

A Novel High-Gain Three-Phase DC-DC PWM Boost Converter

Adel Ali Abosnina and Gerry Moschopoulos
Department of Electrical and Computer Engineering
Western University, London, Canada

Abstract— A new high-gain three-phase DC-DC boost converter that can be used in applications where a high output DC bus voltage must be produced from a low DC source voltage is proposed in this paper. The proposed converter has high voltage gain, low input current ripple, and inherent switch voltage clamping. In the paper, the operation of the converter is explained in detail, its features are discussed and guidelines for its design are given. Experimental results obtained from a converter prototype are presented to confirm the converter's feasibility.

Keywords—DC-DC power conversion, renewable energy systems

I. INTRODUCTION

There are a number of applications that require power converters that can convert a low DC source voltage into a much higher DC output voltage. A common application where such power conversion is needed is for renewable energy systems such as the one shown in Fig. 1. In this system, input DC voltage is provided either by solar panels or fuel cells. The voltage obtained from such renewable power source is typically very low (< 50 V) and needs to be stepped up considerably in order to feed downstream converters and loads. In the system diagram shown in Fig. 1, inverters that interface with the grid, DC loads or DC-DC converters are supplied by a high DC voltage bus that was stepped up from the low voltage DC source by some sort of boost converter.

The boost converter is typically either a single-switch PWM boost converter or a full-bridge converter [1]-[8]. Although these converters have an input inductor that can smooth out input current, considerable input current ripple can still be produced unless an extremely large input filter inductor is used. The ripple can create problems for the DC sources, especially those like batteries, PV cells and fuel cells that have issues with lifetime.

Another issue is that although single-switch PWM boost converters and current-fed full-bridge boost converters can boost input DC voltage, their gains are not sufficiently high for renewable energy applications such as what is shown in Fig. 1. As a result, many high gain DC-DC converters have been proposed in the literature [9]-[12]. These converters achieve high gain by cascading a boost converter so that they are quadratic converters, using coupled inductors, or using voltage multiplier cells. These converters, however, have at least one of the following problems:

- Their topologies have high conduction losses because current is forced to flow through a number of

components in series in order to achieve high voltage gain.

- Their switches are subjected to high voltage spikes unless additional components are added to the circuit to suppress these spikes.
- Their components are subjected to high voltage and/or high current peak stresses.
- Input and output current ripple still remain an issue.

Three-phase DC-DC boost converters with input phases coming out of the DC source have less input current and output voltage ripple as the equivalent converter frequency is three times more than the switching frequency and their switches conduct less current than does the switch in a conventional PWM boost converter. Current ripple is an important consideration for batteries as exposure to high current ripple can reduce their lifetime. Although they have less current ripple and are suitable for higher power applications due to their multi-switch topologies, little research has been done on increasing the gain of three-phase DC-DC converters and only a few high-gain three-phase DC-DC converters have been proposed [13]-[23]. Although these converters address the issue of high current ripple, they still have some of the above-mentioned drawbacks.

A new three-phase DC-DC power converter that can be used for renewable energy applications requiring high voltage gains and that does not have any of the above drawbacks is proposed in this paper. In this proposal, the new converter is introduced, its operation is explained in detail and its features are discussed. Experimental results obtained from a converter prototype are presented to confirm the feasibility of the proposed converter.

II. CIRCUIT DESCRIPTION AND MODES OF OPERATION

The proposed converter is shown in Fig. 1. It consists of three main switches, S_1 - S_3 , a three-phase transformer, whose primary and secondary are both connected in delta configuration, a three-phase diode bridge rectifier at the transformer secondary and an output capacitive filter C_1 . The main switches of the converter are connected to the output through diodes D_{a1} , D_{a2} , and D_{a3} and these diodes are connected to the high side voltage through capacitor C_2 .

