A Novel Three-Phase Bidirectional DC-DC Converter For UPS Applications

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

***Abstract*—Uninterruptible power supplies (UPS) typically require bidirectional DC-DC converters to interface batteries to a DC bus. These converters should allow batteries to supply power when the input AC voltage is down and to be charged when the input AC is up again. A novel bidirectional three-phase DC-DC converter for UPS applications is proposed in the paper. The converter is suitable for UPS systems where batteries have large amounts of current flowing in and out. In this paper, the proposed converter is introduced, its operation is explained, and guidelines for the design of key elements are given. The feasibility of the converter is confirmed with results obtained from a prototype converter.**

Keywords— DC-DC converter, uninterruptible power supply, switch-mode power supply

I. INTRODUCTION

Uninterruptible power supply (UPS) systems [1]-[7] are used to protect sensitive loads that are supplied by AC utility grid voltage from various kinds of voltage disturbances and power outages. If something should happen to the AC grid voltage, then some sort of auxiliary circuitry is activated to ensure that power continues to be supplied to the load. This auxiliary circuitry is typically a converter that interfaces a battery or a bank of batteries and it is through this converter that power is supplied to the load. Since the battery / battery bank must be recharged sometime after they have supplied power during a grid voltage disturbance or power outage, there must be some interface that will allow this to happen. Instead of having two converters interface the battery / battery bank with the DC bus, the interface can be a bidirectional DC-DC converter that allows power to flow from the DC bus to the battery / battery bank and vice versa.

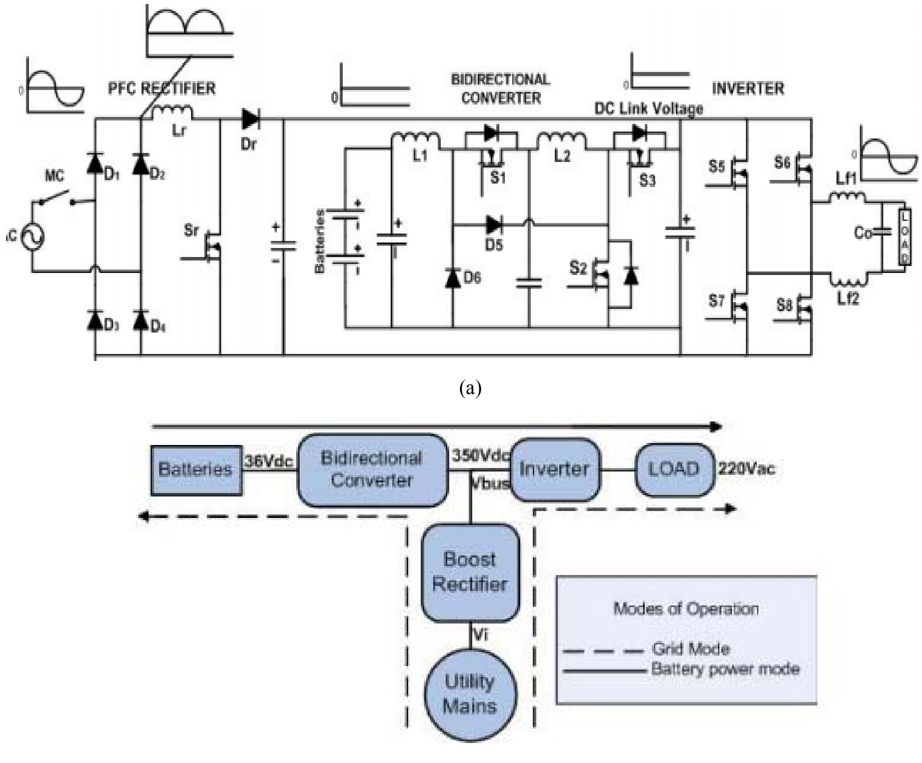
UPS systems can be implemented in various ways. For example, some systems can be implemented with transformer isolation while others may be non-isolated. Whether a UPS has transformer isolation or not will depend on the application. An example of a non-isolated UPS system is the one shown in Fig. 1. Fig. 1(a) shows a circuit diagram of an AC-DC-AC converter with a built-in UPS; Fig. 1(b) shows a block diagram of current flow. In the converter shown in Fig. 1(a), battery back-up is provided through a bidirectional converter connected to the DC bus. The batteries supply power to the DC bus when the AC input is down, thus allowing the converter to operate in an uninterrupted manner. When the AC power is back up, then the DC bus supplies power to charge the batteries through the bidirectional converter until they are fully charged.

