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Minimization of Input Ripple Current for Soft-Switching Buck-Boost Converter

Siddhartha Behera, Brijesh Kumar, Rabindra Kumar Behera

Abstract: ***Among all dc-dc converters, the present trend of utilities is buck-boost converter which is capable enough to operate under on/off control so as to step-up and stepping-down the fixed input voltage by varying its duty-ratio of the switch. This converter possesses hard-switched one that means the switching device operate on non-zero voltage or non-zero current and leads to significant increase in switching loss. This issue leads to use of soft-switching of device. As far as the soft- switching of buck-boost converter is concerned, very few papers appear in literature. But in most of these cases, hardly the attention has been given to look into the aspect of ripple content at the input current level. Higher the ripple content at the input not only affect the electrical equipment (i.,e such as adding core losses to transformer in line thus reduction in efficiency), but also causes electromagnetic interference with nearby telecommunication lines and measuring equipment etc. Though there is an option to include the low-pass filter at input, but that creates a hindrance in providing the oscillation along dc link because of input filter in parallel with secondary components across the switch and load. In this research work, the parallel operation of soft-switching buck-boost converter is proposed by modifying the circuit [15] and the circuit is operated with its optimum level so as to minimize the requirement of components. The components of this converter are properly designed to enable soft-switching for the switch. The simulation of the proposed circuit is carried out by MATLAB (Simulink) to validate performance.***

Keywords: ***Buck-Boost converter, Soft-Switching (Zero-Current Switching, Zero-Voltage Switching), High frequency inductor, High frequency switched capacitors, Minimization of ripple current, MATLAB (Simulink).***

I. INTRODUCTION

The buck-boost converter is one of the prominent family member of dc-dc converters that combines the positive aspects features of buck converter and boost converter. Though the dc-dc and ac-dc converters have significant utilities domestically, commercially and and industrially, but the buck-boost unit possesses special features as compared to other type of converter as far as the dc-dc converter is concerned. The dc-dc converters, their first hand knowledge pertaining to operation and their relevant steady-state behaviors are analyzed [1]. The concept of multi-level, which is well-known in case of an inverter, is utilized in dc-dc boost converter[2]. M.Forouzesh et.al [3] has detailed various voltage boosting techniques for step-up dc-dc converters. The generalized buck-boost converter is shown in Fig.1. But most of the topologies available with dc-dc converters experiences hard-switching and research papers available relevant to soft-switching arefew. In reality, such converter, which operates under soft-switching, becomes smarter than the hard-switched converters in many ways. The novel method of cascaded dc-dc boost converter using single-switch is illustrated [4]. F.Tofoli et.al. [5] has presented a survey on topologies based on non-isolated type boost converters. The soft-switching techniques for dc-dc, dc-ac, ac-dc and ac-ac converters are prime objective in minimizing the losses thus to improve the efficiency with reduction in EMI/EMC phenomena. The various soft-switching techniques for semi-conductor switches have been proposed [6-15]. A novel soft-switching dc-dc converter with significant voltage gain is presented [7]. Zero-voltage transition, which is part of soft-switching methods, is implemented with an built-in transformer [8-9], but this is obvious that high frequency inductor makes the compact to its size and volume. The minimization of switching losses using quasi-resonant principle for current-fed converter is proposed by S. Dobakhshri et.al [10]. This converter preserves inherent advantages of current-fed structures, for instance, zero magnetizing dc offset, low input ripple, and low transformer turn ratio. It is also proposed soft-switching dc-dc converter for high-power and high voltage application [11-12]. A typical application in wind energy conversion system is used in offshore series-dc wind farm concept.The researchers [13] are introducing a new method of operation for a series resonant converter, with intended application in megawatt high-voltage dc wind turbines. The focus of this paper is to identify and analyze the operating modes of the converter with pulse removal technique. In [14], it is proposed a quasi-resonant boost half-bridge dc–dc converter with high power conversion efficiency and a wide input voltage range for a photovoltaic micro-inverter. The proposed converter has a three numbers of half-bridge converters operating on load resonant principle to make 3-phase system from common dc source. By using the quasi-resonance techniques, it achieves zero-voltage. The reserchers[15] present a new soft-switching technology for a buck-boost converter employing a single-switch. But this has limitation of duty-ratio beyond which the soft-switching property is lost.