The converter works as follows: Whenever a switch is turned on, the current in the inductor connected to its drain rises. Whenever a switch is turned off, its drain voltage is clamped to the voltage across C_2 as the inductor current flows to the output through D_{a1} , D_{a2} or D_{a3} and falls. Energy is transferred to C_1

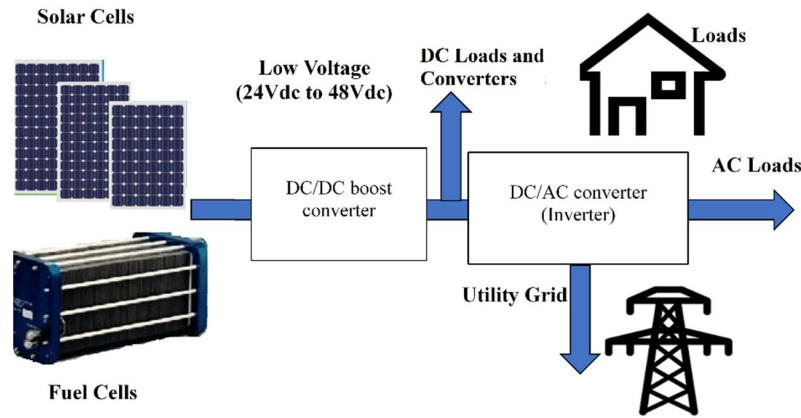


Fig. 1. Block diagram of a renewable energy system.

while the converter is operating, whenever a primary voltage appears across one of the transformer primary windings. For example, this can happen when switch S_2 is on and switch S_1 is off with the current in L_1 flowing in D_{a1} . In this case, the voltage across the AB primary winding is V_{C2} . If the gating signals of the three main switches are such that they are the same but shifted 120° with respect to each other, then ripple reduction will occur due to interleaving.

The modes of operation during a third of a steady-state switching cycle are explained in this section. Typical converter waveforms and circuit diagrams for each mode are shown in Fig. 2. For these diagrams, all converter components are ideal and it is assumed that the input inductors (L_1 , L_2 and L_3) are large enough to keep the current through them continuous over a switching period. It is assumed that switch S_1 was on before $t = t_0$ and that it is conducting the full input current before the start of Mode 1 of operation.

Mode 1 [$t_0 < t < t_1$]: Switch S_2 is turned on at the beginning of this mode. The current through S_2 is gradually increased due to the leakage inductance of the primary of the transformer. The current through switch S_2 increases, whereas the current through switch S_1 decreases. In this mode, Switches S_1 and S_2 are turned on, whereas switch S_3 is turned off. Energy is transferred through the three-phase transformer through the windings that

have voltage impressed across them. Secondary current flows through diodes D_2 , D_4 and D_5 .

Mode 2 [$t_1 < t < t_2$]: At the beginning of this mode, Switch S_1 is turned off and the diodes D_{a1} and D_{a3} start to conduct; current flows to output through them. In this mode, the current through D_{a1} and D_{a3} starts to decrease and the current through S_2 increases. During this mode, energy is transferred to the output through the three-phase transformer as well as through the diodes D_{a1} and D_{a3} . In the secondary of the transformer there is no change. At the end of this mode, D_{a1} and D_{a3} is disconnected and all the input current flows through switch S_2 . In this mode, the voltage across capacitor C_2 reaches to the level of the voltage across the transformer's primary and this voltage is applied across switch S_1 .

Mode 3 [$t_2 < t < t_3$]: At $t=t_3$, the diode D_{a1} stops conducting and switch S_2 carries all input current. During this mode, all energy is transferred to the output through the three-phase transformer.

Mode 4 [$t_3 < t < t_4$]: At the beginning of this mode, switch S_3 is turned on and the next one-third switching cycle begins. The converter operates in the same manner as in Mode1 except that switches S_2 and S_3 are turned on instead of switches S_1 and S_2 . In this mode, energy is transferred to the output through three-phase transformer and diodes D_1 , D_4 and D_6 .