The block diagram in Fig. 1(b) illustrates how power flows in the converter shown in Fig. 1(a), depending on whether the converter is in grid mode, when power is supplied by the grid, or battery mode, when power is supplied by the batteries. It should be noted that the battery voltage tends to be low, in the range of about 36 – 72 V_{DC} for many telecom applications for example, while the DC bus voltage tends to be much higher, in the range of about 350 – 400 V_{DC}. The bidirectional converter interface therefore must be such that it can step up voltage when power flows from battery to DC bus and step-down voltage when power flows from DC bus to battery. DC-DC bidirectional converters can be low power buck/boost type topologies, higher power isolated voltage-fed/current-fed topologies, or topologies with three-phase transformers. The focus of this paper is on three-phase DC-DC bidirectional converters that can be used in UPS applications.

Three-phase DC-DC converter topologies for higher power and current applications produce less ripple current and less current stress on the devices. Low ripple current is a particularly important features as high ripple current can result in reduced lifetime of batteries in UPS systems. Three-phase DC-DC converter topologies can either voltage-fed or and current-fed. Voltage-fed converters are used at the high voltage side of bidirectional converters to step down voltage, while current-fed converters are used at the low side to step up voltage. The three-phase voltage-fed converter proposed in [8] is the most common converter of its type used as the high side converter, with some variations [9]-[14]. As for the low side, more options for three-phase current-fed converters have been considered [15]-[21], but they have the following drawbacks:

- They use at least six switches, thus increasing cost.
- They lack a clamping circuit or snubber, thus they are not practical for UPSs where lighting EM pulses may impact gating signals and cause switches to misfire so that a current path is needed to avoid their destruction.
- They have a clamping circuit(s) or snubber(s) that are either sophisticated or lossy.

A three-phase DC-DC bidirectional converter for UPS applications with a low voltage side converter that has interleaving and does not have these drawbacks is proposed in this paper. In this paper, the 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 bidirectional converter.



(a)

(b)

Fig. 1. (a) Configuration of UPS System. (b) Simplified block diagram (reproduced from [6]).

II. CONVERTER OPERATION

The proposed converter is shown in Fig. 2. The low side converter is a three-phase boost converter with a flyback snubber. The high-side converter is the three-phase step-down converter proposed in [8]. The novelty of the proposed topology is in the low-side converter. The converter has two fundamental modes of operation: boost mode (or discharging mode) and buck mode (or charging mode).

In boost mode, switches S_1-S_3 are active and the body diodes for switches Q_1-Q_6 are used as three-phase rectifier. A flyback converter is used to discharge the clamping capacitor C_c so that its voltage does not become excessive. Energy stored in C_c is fed to the high side instead of being dissipated.

In buck mode, power is converted from the high voltage side to the low voltage side to charge the battery. Switches Q_1-Q_6 are active and body diodes of switches S_1-S_3 operate as a rectifier. Inductors L_1-L_3 work as an output filter and the flyback circuit is deactivated during this mode.

A. Step-Up (Boost) Mode Operation

The basic operation of the converter in boost mode is as follows: Whenever a main switch is turned on, the current in the inductor connected to its drain rises; when this switch is turned off, the current in that inductor falls as it flows in the transformer. Energy is transferred through a three-phase transformer winding whenever there is voltage across it, as can be the case for example for the AB primary winding when S_1 is off and S_2 is on. The voltage level across a switch at any given time depends on the on/off state of the other switches and is clamped by C_c. The voltage across C_c is dependent on the operation of the flyback converter – the longer it is activated during a switching cycle, the lower this voltage will be. Switches Q_1-Q_6 are all off and rectify the secondary output of the transformer. If the gating signals of the three main switches are the same but shifted 120^o with respect to each other, then the input current will have low ripple due to the interleaving of the currents through L_1-L_3.

The modes of operation during third of a steady-state switching cycle are explained in this section. Typical converter waveforms are shown in Fig. 3 and circuit diagrams for each mode are shown in Fig. 4. 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 at $t = t_0$. The transfer of current from the transformer to switch S_2 is gradual due to primary leakage inductance. The current through S_2 increases while the current through S_1 decreases. In this mode, switches S_1 and S_2 are on, whereas switch S_3 is off. Energy is transferred through the three-phase transformer through the windings that have voltage impressed across them. Secondary current flows through the body diodes of Q_2 and Q_5.

