A Novel ZCS High Step-Up DC-DC Converter for Energy Storage Systems in DC Traction Vehicles

V.V.Subrahmanya Kumar Bhajana[1,2], Pavel Drabek[2], Pramod Kumar Aylapogu[1]
[1]School of Electronics Engineering, KIIT University, Bhubaneswar, India
[2]Regional Innovation Centre for Electrical Engineering, University of West Bohemia, Pilsen, Czech Republic
kumarbvvs@yahoo.co.in, kumarbvv@rice.zcu.cz, drabek@ieee.org,aylapogu.pramodkumar@gmail.com

***Abstract* –This paper proposes a new soft-switched High Step-up DC-DC converter for energy storage systems in DC traction vehicles. In this converter, soft-switching operation, i.e., zero current switching has been obtained by employing dual resonant auxiliary circuits to the conventional step-up DC-DC converter. The auxiliary resonant consists of additional auxiliary switches; inductor and capacitor are used to achieve soft-commutation especially when the main active switching devices are being turned-on to turned-off. The main active switching device of this converter achieves soft commutation with reduced voltage stresses and reduced switching losses. Firstly, the operation principles and its design analysis are discussed in detail. Finally, the simulation verification on an input with 100V and 350V/2kW converter system operated at 50kHz switching frequency to validate the theoretical expectations and its effectiveness.**

Keywords- Zero Current Switching (ZCS); DC-DC; Energy Storage systems; DC traction Vehicles.

I. INTRODUCTION

The high-gain, high step-up non-isolated DC-DC converters are being widely used in the applications of energy storage applications (hybrid electric vehicles). In recent years, there are various types of non-isolated step-up converters are implemented; they are operating under hard-switching and soft-switching operations. Firstly, high step-up DC-DC converter [1] based on the integration of three boost converters; this converter switching devices operated under hard-switching condition, achieved the 93% efficiency at 500W output power. The soft-switching operation of the semiconductors in a converter is an alternate way to achieve higher efficiencies, to reduce the voltage/current stresses and improve the overall performance respectively. The soft-switching operation was achieved by adopting the conventional resonant network/auxiliary active resonant network are the sources. A resonant soft-switched step-up converter [2-3] has achieved the zero voltage switching (ZVS) and zero current switching (ZCS) to the semiconductors. However, this converter can be applicable for the lower output voltage and low output power. A parallel resonant based high voltage gain converter [4] has been achieved the zero voltage switching operation to the main semiconductor switching devices at higher switching frequency. However, they achieved low efficiency at low output power. Similarly, researchers focused on a new kind of step-up DC-DC converter [5] employed with a voltage-double-flyback unit to the conventional resonant converter [1] with soft turn-on/turn-off conditions (efficiency 90% at 100W output power). A resonant network based interleaved step-up isolated converter [6] has achieved the ZVS operation. In literature different step-up converters are reported, they are coupled-inductor, switched-capacitor techniques [7] and another converter based on active-passive inductor cells [8] to obtain high-gain and soft-switching operation as well.

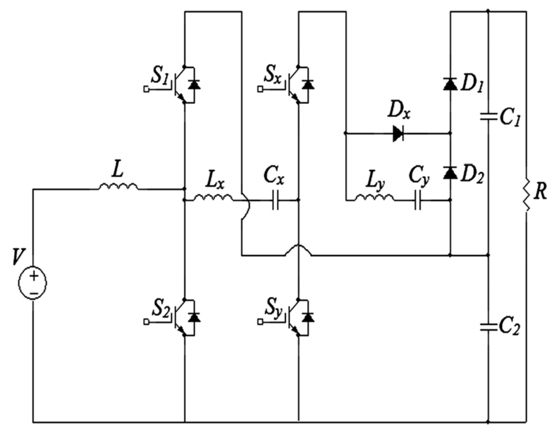


Figure 1. Proposed ZCS High Step-up DC-DC converter

The main attention of this work is to design a new, efficient converter with high gain and high power applications (especially in Battery Back-up systems). This paper mainly proposed a new soft-switching high step-up DC-DC converter for energy storage systems with dual auxiliary resonant circuit. It has major advantages of reduced switching losses, reduced voltage stresses and higher efficiency. The additional advantages of this converter are dual auxiliary active switches operated under soft-turn-on/turn-off conditions. The following section describes the

ISBN 978-80-261-0642-5, © University of West Bohemia, 2017

proposed converter and its operating principles, Section III deals the design analysis and the simulation results are presented in Section IV.