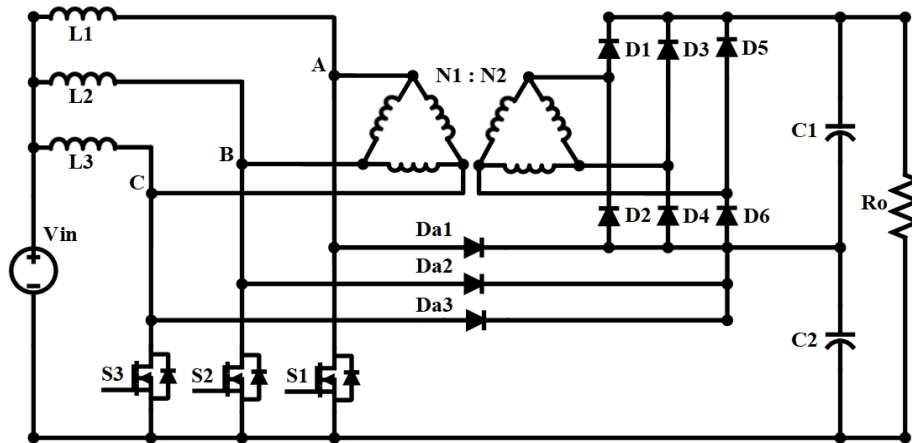


Fig. 2. Proposed high-gain three-phase DC-DC PWM boost converter.

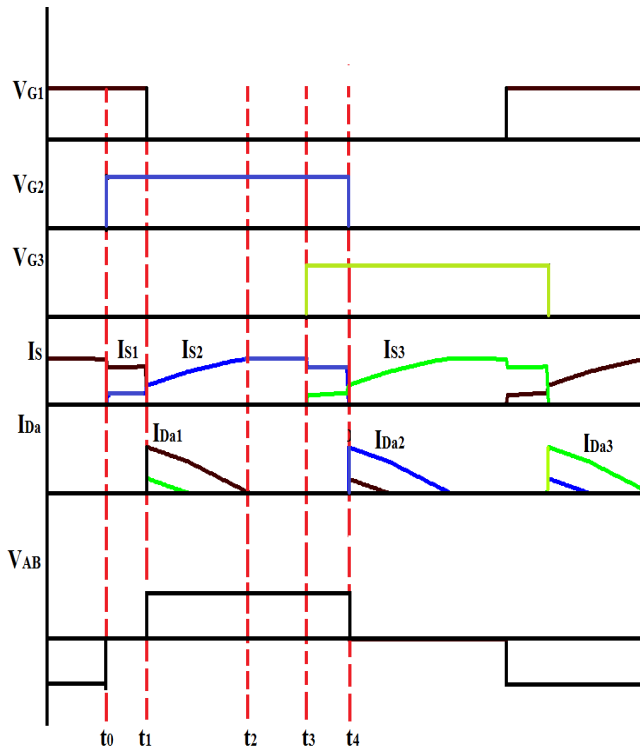


Fig. 3. Typical converter waveforms.

III. CONVERTER FEATURES

The features of the proposed converter are discussed in detail in this section. The converter has the following features:

A. Current Ripple Reduction

As discussed in the Introduction, conventional single-phase high gain DC-DC converters have issues with current ripple and a bulky input inductor is needed to reduce it. Moreover, the same holds true for the output if the converter is operated with heavy loads. Current ripple is not an issue with the proposed converter as it is a three-phase DC-DC converter. It has an interleaved three-phase input, which reduces input current ripple. It also has reduced output current ripple as it is three times the switching frequency and thus easier to filter. This allows two smaller capacitors to be used instead of one big output capacitor.

A. High Output Gain

The proposed converter can be made to operate with high voltage gain because it has two separate mechanisms by which voltage can be stepped up. The first mechanism is the three-phase transformer section, the second is the non-isolated boost converter section. Each section can step up voltage by itself. In the case of the three-phase transformer, it is just a matter of adjusting the turns ratio of the transformer. In the case of the boost converter, it is just a matter of increasing the converter duty cycle.

A net increase in gain can be achieved by stacking the output of the two sections one on top of the other. This is different than many other high gain converters, which have only one mechanism for increasing gain and only one output.