Mode 2 [$t_1 < t < t_2$]: At the beginning of this mode, switch S_1 is turned off and the clamping diode D_{c1} starts to conduct; current i_{dc1} flows into the clamping capacitor. During this mode, the current through main switch S_2 starts to increase. At the end of

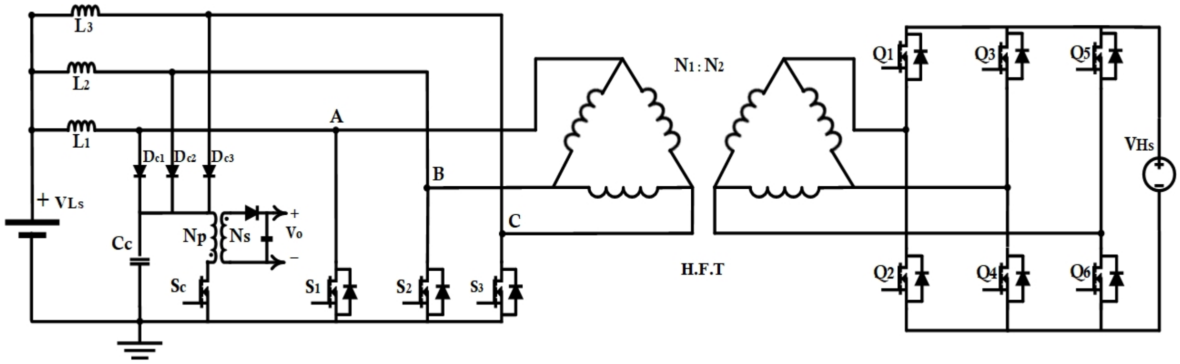


Fig. 2. Proposed bidirectional three-phase DC-DC PWM converter

this mode, switch S_2 carries all input current and the current i_{dc1} (t_2) (= i_{L1} (t_2) - i_{p1} (t_2)) drops to zero.

Mode 3 [$t_2 < t < t_3$]: At t = t_2, the clamping diode D_{c1} stops conducting and C_c is charging. In this mode, S_1 and S_3 remain off and S_2 stays on. Power is transferred to the output through the body diodes of Q_1, Q_4 and Q_5. It can be seen in Fig. 4(d), that switch S_c is turned on. It should be noted that S_c can be turned on and off at any time during the switching period to discharge C_c.

Mode 4 [$t_3 < t < t_4$]: At t = t_3, the flyback switch is turned off and the energy stored in the flyback transformer is transferred to the high-side output. Note that the main switches have the same on/off state and that this mode has been included to show how the circuit operates when switch S_c is turned off. This mode can happen at any time during the switching period.

Mode 5 [$t_4 < t < t_5$]: At t = t_4, main switch S_3 is turned on and the next one-third switching cycle begins. The converter

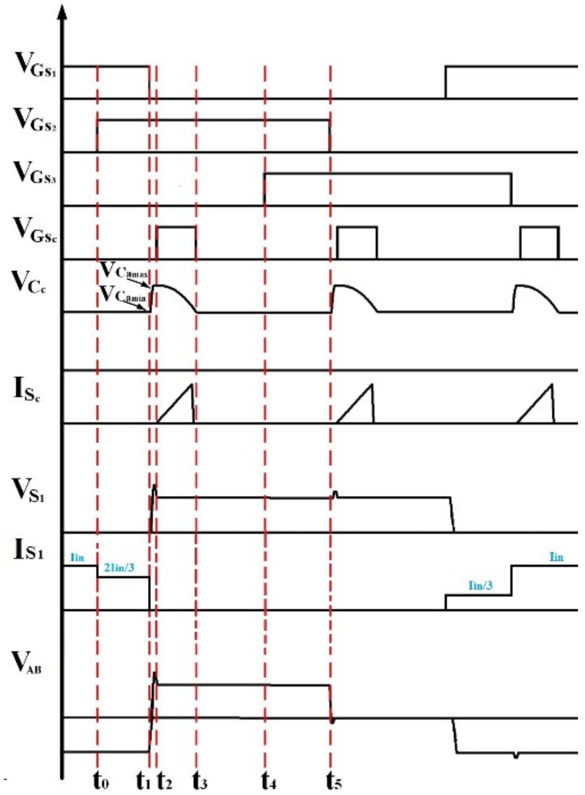
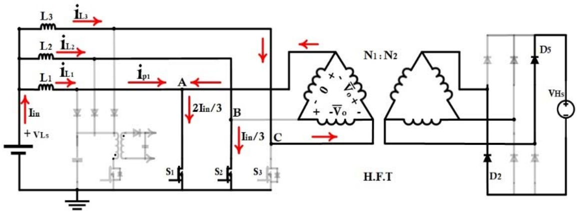
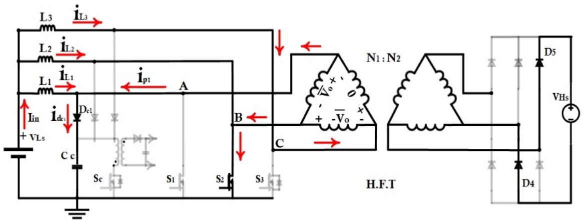