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* Correspondence Author
Siddhartha Behera*, Electrical Engg Dept, I.G.I.T Saranga, BPUT Odisha, India, E-mail: siddharthabehera95@gmail.com
Brijesh Kumar, Electrical Engg Dept, I.G.I.T Saranga, BPUT Odisha, India. Email: brijesh@igitsarang.ac.in
Rabindra Kumar Behera, EE Dept, I.G.I.T Saranga, BPUT Odisha , India. Email: : b_rabindra@yahoo.co.in

The optimized design procedure for a dc-dc buck-boost converter associated with a dissipative snubber is presented [16]. The static gain of the converter is determined from the charging and discharging times of the inductor which does not depend on the load condition. The researchers [17] proposed dc-dc boost converter along with three switchesis presented with its operating principles, analysis, parameter design guidelines, and simulation results. The major features of the proposed converter are as follows: 1) continuous input current; 2) reduced one active switch, one additional diode, and one additional capacitor; 3) unchanged primary and secondary voltage waveforms of the transformer when the duty cycle is changed; and 4) removal of the snubber circuit. This paper presents the operating principles, analysis, parameter design guidelines, and simulation results for the proposed converter.

In [18], it is proposed a nonlinear control strategy to regulate the output voltage in a boost converter which supplies power at constant load. Also it is used state-feedback linearization to transform the inductor current of converter into a linear average dynamics that consists of a series connection of a voltage source, a resistor, and the converter inductor.

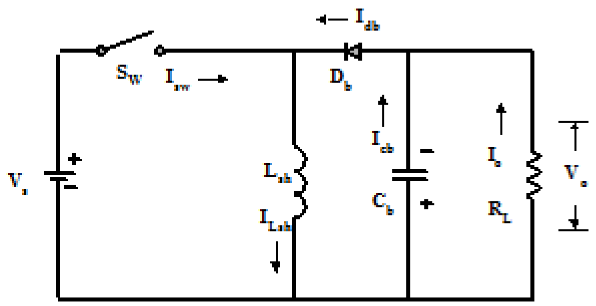

Fig.1. Conventional Buck-Boost Converter

The present work is the extension of paper[15]. This paper though ensures soft-switching for limited duty-ratio, but it lacks in providing poor input current ripple profile. So a parallel connection of buck-boost converter along with a common load and boots capacitor is proposed. So simulation is carried out to validate in improving the performance in terms of reduction ripple content of input current.

II. PROPOSED TOPOLOGY AND MODES OF OPERATION

Thesoft-switching topology shown in Fig.2,which is slightly modified over conventional buck-boost converter for facilitating the soft-switching operation is shown in Fig.2[15].

The operation of this buck-boost converter is explained briefly through various modes (I~VII) shown in Fig.3. This is based upon steady-state application.

Mode-I: (t_1) The Mode-I commences with turning-on the switch during time t0. The zero-current through switch during starting is ensured due to the shunt inductor and simultaneously discharging of snubber capacitor through inductor and resistor under critical damping.

Mode-II: (t_2) The snubber capacitor which is oppositely charged makes a resonating condition with the shunt inductor and decays very fast to zero.

Mode-III: (t_3) The inductor current continues to rise till the switch is turned-off.

Mode-IV: (t_4) At the beginning of this mode, it is initiated with the turned-off of the switch. The switching device is operated on zero-voltage switching as the snubber capacitor bypass the device current. During the process, the shunt inductor diverts the current through the boost capacitor and boost diode. The switch is subjected to approximately twice of the supply voltage(i.e., combinely source voltage and reverse snubber capacitor voltage). The capacitor voltage decays to zero when this mode is terminated.

Mode-V: (t_5) This is the period of conduction of boosting diode and the current through shunt inductor decays to zero.

Mode-VI: (t_6) As the current through boosting diode falls to zero, the boost capacitor is disconnected from source. So the voltage of boost capacitor falls to its steady state value after ringing with parasitic inductance and load parameters.

Mode-VII: (t_7) This is the mode of steady-state period of boost capacitor. Though the boost capacitor delivers the energy to load, but because of its comparative larger value and high switching frequency, the drop in voltage level of boost capacitor is significantly very small.