II. DESCRIPTION AND OPERATION PRINCIPLE

Fig.1 shows the proposed new high step-up DC-DC converter. This converter can be operated at high power and to produce high-gain than previously reported resonant topologies [2-3]. The proposed converter semiconductor devices S_1,S_2 are used to regulate the output voltage. By varying the duty cycles of S_1, S_2 are control the output voltage. For S_1,S_2 switches the asymmetrical PWM technique was used to obtain high voltage gain. The PWM signals generated for S_x,S_y are used to achieve soft-commuation of S_1,S_2. The duty cycles of auxiliary switching devices are chosen as 0.1%. The main switching devices S_1,S_2 duty cycles are 0.7 chosen for S_1 and 0.35 for S_2. Here, S_1, S_2 are the main switching devices and dual auxiliary resonant circuit switches are S_x, S_y. The resonant inductor L_y capacitor C_y are resonating, while the S_x is being conducted and D_x will provide a path to flow of the trapped energy of inductor L_y. S_x is turned-on before the main switch S_1 gets turned-off. Similarly, while the S_2 is commutated, the auxiliary switch S_y will be turned-on. However, these dual auxiliary switching devices turned-on for a short time interval. The input inductor current is considered as constant. The equivalent current flow schematics are shown in Fig.3 and the operation of this converter is divided into seven intervals as shown in Fig.2 with key waveforms described as follows.

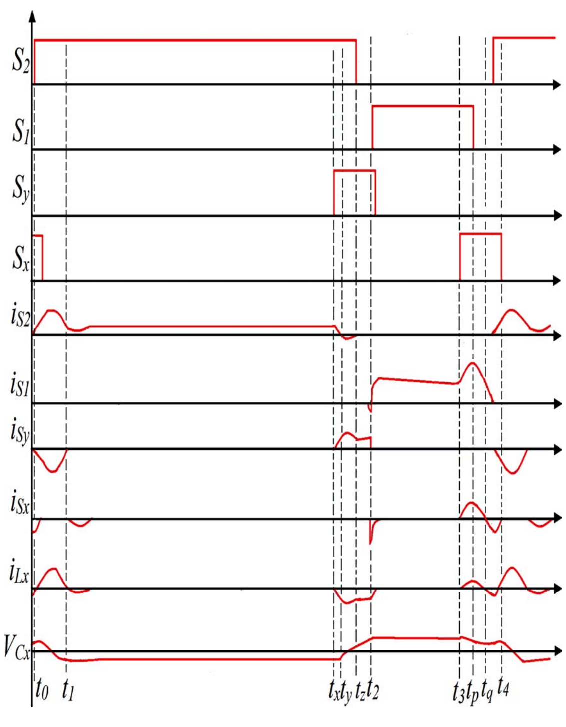


Figure 2. Keywaveforms

Interval (t_0-t_1): Prior to t_0, the auxiliary switching device S_x is already being conducted. At t_0, the S_2 is turned-on, then due to the resonant tank (L_x and C_x), the current flows through it. Current of S_2 flows linearly and whenever it reached the peak (which is equal to inductor current), the capacitor voltage C_x is being discharged to zero and then again starts charging in reverse direction.

$$i_{Lr} = I_{in} + \frac{V_o}{Z}\sin \omega t \qquad (1)$$

$$i_{Cr} = -\frac{V_o}{Z}\sin \omega t \qquad (2)$$

$$V_{Cr} = V_o \cos \omega t \qquad (3)$$

$$\omega = \frac{1}{\sqrt{L_r C_r}}; Z = \sqrt{\frac{L_r}{C_r}}$$

Interval (t_1-t_x): During this stage, the S_2 is conducting and the energy of the input inductor has been accumulated and capacitor voltage is charged up to the half of the output voltage.

Interval (*t_x-t_y-t_z*)*:* at the beginning of this interval, the auxiliary switching device S_y is turned-on under zero-current condition, starting a resonance between L_x and C_x. This resonance current forces the IGBT S_2 current to decrease in a sinusoidal fashion. While the inductor and S_2 currents reached peak value, the capacitor voltage is discharged to zero. The maximum peak current of the inductor expressed as follows:

$$I_{Peak} = \frac{V_{Cr\_peak}}{Z} \qquad (4)$$

$$i_{Lr} = I_{in} - \frac{V_o}{Z}\sin \omega t \qquad (5)$$

$$i_{Cr} = \frac{V_o}{Z}\sin \omega t \qquad (6)$$

$$V_{Cr} = -V_o \cos \omega t \qquad (7)$$

To achieve the zero current turn-off for the S_2, the maximum peak value of the inductor L_x should be greater than the input current. During this interval, at t_y, the ZCS condition is obtained for S_2 at the instant that current drops to zero and then its anti-parallel diode of S_2 which provides a path for resonant tank current. End of this interval at t_z the anti-parallel diode of S_2 is turned-off.