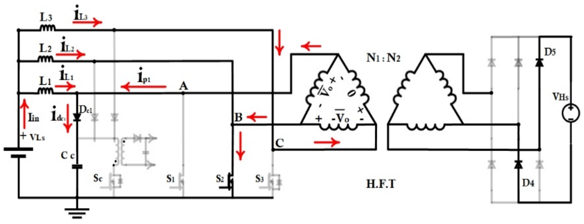
Fig. 3. Typical wveforms for boost operation



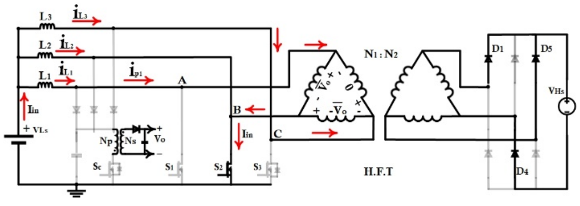
(a) Mode 1



(b) Mode 2



(c) Mode 3



(d) Mode 4

Fig. 4. Modes of operation for step-up operation

operates in the same manner as in Mode 1 except that switches S_2 and S_3 are on instead of switches S_2 and S_1. Since Mode 5 is the same as Mode 1, a circuit diagram is not shown in Fig. 4.

B. Buck Mode Operation

In the step-down mode, switches that are connected on the high side voltage, Q_1-Q_6, are controlled to transfer power from high side voltage to low side voltage. The gating signals of switches Q_1, Q_3 and Q_5 are shifted with respect each other by 120^{o} and the gating signals of switches Q_2, Q_4 and Q_6 are the complements of switches Q_1, Q_3 and Q_5 respectively. The modes of operation during a third of a steady-state switching cycle are shown in Fig. 5. It is assumed that in Mode 1 (Fig. 5(a)), switches Q_2, Q_4 and Q_5 conduct. What should be noted here is how the low voltage converters acts like a rectifier and how current flows through the body diodes of S_1, S_2 and S_3. Current usually flows through one body diode, but can flow through two during a switching transition when a high-side switch is turned off and its complementary switch is about to be turned on (Fig.(5(b)). Also, it should be noted that since there is less current in the high side converter, standard snubbers and clamps can be implemented without modifying the topology as is the case with the low-side converter.

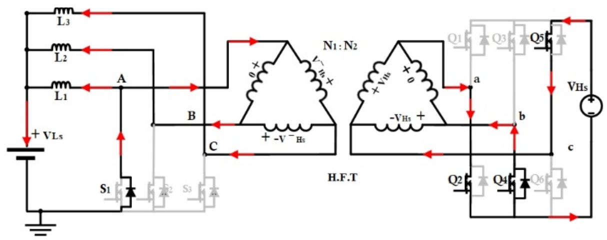
The modes of buck converter operation during a third of a steady-state switching cycle are as follows:

Mode 1 [$t_0 < t < t_1$]: At the start of this mode, switch Q_4 is turned on; switches Q_2 and Q $_5$ are already on. The current through Q_2 and Q_5 does not change whereas the current in switch Q_4 goes from being zero to a negative value, thus, current freewheels through switches Q_2 and Q_4 and the transformer. In this mode, energy is transferred from the high voltage side to the low voltage side through phase c of the transformer. In the low voltage side, the body diode of switch S_1 conducts to transfer power to the battery.

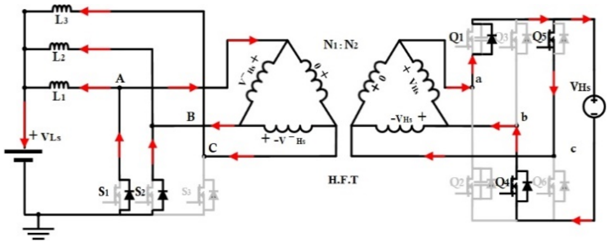
Mode 2 [$t_1 < t < t_2$]: This mode is a transition mode as switch Q_2 is turned off at the start. In this mode, the output capacitor across Q_2 starts to charge and the output capacitor across Q_1 starts to discharge. At the end of this mode, the body diode of switch Q_1 conducts and Q_1 can be turned on with ZVS. At the low voltage side, the body diode of S_2 starts to conduct due to changes in the transformer winding voltages.

Mode 3 [$t_2 < t < t_3$]: Switch Q_1 turns on with ZVS at the beginning of this mode. The current through Q_4 reverses direction and energy is transferred to the low voltage side via phases a and c, through the transformer. At the low voltage side, the body diode of S_1 stops conducting while the body diode of S_2 continues to conduct.