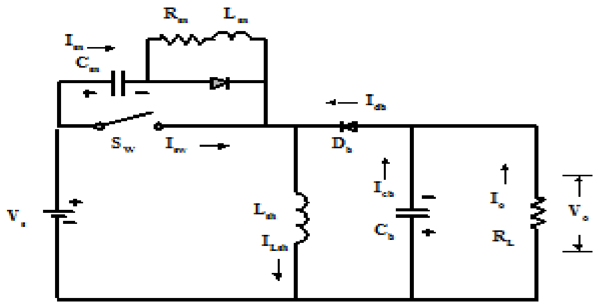

Fig.2. Soft-Switched Buck-Boost Converter

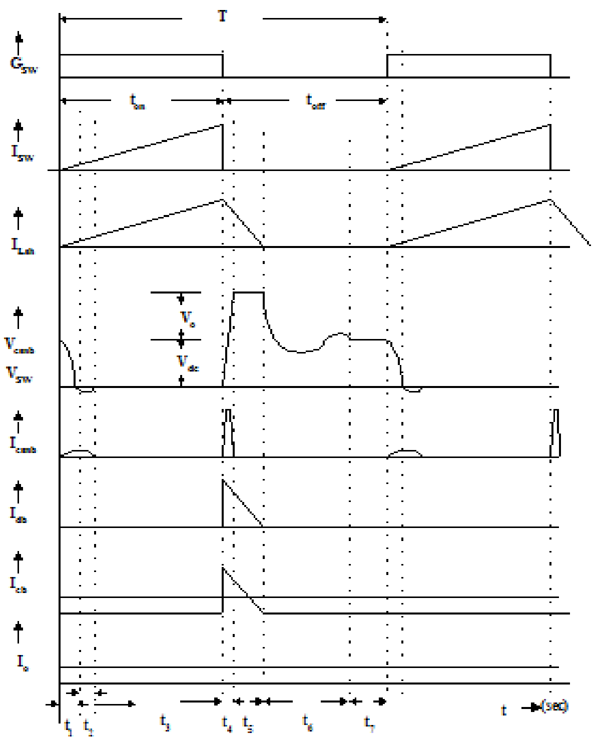

Fig. 3. Waveforms of Soft-Switching Buck-Boost Converter

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he above topology facilitates soft-switching for the single switch in order to minimise switching loss. The limitation of this topology is having duty-ratio limited to 0.7 approximately, as it is subjected under discontinuous operation of source current. Hence the source current whose nature is saw-tooth type contains considerable harmonics. In order to minimize the harmonics of source current, it is proposed a parallel operation of the above topology having slight modification over figure 2 [15] and is shown with a common load shown in Fig. 4.

This proposed topology possesses with a common capacitor in parallel with load. The switching devices of this proposed parallel topology are operated in phase-shifted manner in order to make continuous the source current without affecting switching period operation. The switching operation of this proposed one is shown in Fig.5. Both switching devices are operated in phase-shifted manner but with common switching period.

The steady-state operation of this parallel topology of soft-switching converter is shown in Fig. 6 in four modes.

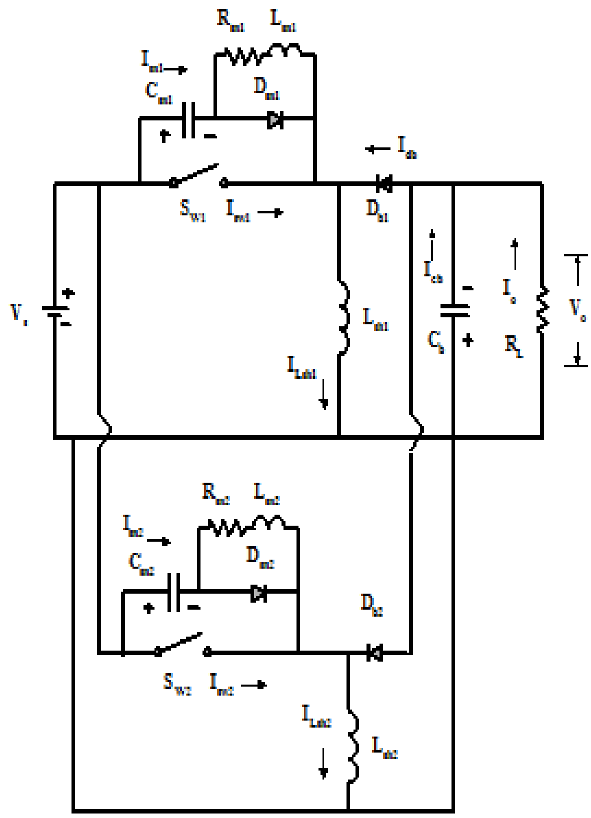


Fig. 4. Waveforms of current and voltage through snubber capacitor respectively.