Interval (t_z-t_2): Starting of this interval, the anti-parallel diode stops conducting and only the auxiliary switching device is in conduction state. At the end of this interval, S_y is turned-off and S_1 is turned-on under zero voltage switching. The resonant inductor current is reached zero and capacitor voltage is charged to the half of the output voltage.

Interval (t_2-t_3): At t_2, S_1 is turned-on with ZVS condition. During this interval, the accumulated energy by the inductor L will delivered to the load via S_1 and output diode D_1. End of this interval, the auxiliary switch S_x is turned-on.

Interval (t_3-t_p-t_q): Before the main switch is turned-off, the S_x is turned-on at t_3. The resonant elements start to resonate again. The path of resonant current flows through the L_y,C_y and the output voltage V_o. The currents of the S_x, S_1 increases from zero to peak and

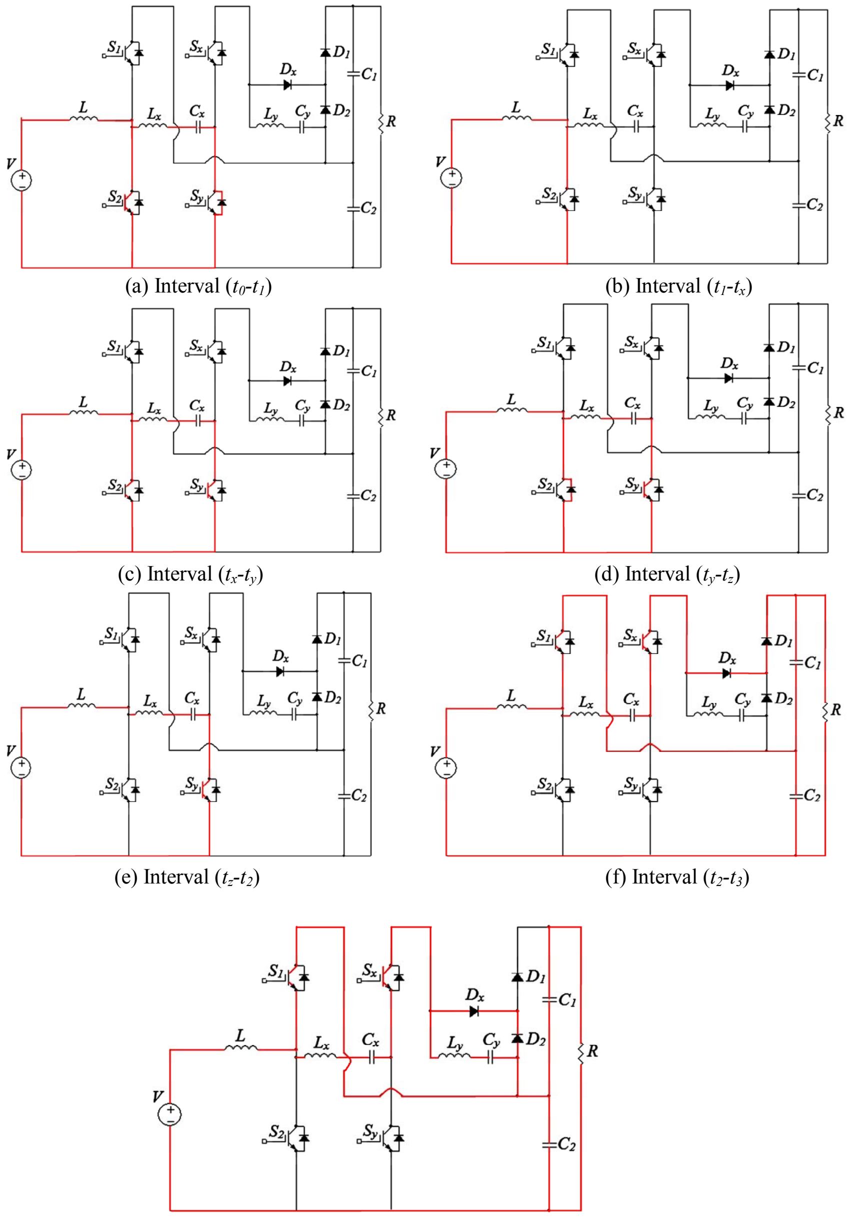
ISBN 978-80-261-0642-5, © University of West Bohemia, 2017

then decreases. At t_q, the S_1 and S_x are turned-off under the ZCS operation.