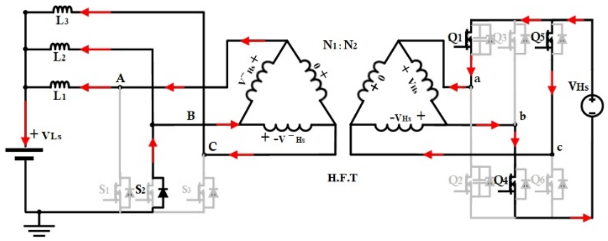
Mode 4 [$t_3 < t < t_4$]: At $t=t_3$, the next one-third switching cycle begins. At the beginning of this mode, Q_6 is turned on whereas switch Q_5 is turned off. Switches Q_1 and Q_4 remain on and switches Q_2 and Q_3 remain off. In this mode, the converter operates in the same manner as in Mode 1 except that energy is transferred to the low voltage side through phase a of the transformer instead of phase c. Also, the body diode of switch S_2 conducts instead of switch S_1.



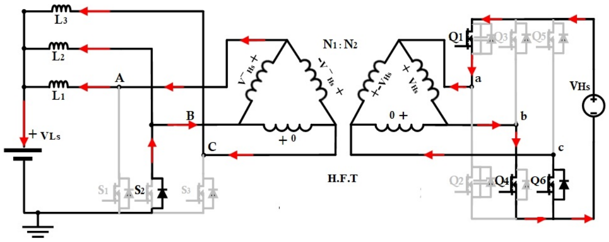
(a) Mode1



(b) Mode 2



(c) Mode 3



(d) Mode 4

Fig. 5. Modes of operation for step-down operation

III. CONVERTER SWITCH MISFIRING

Reliability is a key concern in any UPS system as power must be supplied to critical loads in the event of grid voltage disturbances or power outages. When such events occur, it is imperative that the bidirectional converter that interfaces batteries to the DC bus be operational and not malfunction as well. One type of malfunction that can occur is that the converter gating signals misfire for some reason when the converter is operating in boost mode. This can happen in the case of lightning when electromagnetic pulse can impact the converter gating signals.

A momentary turning on of converter switches in an inappropriate manner will cause damage to the converter. The greater concern is if converter switches do not turn on so that a path is provided for current to flow through. If such a path is not provided, then current will try to force its way through the converter switches thus damaging them.

Such a path is provided in the main converter in the form of the flyback snubber capacitor C_c. If for some reason, there is a misfiring of converter switches when the converter is operating during step-up mode current will flow through the snubber capacitor and the converter switches will not be damaged. This makes the proposed converter suitable for implementation in a UPS system.

It should be noted that the misfiring of switches when the converter is operating in buck mode is less of a concern as it is unlikely that a voltage disturbance of some kind will occur as the batteries are charged. In the event that some sort of switch misfiring does occur in buck mode of operation, it is the short-circuiting of a converter leg caused by the simultaneous turning on of the two switches that can create damage. Traditional methods of short-circuit protection used in voltage-fed type converters can be used to avert such a situation.

IV. DESIGN CONSIDERATIONS

Several key considerations should be taken in account in the design of the proposed converter. This section will focus mainly on the design for boost mode operation as the design for buck mode operation is much better known.

A. Clamping Capacitor C_c and Leakage Inductance L_k

In the boost mode of operation, the clamping capacitor is mainly used to clamp the voltage across the main switches when they are turned off, to eliminate any voltage spikes that may occur. Voltage spikes can be caused by energy that is trapped in the primary leakage inductance of the main transformer and thus some sort of snubber is needed to protect the converter switches.

At the end of Mode 2 of step-up operation, the voltage across the clamping capacitor reaches its peak value. This value can be determined from the following differential equations that define the mode:

$$\frac{I_{in}}{3} = C_c\frac{dv_c}{dt} - \left(i_{Lk1}(t) + i_{Lk2}(t)\right) \tag{1}$$

$$L_{k1}\frac{di_{Lk1}(t)}{dt} = v_c(t) - \frac{V_{Hs}}{n} \tag{2}$$

$$L_{k2}\frac{di_{Lk2}(t)}{dt} = v_c(t) - \frac{V_{Hs}}{n} \tag{3}$$

where

i_{Lk1} and i_{Lk2}: the leakage inductance current of the first and second phases the main transformer.

$L_{k1} = L_{k2}$: the leakage inductances for the main transformer.

$n = \frac{N_2}{N_1}$: the main transformer turns ratio

$\frac{V_{Hs}}{n}$: primary voltage across the main transformer, and V_{Hs} is the high side voltage of the converter. If the initial value of V_c is defined as $v_c(0) = \frac{V_{Hs}}{n}$, the voltage across the capacitor is

$$v_c(t) = \frac{V_{Hs}}{n} + \frac{I_{in}}{3}Z_0\sin(\omega_0 t) \tag{4}$$

The peak voltage, which is also the peak voltage across the switches is

$$V_{c(\max)} = \frac{V_{Hs}}{n} + \frac{I_{in}}{3}Z_0 \tag{5}$$

where

$$\omega_o = \sqrt{\frac{1}{L_k C_c}} \tag{6}$$

$$Z_o = \sqrt{\frac{L_k}{C_c}} \tag{7}$$

$$\frac{1}{L_k} = \frac{1}{L_{k1}} + \frac{1}{L_{k2}} \tag{8}$$

From (5), the voltage across C_c increases as the capacitor value is decreased. To reduce the voltage across the capacitor, (i.e. reduce the voltage stress across main switches), a larger capacitor must be used as there must be enough energy stored in the capacitor to force the current to diverted away from the clamping diodes. A larger capacitor, however, means more time is needed to reach maximum voltage, which causes more conduction losses in the converter.