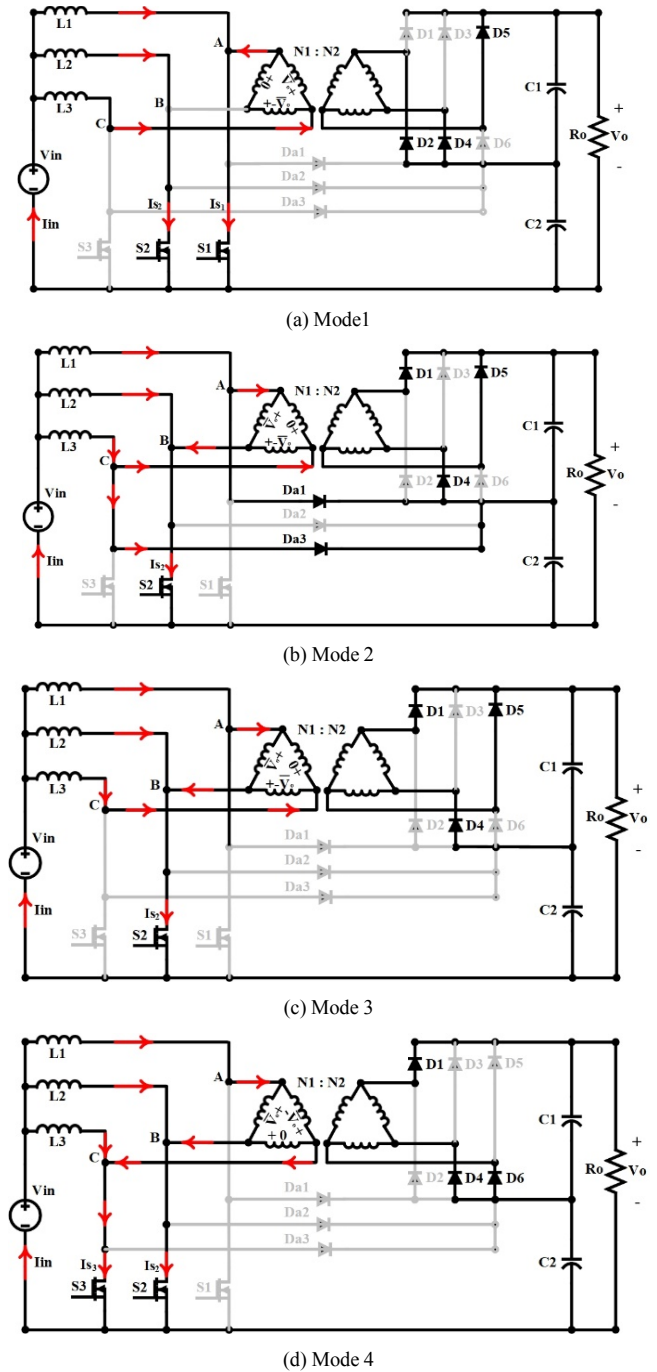


Fig. 4. Converter modes of operation.

B. Single-Stage Power Processing

Many high gain converters use multiple cascaded cells to increase their gain. These cells can be based on additional active converters or passive voltage multiplier cells.

Cascaded high gain converters use multiple converters to increase gain. In these converters, the output of one converter is fed to the input of another converter so that gain is increased. Sometimes, redundant elements in these converters can be

removed to reduced cost. So-called quadratic converters, which are converters whose gain depends on the square of the duty cycle rather than the duty cycle itself, are just such converters.

Although the use of cascaded converters and quadratic converters has been established in the literature, these converters are rarely used except in low power applications. This is mainly because current must flow through numerous circuit elements so that conduction losses become significant. Such converters therefore cannot be used in renewable energy applications because of the high current that converter components must conduct.

The same issue arises when the use of passive voltage multiplier cells is considered. Passive voltage multiplier cells take the voltage of one cell then feed it to the input of another cell, which then feeds another cell until the last cell. Many of these multiplier cells are based on capacitors that are stacked one on top of the other. This can work if the current through the cells is low and in fact it is common to use such cells at the secondary output of high gain converters where the output voltage is already high and the output current is low to provide an additional increase in gain. If such cells are considered in renewable energy applications, then they should not be exposed to high current.

In the proposed converter, power is processed by only one converter: power is either processed by the three-phase transformer section or by the non-isolated boost section. As a result, current flows through only one converter instead of multiple converters and thus significant increases in conduction losses are avoided.

C. Inherent Snubber Circuit

In many high gain converters, the presence of voltage spikes due to parasitic elements is a concern; this is especially true for coupled inductor high gain converters. In such converters, the use of coupled inductors means that the converter switches are not clamped to any voltage and any difference in the current of the coupled inductors will try to force its way through the switches when they are turned off. As a result, such converters cannot operate unless additional snubbers are needed.