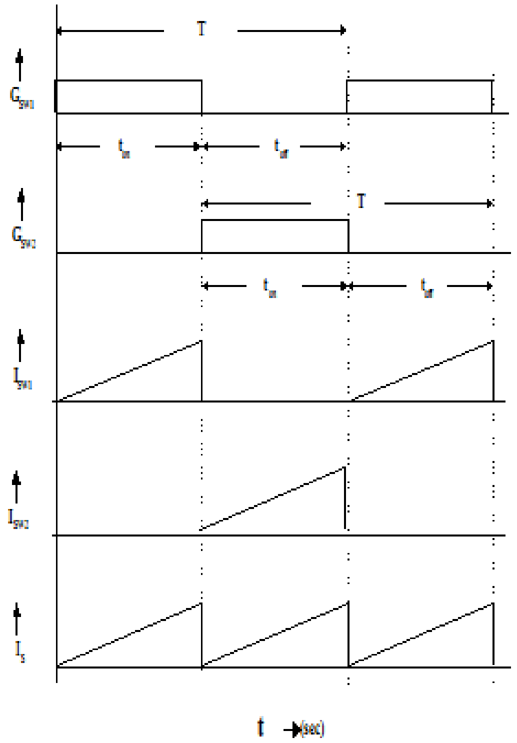
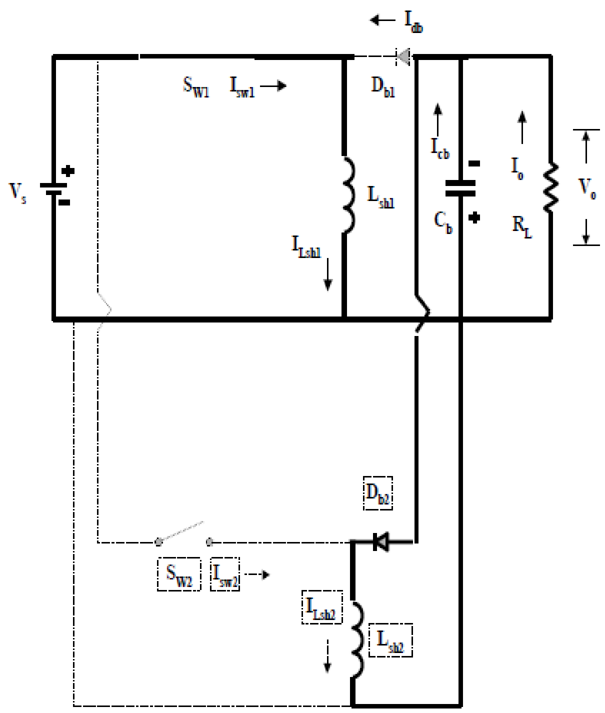
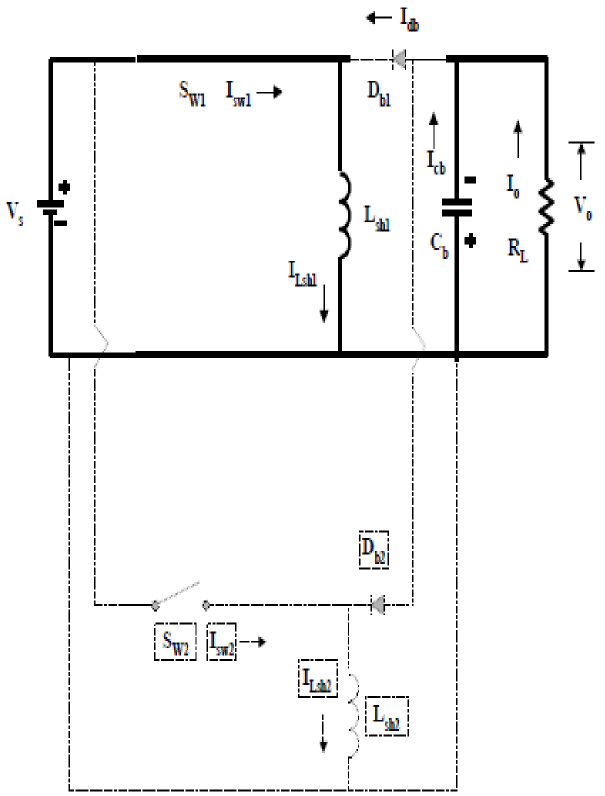


Fig. 5. Waveforms of current and voltage through snubber capacitor respectively.

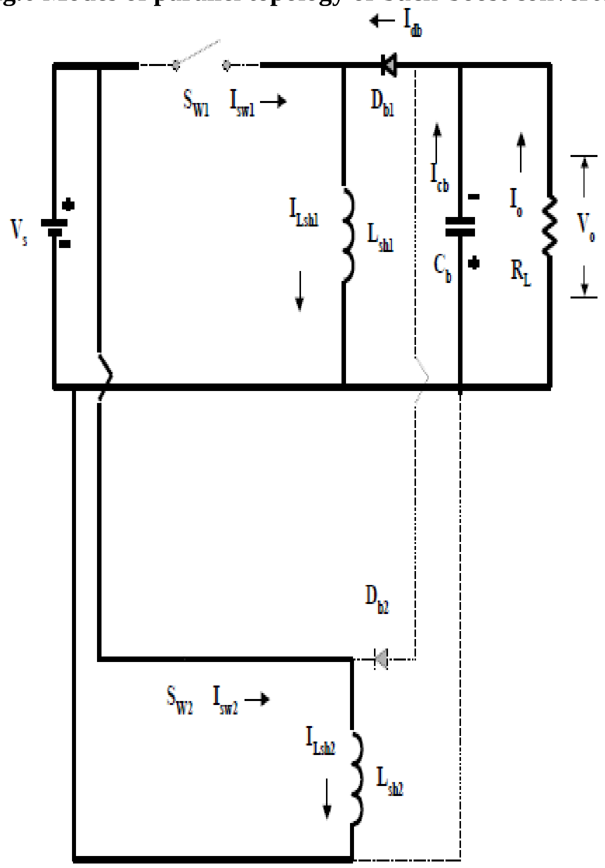


(a)