Interval (t_q-t_4): From the beginning of this interval, the current of the S_x becomes negative, and then its anti-parallel diode will allow the resonant tank current.

The soft-switching (zero current switching) condition is

$$Z \leq \frac{V_o}{I_{in}} \quad (8)$$



(a) Interval (t_0-t_1)

(b) Interval (t_1-t_x)

(c) Interval (t_x-t_y)

(d) Interval (t_y-t_z)

(e) Interval (t_z-t_2)

(f) Interval (t_2-t_3)

(g) Interval (t_3-t_q)

Figure 3. Operating modes

III. Design Anlaysis

The soft-switching condition of the semiconductor devices of proposed converter can be achieved, if the peak input inductor current below the resonant inductor current. The peak current of input inductor L and L_x,L_y actually depend on the source input current, it can be estimated as follows:

$$I_{in} = \frac{2 V_o I_o}{V_{in\_max}} \quad (8)$$

Where $I_o = \frac{P_o}{V_o}$ is the maximum output current.

Z is the impedance of the resonant circuit

$$Z \leq \frac{V_o}{I_{in}} \quad (9)$$

Z is the impedance of the resonant circuit

$$f_r = \frac{1}{2\pi \sqrt{L_n C_n}} \quad (10)$$

The values of L_y = 2μH; C_y =45nF chosen to keep the resonant frequency 0.53 MHz, which is always above the resonant tank frequency of L_x,C_x.

ISBN 978-80-261-0642-5, © University of West Bohemia, 2017

The chosen values for L_x=2µH and C_x=85nF are selected and resonant frequency (10) about 0.38 MHz.

Where, n = x or y

The impedance of the resonant networks Z= 8.16 Ω (Ly, Cy) and Z=4.85Ω (L_x,C_x). The values of impedance of these dual auxiliary resonant networks always less than the output voltage versus maximum input current ratio(8), then the soft-switching condition can be obtained for all switching devices of the converter.

The duty cycle of auxiliary switch is 0.1 which is from t_x-t_2. The total time of t_{xy} obtained from (11) and t_{yz} are obtained from (12)

$$t_{xy\approx 3p} = \sqrt{L_x C_y}\,\sin^{-1}\left(\frac{ZI_o}{V_i}\right) \quad (11)$$

$$t_{yz\approx pq} = \sqrt{L_x C_y}\left(\pi - 2\sin^{-1}\left(\frac{ZI_o}{V_i}\right)\right) \quad (12)$$

The obtained time of t_{xy}= 0.1µsec and t_{yz}=0.7µsec.The total time of zero current switching of S_2 is obtained for the values of L_x= 2µH and C_x=85nF. Where t_{yz} is the period of zero current turn-off of S_2. In this proposed converter the turn-on time of S_2 is 13µsec and S_x turn-on time is 1.6µsec used. Similarly for the switching turn-on times of IGBT S_1= 6µsec and S_y 2µsec respectively. The zero current turn-off of the IGBT S_1 t_{pq} is 1.1µsec and t_{3p} is 0.1µsec.

TABLE I. SIMULATION PARAMETERS

Parameters	Values
Input voltgae(V)	100
Output voltage	350
Output Current	5A
Switching frequency	50kHz
Input Inductor(L)	200µH
Resonant Inductor(L_x L_y)	2µH
Resonant Capacitor(C_x)	85Nf
Resonant Capacitor(C_y)	45Nf