These snubbers can either be passive snubbers or active snubbers. Passive snubbers tend to dissipate energy or involve the addition of numerous components. Active snubbers involve the use of additional active switches thus increasing the cost and complexity of the converter.

The proposed converter has an inherent snubber circuit and thus does not require that sophisticated clamping or dissipative passive snubber circuits be added to it. When a converter switch is turned off, the voltage across the switch is naturally clamped to the voltage across output capacitor C_2 , which is a bulk capacitor.

D. Reduced Peak Switch Voltage Stress

Due to the high gain of high voltage gain converters, the switches of some previously proposed converters are exposed to high peak voltage stresses. This is because the high output DC voltage appears directly across the switch. High gain converters where the switches are not directly exposed to the output voltage have numerous circuit elements between them and the output.

This, however, results in increased conduction losses as current must flow through these series elements.

In the proposed converter, peak switch voltage stress is not excessive. It is in fact less than the output voltage as the maximum voltage that appears across any converter switch is the voltage across C_2 . This allows lower voltage rated semiconductor devices with lower values of on-state resistance R_{DSon} to be used as the converter switches.

IV. DESIGN CONSIDERATIONS

Several key considerations should be taken into account when designing the proposed converter. Some of these considerations are discussed in this section.

A. Input-Output Voltage Gain

The proposed converter can be divided into two stages with the output voltage being the sum of the voltage across each stage. The first stage works as a three-phase interleaved boost converter with three-phase high frequency transformer. Assuming that the transformer leakage inductance is negligible, the gain of this section can be described by the following equation

$$\frac{V_{C1}}{V_{in}} = \frac{n}{1-D} \quad (1)$$

where, V_{C1} is the voltage across C_1 , V_{in} is the input voltage, n is the transformer turns ratio $n = \frac{N_2}{N_1}$, and D is the converter duty cycle.

The second stage (auxiliary circuit) works as a conventional interleaved boost converter. the output to input ratio in this section can be expressed as

$$\frac{V_{C2}}{V_{in}} = \frac{1}{1-D} \quad (2)$$

where V_{C2} is the voltage across C_2

The overall voltage gain, G , of the proposed converter can be derived as following

$$G = \frac{V_o}{V_{in}} = \frac{n+1}{1-D} \quad (3)$$

From (3), the overall voltage gain depends on the transformer's turns ratio and the duty ratio of the converter. The gain of the proposed converter increases whether the transformer's turns ratio or the duty cycle is increased. There is, however, a trade-off between the turns ratio and the duty cycle. Although smaller duty cycle means lower voltage stress across the switches, it results in higher turns ratio, which increases the amount of current circulating in the primary circulation current, thus increasing conduction losses.

B. Transformer turns ratio, n

The transformer's turns ratio should be chosen to minimize the voltage stress across the converter switches. The voltage stress across the switches is the voltage across the output capacitor, V_{C2} . It should be noted that V_{C2} can be calculated using (2) or it can be also approximated to be the voltage across

the primary transformer that is reflected from the output voltage across C_1 ($V_{C2} = V_{pri} = \frac{V_{C1}}{n} = \frac{V_{in}}{1-D}$). For constant duty cycle D , increasing the turns ratio will result in more voltage appearing across capacitor C_1 while the voltage across the primary does not change (i.e. the voltage stress across the switches does not increase). Higher voltage stress across the output bridge diodes, however, will appear.

The transformer's turns ratio also has a significant effect on the distribution of the output voltages ($V_{C2}:V_{C1}$). This ratio can be determined by using (1) and (2), (i.e. the ratio $V_{C2}/V_{C1}=1/n$). Higher turns ratio means more voltage across capacitor C_1 and more energy transferred to the output through the transformer, but more energy results in more losses and higher rating for the transformer. On the other hand, lower turns ratio means higher voltage across C_2 and more components stresses. The turns ratio of the transformer therefore should be chosen as a compromise between the transformer size and the stress of the converter components.

