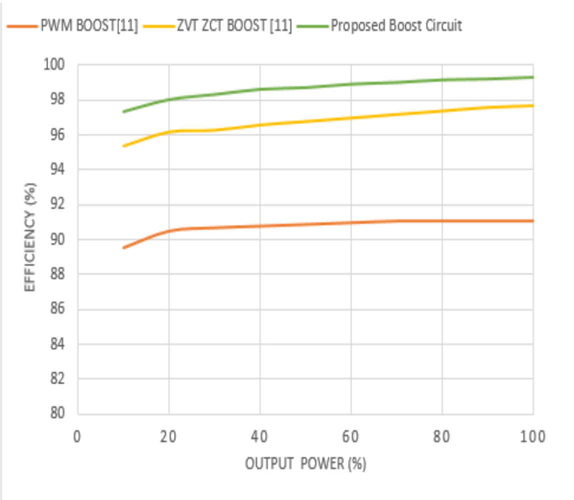

Figure 9. Efficiency of Proposed Boost Converter, ZVT-ZCT Converter and PWM Boost Converter

5. Conclusion

In this paper, a Novel Boost convertor which steps up the input voltage to 400V output voltage was designed in PSIM software with a switching frequency of 100KHz. The simulation results show that the proposed convertor has better efficiency than the conventional convertor over a wide load range. The features of the proposed Boost converter could be summarized as:

- Both the main and the auxiliary switch operate under soft switching conditions.
- All the semiconductor devices are not subjected to any additional voltage stress.
- Soft switching conditions are maintained for wide load range.
- The switching frequency of the proposed converter is constant.

However, in the proposed converter the compromise that is made is the addition of few components such as an auxiliary diode, and a zero-current detector. The compromise on additional components however results in the tremendous increase in efficiency. At a nominal output power, the efficiency of the proposed converter reaches approximately to a value of 99.3%.

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Authors

Furqan Zahoor, he was born in Srinagar, Jammu and Kashmir, India in 1990. He received the B. Tech degree in electronics and communication engineering from University of Kashmir, Srinagar, India in 2014 and M. Tech degree in electronics and communication engineering from Shri Mata Vaishno Devi University, Katra, India in 2016. His research interests include efficiency improvement of Boost converters, switching power supplies, snubber cells in power electronics.

Swastik Gupta, he was born in Jammu, Jammu and Kashmir, India. He received the B. Tech degree in Electrical Engineering from University of Jammu in 2010 and M. tech degree in electronics and communication engineering from Indian Institute of Technology (IIT), Kanpur, India in 2014.His research interests include Embedded Systems, Virtual Instrumentation, Distributed Control Systems.

Vipan Kakkar, he was born in Amritsar, India, in 1973. He received the B.E. degree in electronics and communication engineering from Nagpur University, India, in 1994 and M.Sc. degree from Bradford University, UK, in 1997. He received his Ph.D. degree in electronics and communication engineering from Delft University of Technology, Netherlands in 2002.

He worked in Research & Development at Phillips, Netherlands as engineer and system architect from 2001 to 2009. Since 2009, he has been an Associate Professor with the Department of Electronics and Communication Engineering, Shri Mata Vaishno Devi University, Katra, India. His research interests include ultra low power analog and mixed signal design, MEMS design, synthesis and optimization of digital circuits, biomedical system and implants design, audio and video processing.