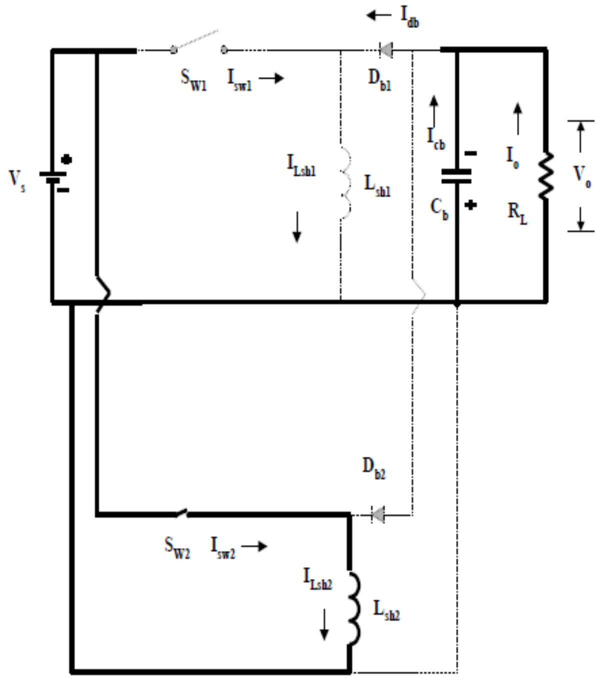


(b)

Fig.6 Modes of parallel topology of buck-boost converter



(c)



(d)

Fig. 6. Modes of parallel topology of buck-boost converter

At any instant, both the switches are turned off or turned on alternately. The source current is combined value of currents through switch (S_{w1}) and (S_{w2}).

Mode-I: The switch (S_{w1}) is turned on and load is isolated from supply. The load capacitor is charged due to stored energy of inductor(L_{sh2}) through D_{b2} as the switch(S_{w2}) is off.

Mode-II: This mode is initiated when the inductor energy in L_{sh2} is diverted completely to the load capacitor. The S_{w1} still continues to carry the current of shunt inductor. The load capacitor delivers its energy through load.

Mode-III: The switch (S_{w1}) is turned off and Sw2 is turned on. So the energy stored in shunt inductor (L_{sh1}) is diverted gradually through load capacitor. This mode continues till shunt inductor completely delivers its energy

Mode-IV: The switch (S_{w2}) still continues to carry the current and the load capacitor provides energy to load. After this the switching cycle is repeated with mode-I.

III. DESIGN OF CIRCUIT COMPONENTS

The conventional procedure for designing a buck-boost converter is well-documented [1]. But for soft-switching operation, the relevant equations considered are given in following. The critical value of boost capacitor C_b(critical) (i.e., on load side) to operate on the verge of discontinuous state from its continuous conduction mode.

$$C_b \text{ (critical)} = k/(2\, f_{sw} R_L) \qquad (1)$$

where k : duty-ratio

f_{sw} : the switching frequency

R_L : the load resistance

In order to reduce the ripple content drastically on load capacitor voltage, the actual value of C_b must be greater than those obtained in (1).

So a ripple factor 'r' is included in (1) and the above equation is modified as follows. (0 <r<1)

$$C_b = k/(2\, r\, f_{sw} R_L) \quad (2)$$

Similarly the critical value of shunt inductor (Lsh) above which the input current will be verge of continuous conduction from discontinuous conduction mode is given by the following equation.

$$L_{sh}\,(\text{critical}) = (1 - k)R_L/(2\ f_{sw}) \quad (3)$$

The current through snubber capacitor during discharging without considering snubber inductor and power loss incurred in snubber circuit are as follows.

$$i_{sn} = \frac{V_s}{R_{sn}} e^{-\frac{t}{R_{sn} C_{sn}}} \quad (4)$$

$$P = \frac{1}{2}\frac{C_{sn} V_s^2}{T}\left(1 - e^{-\frac{2\tau}{R_{sn} C_{sn}}}\right) \approx \frac{1}{2}\frac{C_{sn} V_s^2}{T} \approx \frac{1}{2} C_{sn} V_s^2 f_{sw} \quad (5)$$

The snubber capacitor is designed as follows.

$$\frac{I_{psh}\, t_{off}}{C_{sn}} = V_s \quad (6)$$

$$C_{sn} = \frac{I_{psh}\ t_{off}}{V_s} \quad (\text{toff} \approx 2 * \text{tq}) \quad (7)$$

where I_{psh} : Peak current through shunt inductor L_{sh}.
t_{off} : Charging time of snubber capacitor;
tq : Turn-off time of the device specified by manufacturer
Snubber capacitor (Csn) is obtained out from eq.(7)

In order to initiate the discharging current at zero value, a small value of inductor is incorporated and is to be under critical damping for smooth operation of circuit.

$$i \approx V_{co}\sqrt{\frac{C_{sn}}{L_{sn}}}\, \sin(w_d\, t) \ \text{ and } \ I_{psn} = V_{co}\sqrt{\frac{C_{sn}}{L_{sn}}} \quad (8)$$

where wd is damped frequency

The condition for critical damping/ overdamping

$$\text{is } R_{sn} >= 2\sqrt{\frac{L_{sn}}{C_{sn}}} \quad (9)$$

Based upon above equations for design criteria, the values of various components are mentioned as follows. These following data are considered as per data available with manufacturers.