C. Reverse recover time in auxiliary diodes

The duration of Mode 2, in which the current in auxiliary diode (D_{a1} , D_{a2} or D_{a3}) gets diverted to the bridge diodes through the leakage inductance (L_k) of the transformer should be greater than $3t_r$ (three times the reverse recovery time of the auxiliary diode). This is a typical value to allow for current to be gradually removed from a silicon fast-recovery diode to keep reverse-recovery current from appearing. The expression for the commutation time t_c can be found from the following equation

$$t_c = (t_2 - t_1) = \frac{\pi}{2} \sqrt{L_k C_2} \quad (4)$$

so that

$$3t_{rr} = t_c = \frac{\pi}{2} \sqrt{L_k C_2} \quad (5)$$

The values of the leakage inductance L_k of the transformer and the output capacitor C_2 should be chosen to satisfy equation (5).

V. EXPERIMENTAL RESULTS

A prototype of the proposed converter was built according to the following specifications: Input voltage $V_{in}=18V-30V$, output voltage $V_o=200V$, output power $P_o=500W$ and switching frequency $f_{sw}=50kHz$. The prototype was implemented with $L_1=L_2=L_3=200\mu H$ and a transformer primary/secondary turns ratio of $n=1:3$. IRFB 4227 devices were used for the switches and ETL 0806 devices were used for the diodes. Typical experimental waveforms obtained with $V_{in}=30V$ are shown in Fig. 6.

Fig 6(a) shows gating signals of the converter's main switches, which are identical but shifted by 120° with respect to each other. Voltage and current waveforms for one of the main switches are shown in Fig. 6(b). It can be seen that the switch voltage is clamped and that it is clamped to a voltage that is less than the output voltage.

Fig. 6(c) shows gating signals for two main switches and a voltage across one of the three-phase transformer primaries. The primary voltage waveform is a square waveform with some zero voltage intervals and that it is not symmetrical. The symmetry or asymmetry of the voltage is dependent on the switch states of the switches. Fig. 6(d) shows the currents for two of the boost inductors I_{L1} and I_{L2} and Fig. 6(e) shows the current of one of the boost inductors and the input current I_{in} flowing out of the DC source. The inductor currents have some ripple and the input current has little due to interleaving.

VI. CONCLUSION

A new high-gain three-phase DC-DC converter is proposed in this paper. It has an input current with low ripple, high gain due to a stacking structure, lower conduction losses due to fewer components in the path of current and the fact that power is only processed once (either by the boost converter or the three-phase transformer), a simple and inherent clamping mechanism (no additional clamping snubbers need to be added to the circuit), and lower voltage and/or current stresses on the components (i.e. the peak voltage stress is clamped to V_{C2} and not V_o).

In this paper, the operation of the converter was explained in detail, its features were discussed and some guidelines for its design were given. The converter's feasibility was confirmed with results obtained from an experimental prototype.

ACKNOWLEDGMENT

The authors would like to acknowledge support from the Libyan Ministry of Education and the College of Electrical and Electronics Technology- Benghazi for this work.

REFERENCES

- [1] C. J. Tseng and C. L. Chen, "A Passive Lossless snubber cell for non isolated PWM DC/DC converters," in *IEEE Trans. on Industrial Electronics*, Vol. 45, P.593-601, August 1998.
- [2] V. Yakushev, V. Meleshin and S. Fraidlin, "Full-bridge isolated current fed converter with active clamp," in *APEC*, 1999, pp. 560-566.
- [3] T. W. Kim, H. S. Kim and H. W. Ahn, "An improved ZVT PWM boost converter," in *IEEE PESC*, 2000, pp. 615 - 619.
- [4] H. Bodur, A. F. Bakan, "A new ZVT-PWM DC-DC converter," in *IEEE Trans. on Power Elec.*, Vol. 17, No. 1, pp. 40-47, Jan. 2002.
- [5] L. Zhu, "A novel soft-commutating isolated boost full-bridge ZVS-PWM DC-DC converter for bidirectional high power applications," in *IEEE Trans. on Power Elec.*, 2006, pp. 422-429.
- [6] A. Averbeg; K. R. Meyer; A. Mertens, "Current-fed full bridge converter for fuel cell systems," in *IEEE PESC*, 2008, pp. 866-872.
- [7] A. Mousavi, P. Das and G. Moschopoulos, "A comparative study of a new ZCS DC-DC full-bridge boost converter with a ZVS active-clamp converter," in *IEEE Trans. on Power Elec.*, 2012, pp.1347-1358.
- [8] B. Akın, "An improved ZVT-ZCT PWM DC-DC boost converter with increased efficiency," *IEEE Trans. on Power Elec.*, Vol. 29, No. 4, pp. 1919-1926, April 2014.
- [9] C. Y. Inaba, Y. Konishi, M. Nakamura and M. Nakaoka, " High frequency PWM boost chopper-fed DC-DC converters with coupled-inductors," in *IEEE IPEC*, 2002, pp. 134 - 138.
- [10] Wuhua Li, Jun Liu, Jiande Wu and Xiangning He, "Design and analysis of isolated ZVT boost converters for high-efficiency and high-stepUp applications," in *IEEE Trans. on Power Electronics*, vol.22, No.6, pp.2363-2374, Nov. 2007.