Higher values of leakage inductance of the main transformer cause higher voltage to appear across the clamping capacitor and the stress across the main switches will be increased significantly. The transformer leakage inductance therefore should be as small as possible so that the clamping capacitor is as small as possible. This is difference than what is typically suggested for voltage-fed, step-down type converters where some leakage inductance can be beneficial in the operation of the converter.

B. Flyback Snubber

The flyback converter is used to transfer the energy that stored in the clamping capacitor to the high side voltage of the converter. This snubber circuit prevents the voltage across the main switches from exceeding their voltage ratings. In general, the flyback switch S_c is turned on when on of the main switches is turned off in order to clamp the voltage across the main switch and eliminate the high spike voltage across it.

The flyback converter power rating can be determined by

$$P_f = \frac{1}{2}C_c\left(V_{cmax}^2 - V_{cmin}^2\right)f_{sf} \tag{9}$$

where V_{cmax} and v_{cmin} are maximum and minimum voltages across C_c respectively and f_{sf} is the switching frequency of the flyback converter. Although, higher capacitor causes less voltage stress across the main switches, the rating and the size of the flyback snubber circuit will increase significantly. Capacitor C_c should be as small as possible yet satisfy (9) and minimize voltage spikes.

C. Duty cycle and Transformer Turns Ratio of the main transformer

The duty cycle and the main transformer's turns ratio play significant roles on the voltage gain of the proposed converter and the stress on the converter's components. If the leakage inductance of the transformer is neglected, then the voltage gain of the proposed converter when operating in boost mode of operation can be expressed as

$$\frac{V_{Hs}}{V_{Ls}} = \frac{n}{1-D} \tag{10}$$

Although higher duty cycle means higher gain, more stress will be applied on the component of the converter. however, lower duty cycle causes lower stress, it results in higher transformer's turns ratio, which increase the primary current and results more conduction losses. In addition, the turns ratio should be chosen to minimize the voltage across the clamping capacitor, i.e. the voltage stress across the main switches.

It should be noted that the duty cycle range when the converter is operating in step-up mode should be limited to be in the range of $0.33 < D < 0.66$. If D is decreased from 0.33, then more current will flows through capacitor C_c and the current rating of this capacitor will increase. Operating the converter with $D < 0.33$ should be done only when the converter is operating under light load conditions. If $D < 0.66$, then the actual voltage gain of the main transformer section will not increase, but will decrease instead. As D is increased from 0.66, there will be less opportunity for power to be transferred through the transformer and the voltage across C_c will increase so that the flyback converter will have to be operated more often and/or for a longer amount of time to discharge C_c.

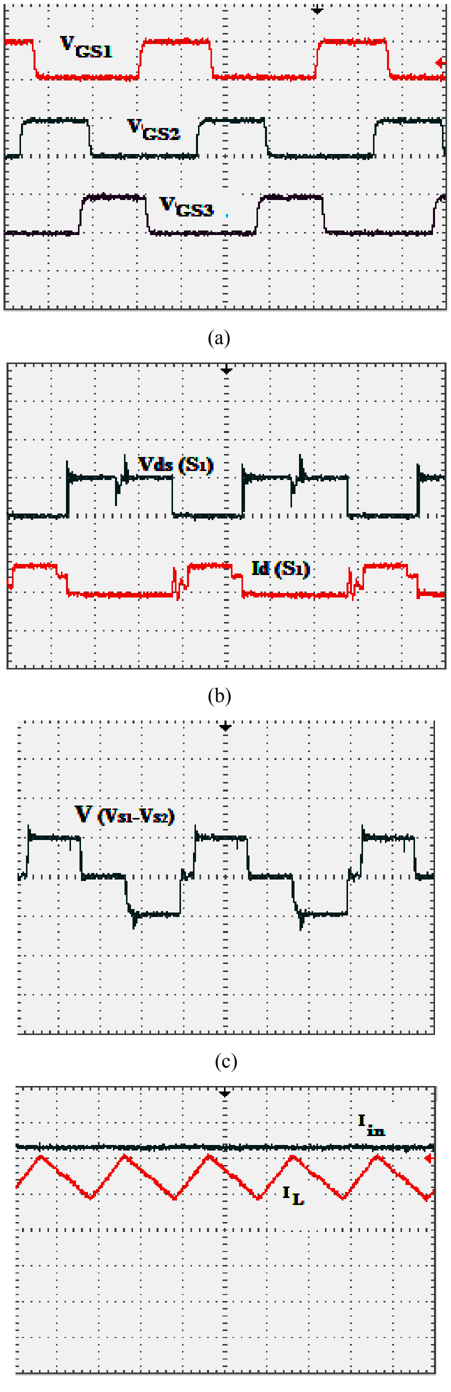
In the buck mode of operation, the voltage gain can be expressed as