Lsh= 50 µH each (Part No- DLFL-0147-35C5)
Cb= 100 µF, ESR=2.2 mΩ
(Part No- C4ATGBW5200A3MJ)
Lsn =1.25 µH each (Part No- B65661D1250K048)
Rsn = 20 Ω, 10 W (part No- 71ALSR1020R00FE12)
Csn = 0.01µF, 630V dc (Part No- R463I310050M1K)
IGBT: 600V,40A, freq range (50~100kHz)
(Part No- STGFW40V60DF)
Diode: 250V, 40A, VD=0.97V (Part No-MBR40250T)

IV. SIMULATION RESULTS

In order to have validation and realistic situation, the specifications of the components available with the manufacturers are considered for analysis. Those values are close to designed value. With the help of MATLAB/Simulink software, the analysis is carried out and the results are shown in figures 7 to12 respectively.

Normal buck-boost converter operates under discontinuous mode of source current. The source current appears to be saw-tooth type and remains discontinuous during off period. Even in soft-switching buck-boost converter, it is of no exception. So it contains significant ripple current at its input, but on other hand, the ripple voltage at boost capacitor is negligible because of its comparatively higher specification.

In Fig.7, the waveforms of voltage and currents of switches (i.e. S_{W1} and S_{W2}) are shown with source current for duty-ratio 0.4. Both the switching devices operates under zero-current switching on and zero-voltage switching off. The source current is the addition of the currents in both switches.

In Fig.8, the waveforms of voltage and current through the boost capacitor are shown along with the currents through both shunt inductors along with source current at duty- ratio of 0.4. This focuses a comparative picture of the behavior of the various components. The current through boost capacitor is bidirectional that indicates charging and discharging of capacitor. Similarly the rising current through shunt inductor shows storage of energy and decaying of its current indicates the delivery of energy to boost capacitor.

The harmonic analyses for the simple and parallel one are shown in Figs. 9 and 10 respectively for duty-ratio of 0.4. The ripple content of voltage /current is the ratio of the rms value of all harmonics to its dc component. Because of low duty-ratio, it has significant ripple current at source (i.e., 149%) in case of a simple soft-switching buck-boost converter, whereas in parallel one, the ripple content is drastically reduced to 79.7%. The efficiency is found to be 92%. With increase in duty-ratio to 55%, the simulation results of voltage and currents are shown in Fig.11 with the source current. The frequency spectrum is shown in Fig.12. Though the source current is continuous, the ripple content of parallel buck-boost converter is decreased to 49.8% for parallel buck-boost converter. Since the duty-ratio is limited for facilitating soft-switching as well as for desired boosting voltage, so the requirement of filter at the input is required, but the problem arises that putting low pass filter at source will slowdown soft-switching process.The detail comparisons of harmonic analysis for both simple and parallel one at different duty-ratios are given in Table-I. It is observed that the percentage ripple content gets reduced as there is increase in duty-ratio.

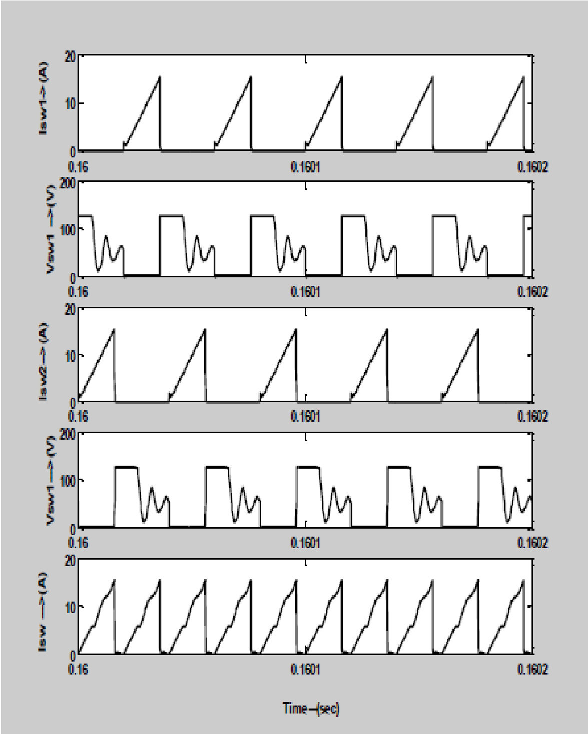


Fig.7. Waveforms of voltage and current of both switches and source current at duty-ratio 0.4