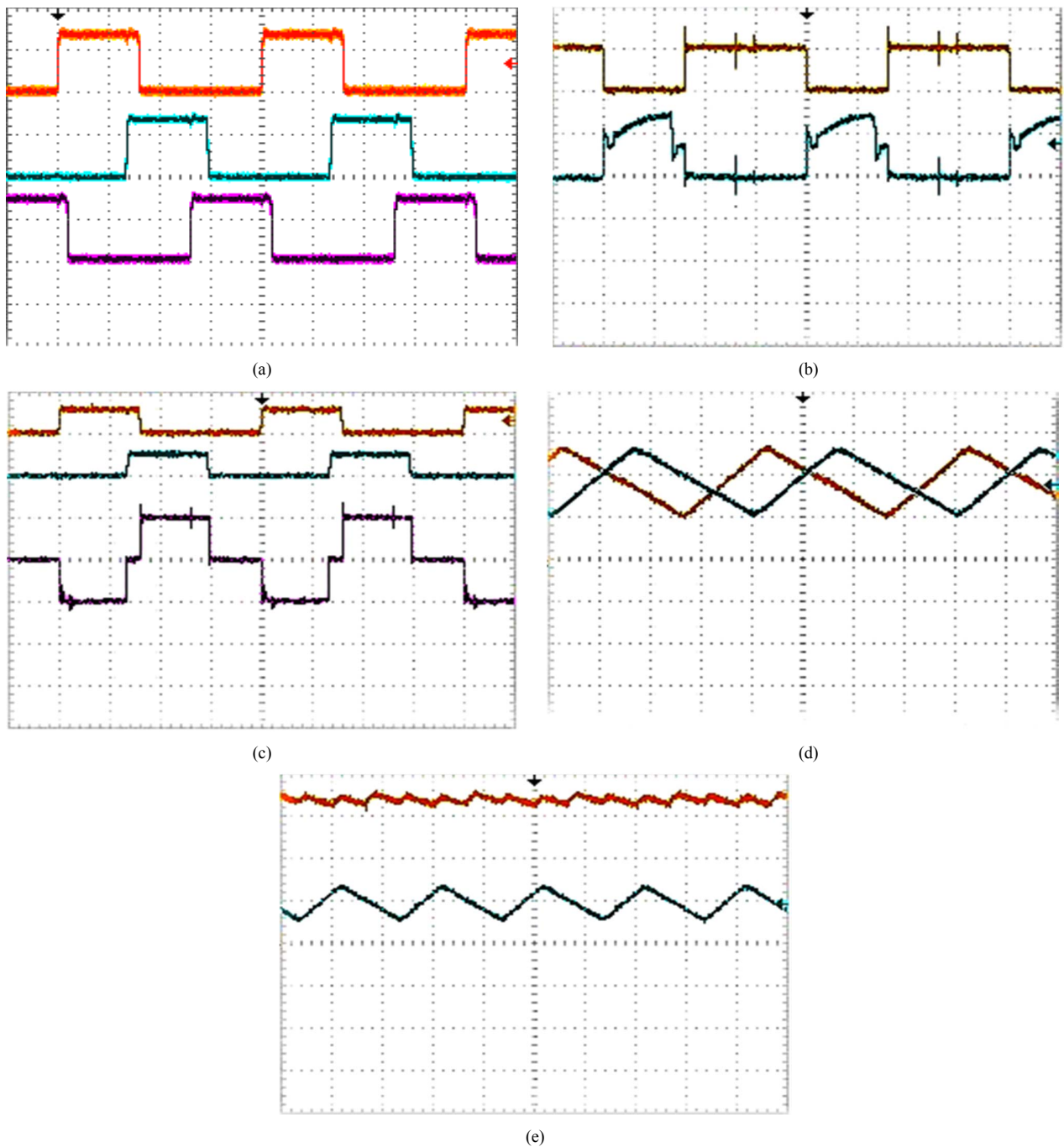


Fig. 5. Experimental results: (a) Gating signal waveforms (V:20V/div., t:5μs/div.), (b) Voltage and current for the main switch (V: 50V/div., I: 5A/div., t: 5μs/div.), (c) Gating signal waveforms for two main switches and primary voltage waveform across the transformer (Vg: 50V/div., Vt: 50V/div., t: 5μs/div., (d) Current through two main inductors (I: 1A/div, t: 5μs/div.), (e) Input current and main inductor current waveform (Iin: 2A/div., IL: 2A/div, t: 10μs/div.)

- [11] B. Revathi and M. Prabhakar, "Non isolated high gain high power dc-dc converter," in *IEEE Electrical Energy Systems (ICEES)*, 2014, pp. 223 – 228.
- [12] M. Garg; R. K. Singh," Coupled inductor boost converter with enhanced esr filter capacitor for dc microgrid applications," in *IEEE ICIT*, 2015, pp. 963-968.
- [13] Rik W. A. A. De Doncker, D. M. Divan and M. H. Kheraluwala, "A three-phase soft switched high-power-density DC /DC converter for high-power applications," in *IEEE Transactions on Industry Applications*, vol. 27, no. 1, pp. 63-73, January/February 1991.
- [14] A. R. Prasad, P. D. Ziogas and S. Manias, "Analysis and design of a three-phase off-Line DC-DC converter with high-frequency isolation," in *IEEE Transactions on Industry Applications*, vol. 28, no. 4, pp. 824-832, July / August 1992.

- [15] J. Jacobs, A. Averberg and R. De Doncker, "A novel three-phase DC/DC converter for high-power applications," in *IEEE PESC*, 2004, pp. 1861-1867.
- [16] D. S. Oliveira and I. Barbi, "A three-phase ZVS PWM DC/DC converter with asymmetrical duty cycle associated with a three-phase version of the hybrid rectifier," in *IEEE Trans. on power electronics*, vol. 20, no. 2, pp. 354-360, March 2005.