$$\frac{V_{Ls}}{V_{Hs}} = \frac{D}{n} \tag{11}$$

Higher duty cycle results in higher voltage gain, but with more voltage stress applied across the converter's components in the high side of the converter. If a higher turns ratio is used, duty cycle can be reduced and thus there will be less voltage stress across the components, but more circulating current will be produced in the converter, resulting in more conduction losses and turn-off losses. When selecting a turns ratio for the main transformer, step-up and step-down considerations must be both considered so that the end result is a turns ratio that will allow the converter to operate satisfactorily in a bidirectional manner.

V. EXPERIMENTAL RESULTS

A proof-of-concept prototype of the proposed converter was built according to the following specifications: Low side voltage $V_{LS} = 36V$, High side voltage $V_o = 400V$, output power $P_o = 500W$ and switching frequency $f_s = 50$ kHz. Typical waveforms for boost mode of operation are shown in Fig. 6.



(a)

(b)

(c)

(d)

Fig. 6. Boost mode waveforms (a) Gating signal waveforms for Q_1-Q_5 (V:20V/div., t:5µs/div.), (b) Main switch voltage and current (V: 50V/div., I: 20A/div., t: 5µs/div), (c) Primary voltage waveform across the transformer (V: 50V/div., t: 5µs/div), (d) Current through two main inductors (I: 1A/div, t: 5µs/div.), (d) Input current and current through an input inductor (I_{in}: 5A/div., I_L: 1A/div, t: 10µs/div.)

Fig. 6(a) shows the gating signals of the converter's main switches V_{Gs1}, V_{Gs2} and V_{Gs3}. It can be seen that the three signals are the same except that they are phase-shifted by 120° with respect to each other. Voltage and current waveforms for one of the main switches, S_1, are shown in Fig. 6(b). It can be seen that the current through the switch is generally flat but there is some difference in current level during some of the time when the switch is on. The change in current level, either an oscillation at the left edge of the waveform or a step down at the right edge of the waveform, is caused by the turning on and off of main switches. The same is true of the voltage signal, which may have a small spike caused by the turning on or off of other main switches due to noise.

Fig. 6(c) shows a voltage across one of the three-phase transformer primaries. It can be seen that it 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 main switches. Fig. 6(d) shows the current flowing through one of the input inductors and the input current I_{in} flowing out of the DC source. It can be seen that the inductor current has some ripple and the input current has little if any. This is because the converter's input section is essentially three interleaved boost converters that are phase-shifted 120^{o} with respect to each other

Fig. 7 shows typical converter waveforms of the proposed converter working in buck mode of operation. Fig. 7(a) shows typical switch voltage and current waveforms of a high-side switch and Fig. 7(b) shows a typical transformer phase voltage waveform. It can be seen that the converter operates like a standard voltage-fed PWM converter with its switches operating with zero-voltage switching (ZVS) and the transformer voltage being a typical square waveform.

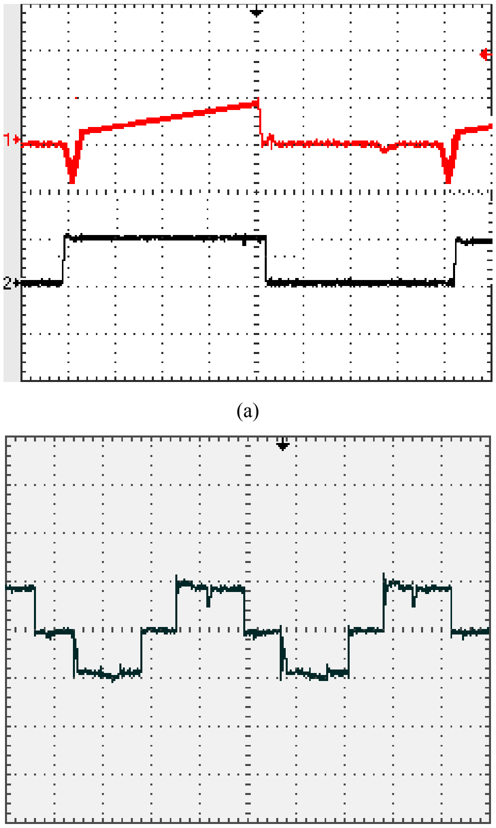
VI. CONCLUSION

A new three-phase bidirectional DC-DC converter that can be used in UPS applications is proposed in the paper. The outstanding features of the converter are that its low voltage side converter uses just four switches, it has a clamping snubber circuit that makes provides a path for current to flow through if the low-side switches misfire in the case of exposure to the lightning electromagnetic pulses, a simple clamping circuit, which is part of a non-dissipative snubber, and an interleaved interface to the UPS battery/ battery bank, thus reducing ripple.