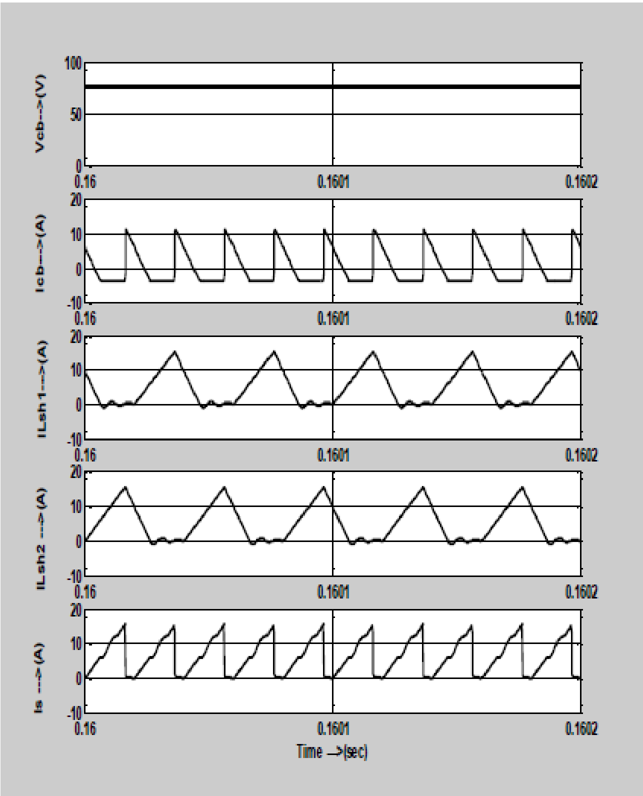


Fig.8. Waveforms of voltage and current of boost capacitor, current through both shunt inductors and source

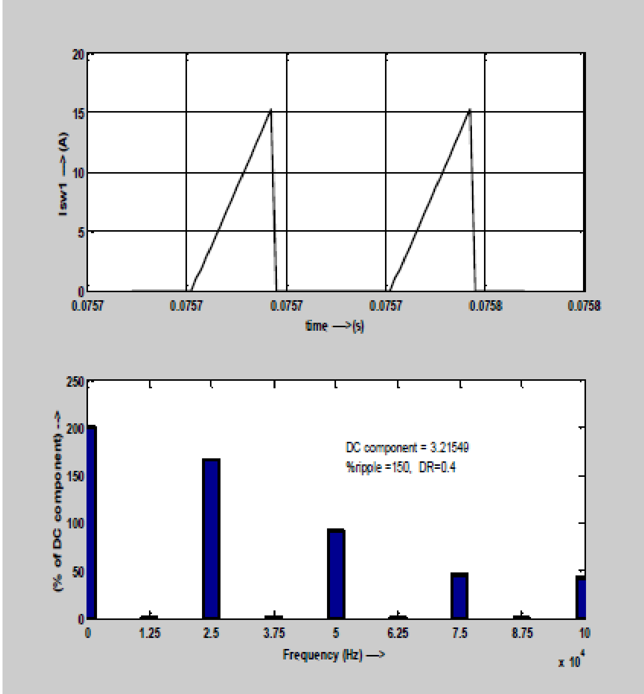


Fig.9. Harmonic Spectrum for a simple soft-switching buck-boost converter under duty-rato 0.4

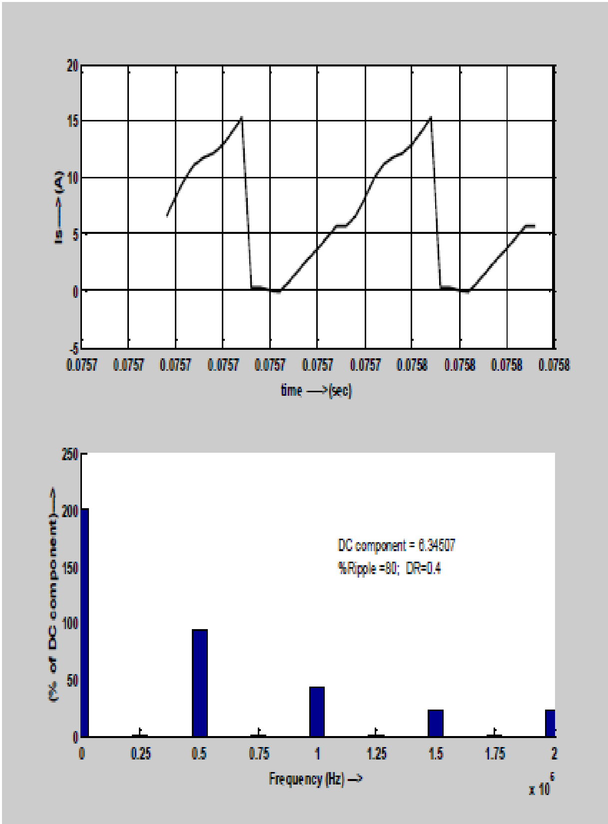


Fig.10. Harmonic Spectrum for parallel soft-switching buck-boost converter under duty-ratio 0.4