IV. SIMULATION RESULTS

The proposed converter model designed for 2kW system by using Matlab. The converter specification is aforementioned as in Table I. The simulations were performed for open loop condition. It was confirmed that the simulation results that ZCS turn-off transitions as described above can be achieved for all IGBTs in the converter. The duty cycles chosen for S_1 is 0.3 and S_2 is 0.7. Fig.4 shows the collector-emitter voltage and current waveforms of the S_2 and S_y, which shows that the voltage of the switches are 350V and currents are 16A respectively. The soft turn-on operation to the S_2 and S_y was observed. The S_2 with the ZCS Turn-off and S_y turned-off with hard switching operation. Fig.5 represents the S_1,S_x voltage and current waveforms, it is observed from the obtained results with voltages of the both switches are 350 V and current of S_1 is 18A, S_x is nearly 18A.The both switches S_1,S_x achieved soft turn-on and while they turning-off S_1,S_x both are turned-off under ZCS condition. So this topology has a reduced switching losses of the main switches, including auxiliary switches Fig.6 show the resonant capacitors(C_x,C_y) voltages. Fig.7 represents the auxiliary inductors currents (L_x,L_y) waveforms, results obtained are same as theoretical analysis. The obtained results were nearly same as the theoretical analysis.

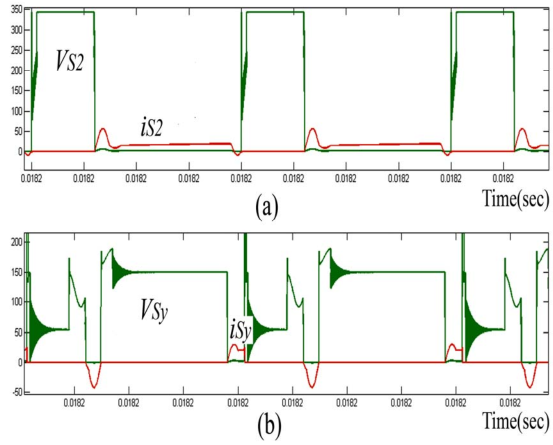


Figure 4. (a) Voltage and Current waveforms of S_2 (b) Voltage and Current waveforms of S_y.

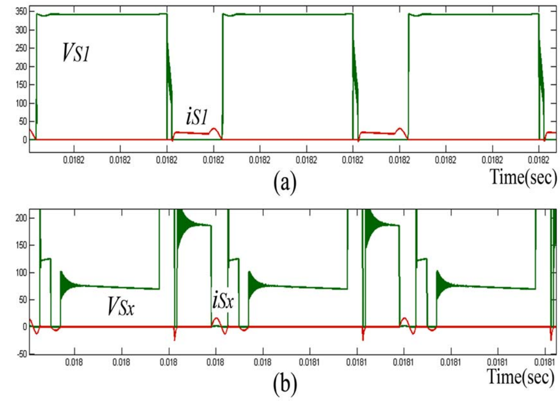


Figure 5. (a) Voltage and Current waveforms of S_1 (b) Voltage and Current waveforms of S_x.

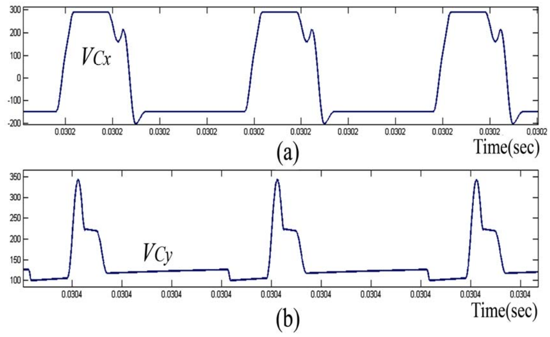


Figure 6. (a) Auxiliary resonant capacitor voltage V_{Cx} (b) Auxiliary resonant capacitor voltage V_{Cy}.

Fig. 8 and Fig.9 ZCS Turn-on Turn-off transitions clearly shows the main switches (S_1,S_2) and auxiliary switches (S_x,S_y).

ISBN 978-80-261-0642-5, © University of West Bohemia, 2017

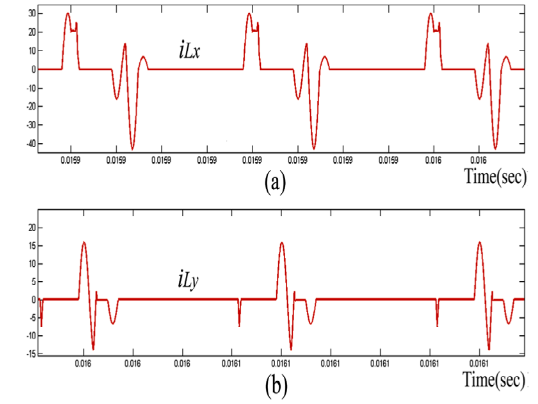


Figure.7. (a) Auxiliary resonant inductor L_x current (b) Auxiliary Resonant inductor L_y current.