In this paper, the proposed converter is introduced, its operation is explained, and guidelines for the design of key elements are given. The feasibility of the converter is confirmed with results obtained from a prototype converter.

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.



(a)

(b)

Fig. 7. Buck mode waveforms (a) current and voltage for switch Q_1 (I: 2A/div, V:400V/div, t:2.5µs /div), (b) high side voltage waveform across the transformer (V:400V/div, t::5µs/div)

REFERENCES

[1] M. Jain, P. K. Jain and M. Daniele, "Analysis of a bi-directional DC-DC converter topology for low power application " in IEEE CCECE, 1997,pp. 548-551.

[2] R. Morrison and M. G. Egan, "A new power-factor corrected single-transformer UPS design", in IEEE Trans. on Industry Applications, Volume: 36, no. 1, Jan.-Feb. 2000.

[3] M. Jain, M. Daniele and P. K. Jain,"A Bi-Directional DC-DC Converter Topology for Low Power application," in IEEE trans. On Power Electronics, vol. 15, no. 4, pp. 595-606, July 2000.

[4] N. Vgzquez, C. Aguilar. J. Aratt, R. o. Caccrcs, I. Barbi, and J. A. Gallegos, "A Novel Uninterruptible Power Supply System With Active Power Factor Correction," in IEEE Trans. on Power Electronics, Vol. 17, No. 3, pp. 405-412. May 2002.

[5] R. P. T-Bascopr, D. S. Oliveira, C. G. C. Branco, F. L. M. Antunes and C. M cruz, " A high frequency tranformer isolation 110V/220V input voltge UPS sytem," in IEEE Applied Power Electronics, 2006, pp. 362-368.

[6] M. Aamir and H-J. Kim,"Non-isolated single phase uninterruptible power supply (UPS) system," in IEE ECCE, 2011, pp. 2282-2289.

[7] M. F. Apolinário, R. P. T-Bascopé and Sérgio Daher," A 110V/220V grid voltage on line UPS based on high frequency isolated four-port circuit," in IEEE COBEP/SPEC, 2015, pp. 1-6.

[8] A. R. Prasad, P. D. Ziogas and S. Manias, "Analysis and design of a three-phase offline DC-DC converter with high frequency isolation," in Proc. IAS, pp. 813- 820. 1988.

[9] 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 Trans. on Industry Applications, vol. 27, no. 1, pp. 63-73, Jan./Feb. 1991.

[10] 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 Trans. on Ind. Appl., vol. 28, no. 4, pp. 824-832, July / Aug. 1992.

[11] 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.

[12] 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

hybridge rectifier," in IEEE Trans. on power elec., vol. 20, no. 2, pp. 354-360, Mar. 2005.

[13] 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 Elec., vol. 21, no. 5, pp. 1292-1300, Sep. 2006.

[14] 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 Ind. Elec., vol. 55, no. 1, pp. 173-183, Jan. 2008.

[15] M. Mohr and F. -W. Fuchs, "Voltage fed and current Fed full bridge converter for the use in three phase grid connected fuel cell systems," in CES/IEEE Power Elec. and Motion Contr. Conf., 2006, pp. 1-7.

[16] H. Cha, and P. Enjeti, "A novel three-phase high power current-fed dc/dc converter with active clamp for fuel cells," in Power Electronics Specialists, 2007, pp. 2485–2489.

[17] H. Cha, J. Choi, and B. Han, "A New Three-Phase Interleaved Isolated Boost Converter with Active Clamp for Fuel Cells", in IEEE Power Electronics Specialists, 2008, pp. 1271-1276.

[18] 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 Elec., vol. 23, no. 6, pp. 2784-2793, Nov. 2008.

[19] H. Cha, J. Choi, W. Kim, V. Blasko; " A new Bi-directional three-phase interleaved isolated converter with active clamp," in IEEE APEC, 2009. pp. 1766-1772.

[20] 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 Elec., vol. 25, no.8, pp. 2115-2123, Aug. 2010.

[21] 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 Elec., vol. 31, no. 1, pp . 81-88, Jan. 2016.