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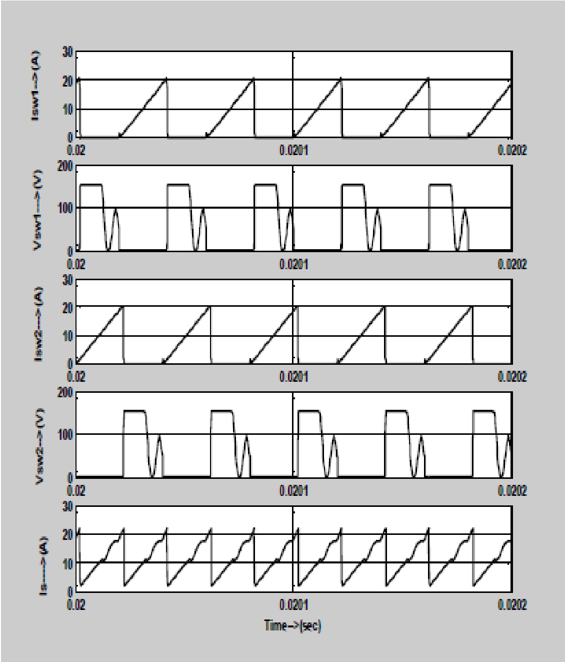

Fig11. Waveforms of voltage and current of both switches and source current at duty-ratio 0.55

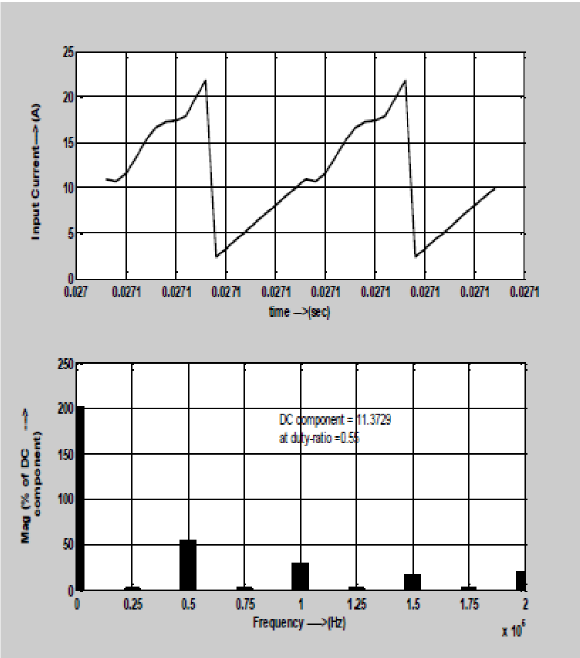

Fig.12. Harmonic analysis of parallel buck-boost converter at duty-ratio 0.55

TABLE- I: Results from Simulation

SL.No	% Duty-Ratio	% Ripple of Single switch Buck-Boost Converter	% Ripple of parallel switch Buck-Boost Converter
1	40	149	79.7
2	45	135	64.6
3	50	126	55
4	55	119	49.84

V. CONCLUSION

In a conventional buck-boost converter having single switch (i.e. with hard-switching or soft-switching), the ripple content at the input is high because the input current remains completely discontinuous during off-period of switching cycle. The proposed parallel topology of buck-boost soft-switching converter overcomes this problem.by allowing the input current to appear in both on and off period of individual switch. So this is analyzed with the help of MATLAB (Simulink) and validated with improvement in profile of ripple content. Though theripple factor is drastically reduced with the proposed topology, but this reduction is not sufficient for which it may require low-pass filter at input. But there is still problem when it is incorporated with a low pass filter at sourceas it may slowdown soft-switching process. So it needs further investigation. Both the switches of this buck-boost converter turn-on ZCS and turn-off under ZVS.

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AUTHORS PROFILE

Siddhartha Behera, is persuing MTech in , Electrical Engg Dept, IGIT Sarang (Govt Insitute) Odisha, .

Brijesh Kumar, is Assistant Professor **in** Electrical Engg, IGIT SArang. He has guided number of MTech thesis to his credit and also is on verge of completion of his PhD.

Rabindra Behera, PhD is Associate Professor, Electrical Engg, IGIT Sarang, (Odisha). He has guided number of MTech Thesis and currently guiding few PhD students. He is also having AICTE project and involved in TEQIP(MHRD) of the institute. .

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