- [17] C. Liu, A. Ridenour and J. -S. Lai, "Modeling and control of a novel six-leg three-phase high-power converter for low voltage fuel cell applications," in *IEEE Trans. on Power Electronics*, vol. 21, no. 5, pp. 1292-1300, Sep. 2006.
- [18] G. Franceschini, E. Lorenzani, M. Cavatorta and A. Bellini, "3boost: a high-power three-phase step-up full-bridge converter for automotive applications," in *IEEE Trans. on Industrial Electronics*, vol. 55, no. 1, pp. 173-183, Jan. 2008.
- [19] H. Cha, J. Choi and P. N. Enjeti, "A three-phase current-fed dc/dc converter with active clamp for low-DC renewable energy sources," in *IEEE Trans. on power electronics*, vol. 23, no. 6, pp. 2784-2793, Nov. 2008.
- [20] H. Kim, Ch.Yoon and S.Choi, "A three-phase zero-voltage and zero-current switching DC-DC converter for fuel cell applications," in *IEEE Trans. on power electronics*, vol. 25, no. 2, pp. 391-398, Feb. 2010.
- [21] J. Choi, H. Cha and B-M. Han, "A three-phase current-fed dc/dc converter with active clamp for fuel cells," *IEEE Trans. on Power Electronics*, vol. 25, no.8, pp. 2115-2123, Aug. 2010.
- [22] L. Zhang, D. Xu, H. li, G. Shen and M. Chen, "Three-phase interleaved high step-up boost converter with voltage multiplier for fuel cell power sysyem," in *IEEE ECCE*, 2015, pp. 4804-4811.
- [23] Ke Jin, and Chang Liu "A novel PWM high voltage conversion ratio bidirectional three phase DC/DC converter with Y- Δ connected transformer," in *IEEE Trans. on power electronics*, vol. 31, no. 1, pp . 81-88, Jan. 2016.