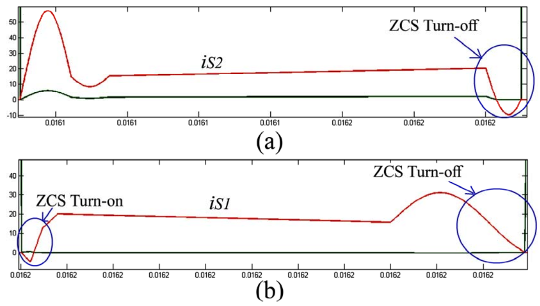


Figure 8. (a) Turn-on and Turn-off Transition of S_2
(b) Turn-on and Turn-off Transition of S_1

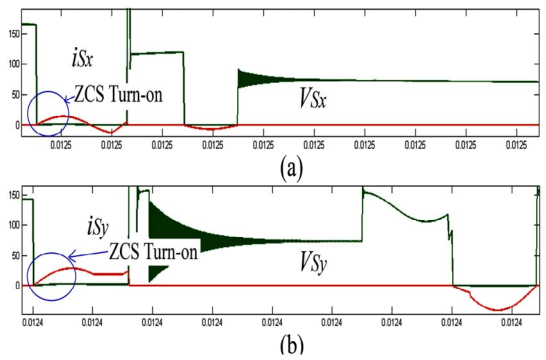


Figure 9. (a) Turn-on and Turn-off Transition of S_x
(b) Turn-on and Turn-off Transition of S_y

V. Conclusion

This proposed work is a new ZCS high step-up DC-DC converter, which is applicable in battery operated electric vehicles. The operation principles, design and its simulation analysis were presented. The zero current switching turned-off operation was obtained for all the switches in this converter, it is one major advantage, because the auxiliary circuit does not increase additional switching losses and also reduced voltage stresses to the main switches. The simulation results were observed in order to verify the theoretical analysis. This converter can be applicable for high-gain and high power applications with improved efficiency over the existing topologies of DC battery back-up systems. The experimental verification of this topology is under progress.

Acknowledgment

This research has been supported by the Ministry of Education, Youth and Sports of the Czech Republic under the RICE – New Technologies and Concepts for Smart Industrial Systems, Project No. LO1607.

References

[1] R. G. d. A. Cacau, T. B. Lazzarin, M. C. T. Villanueva and I. Barbi, "A high step-up non-isolated DC-DC converter based on the integration of conventional boost converters," IEEE 25th International Symposium on Industrial Electronics (ISIE), Santa Clara, CA, 2016, pp. 408-420.

[2] Y. Park, B. Jung and S. Choi, "Nonisolated ZVZCS Resonant PWM DC–DC Converter for High Step-Up and High-Power Applications," IEEE Transactions on Power Electronics, vol. 27, no. 8, pp. 3568-3575, Aug. 2012.

[3] M. Kwon, S. Oh and S. Choi, "High Gain Soft-Switching Bidirectional DC–DC Converter for Eco-Friendly Vehicles," IEEE Transactions on Power Electronics, vol. 29, no. 4, pp. 1659-1666, April 2014.

[4] D. Patii, A. K. Rathore, D. Srinivasan and S. K. Panda, "High-frequency soft-switching LCC resonant current-fed DC/DC converter with high voltage gain for DC microgrid application," IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society, Dallas, TX, 2014, pp. 4293-4299.

[5] X. Lin, J. Xu, X. Zhou and G. Zhou, "Zero-voltage zero-current switching DC/DC converter with high step-up and high efficiency," Electronics Letters, vol. 52, no. 14, pp. 1250-1252, June 2016.

[6] F. Shang; G. Niu; M. Krishnamurthy, "Design and Analysis of a High Voltage-Gain Step-up Resonant DC-DC Converter for Transportation Applications," in IEEE Transactions on Transportation Electrification , vol.PP, no.99, pp.1-1, March 2017.

[7] H. M. Maheri; E. Babaei; M. Sabahi; S. H. Hosseini, "High Step-up DC-DC Converter with Minimum Output Voltage Ripple," IEEE Transactions on Industrial Electronics , vol.PP, no.99, pp.1-1, January 2017.

[8] N. Molavi, E. Adib and H. Farzanehfard, "Soft-switched non-isolated high step-up DC–DC converter with reduced voltage stress," IET Power Electronics, vol. 9, no. 8, pp. 1711-1718, June 2016.