A Three-Phase Zero-Voltage and Zero-Current Switching DC–DC Converter for Fuel Cell Applications

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Abstract—In spite of having many advantages, such as low switch voltage and easy implementation, the voltage-fed dc-dc converter has been suffering from problems associated with large transformer leakage inductance due to high transformer turn ratio when it is applied to low-voltage, high-current step-up application such as fuel cells. This paper proposes a new three-phase voltagefed dc-dc converter, which is suitable for low-voltage, high-current applications. The transformer turn ratio is reduced to half owing to Δ -Y connection. The zero-voltage and zero-current switching (ZVZCS) for all switches are achieved over wide load range without affecting effective duty cycle. A clamp circuit not only clamps the surge voltage but also reduces the circulation current flowing in the high-current side, resulting in significantly reduced conduction losses. The duty cycle loss can also be compensated by operation of the clamp switch. Experimental waveforms from a 1.5 kW prototype are provided.

Index Terms—Fuel cells, high power dc–dc converter, three-phase dc–dc converter, ZVZCS.

I. INTRODUCTION

S INCE a dc voltage generated from fuel cells is usually low and unregulated, it should be boosted and regulated by a dc–dc converter and converted to an ac voltage by a dc– ac inverter. High-frequency transformers are usually involved in the dc–dc converter for boost as well as galvanic isolation and safety purpose. The single-phase dc–dc converter based on the push–pull [2] or full-bridge [3]–[7] topology has been used as an isolated boost dc–dc converter for less than several kilowatt power levels. For higher power level, the single-phase converter could suffer from severe current stresses of the power components.

The three-phase dc-dc converter has been proposed [8]-[12] as an alternative for high-power application. The three-phase dc-dc converter has several advantages over the single-phase dc-dc converter: (1) easy MOSFETs selection due to reduced current rating; (2) reduction of the input and output

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filters' volume due to increased effective switching frequency by a factor of three compared to single-phase dc-dc converter; and (3) reduction in transformer size due to better transformer utilization. The three-phase isolated boost dc-dc converter can be classified to dual active bridge (DAB) converters [8], currentfed converters [10], [11], and voltage-fed converters [12].

The DAB can achieve ZVS on both high- and low-side switches and has no inductors involved in the power circuit. However, the DAB has many active switches and high ripple currents. Also, the VA rating of the transformer is comparably large, and manufacturing of the high-frequency transformer with large leakage inductance is a challenging issue.

The current-fed converter, in general, exhibits lower transformer turns ratio, smaller input current ripple, lower switch current rating, and lower diode voltage rating. However, higher switch voltage rating of the current-fed converter implying larger R_{ds(ON)} of MOSFET switches is a major disadvantage since switch conduction loss at the primary side is actually a dominant factor in determining overall efficiency of the dcdc converter for low-voltage high-current application such as fuel cells. A clamping or snubber circuit is usually required for the current-fed converter to limit the transient voltage caused by transformer leakage inductance. The current-fed converter is also lack of self-starting capability and, therefore, it necessitates an additional start-up circuitry. The three-phase current-fed dcdc converter proposed for step-up applications [10] has only three active switches, but the active switches are hard switched and the passive clamping circuit on the high-current side may cause large amount of losses. The three-phase current-fed dc-dc converter with an active clamping circuit [11] not only clamps the surge voltage but also offers ZVS on the active switches. However, this scheme suffers from the high ripple current imposed on the clamp capacitor located at the high-current side.

The voltage-fed dc–dc converter has also been used in fuel cell applications. An important advantage of the voltage-fed type is *lower* switch voltage rating since the switch voltage is fixed to input voltage, and therefore MOSFETs with lower $R_{ds(ON)}$ can be selected. This is critically beneficial in the fuel cell application where more than 50% of the power loss is lost as a switch conduction loss at the low-voltage side. Also, the voltage-fed converter does not have a self-start problem unlike the current-fed converter. However, the voltage-fed converter suffers from a high transformer turns ratio, which causes large leakage inductance resulting in large duty cycle loss, increased switch current rating, and increased surge voltage on the rectifier diode. The three-phase voltage-fed dc–dc converter, so-called

Fig. 1. Proposed three-phase dc-dc converter.

V6 converter, proposed for step-up applications, [12] significantly mitigates the problem associated with high transformer turn ratio of the voltage-fed type by utilizing the open Δ -Y type transformer connection, which reduces the required turn ratio to half. Also, the size of the input filter capacitor to reduce the input current ripple is reduced, since the effective switching frequency is increased by three times due to the interleaved operation.

In this paper, a three-phase voltage-fed dc–dc converter for isolated boost application such as fuel cells is proposed. The turn ratio of the high-frequency transformer is reduced to half by employing the Δ -Y connection. A clamp circuit that is located at low-current, high-voltage side not only clamps the surge voltage but significantly reduces the circulating current flowing through high-current side, resulting in reduced switch conduction losses and transformer copper losses. Further, with the help of the clamp circuit zero-voltage and zero-current switching (ZVZCS) for all switches over wide load range is achieved. The duty cycle loss can also be compensated by the clamp switch. The operating principles and features of the proposed converter are illustrated and experimental results on a 1.5 kW prototype are also provided to validate the proposed concept.

II. OPERATING PRINCIPLES

As shown in Fig. 1, the proposed three-phase voltage-fed dc– dc converter includes six MOSFET switches at low-voltage side and a three-phase diode bridge, an *LC* filter, and a clamp circuit consisting of a MOSFET switch and a capacitor at high-voltage side. The three-phase transformer could be configured in Y-Y, Δ - Δ , Δ -Y, or Y- Δ as shown in Table I. Among them, the Δ -Y configuration is shown to be the best choice in two aspects.

First, the Δ -Y transformer requires the smallest turn ratio for step-up application, and in fact the required turn ratio is half that of Y-Y or Δ - Δ transformers [12]. The reduction of turn ratio significantly mitigates problems associated with large leakage inductance, which are large duty cycle loss, increased switch current rating, and surge voltage on the rectifier diode. This is a big advantage of the three-phase dc-dc converter over the single-phase dc-dc converter based on the push-pull or fullbridge type and makes the voltage-fed dc-dc converter viable for high gain step-up application. Second, the Δ -Y configuration is also shown to have the smallest transformer kVA rating and switch current rating. The transformer winding voltage and current waveforms of each transformer configuration are shown in Table I for a specific gating signal. In Δ -Y transformer configuration, three switches conduct at one time while in Y-Y or Δ - Δ transformer configurations only two switches conduct. This reduces the transformer winding voltage and current and in turn reduces the switch and diode current. The kVA rating of the Δ -Y transformer is 81.6% and 86.7% of those of Δ - Δ and Y-Y transformers, respectively. The rms switch and diode currents of the Δ -Y configuration are 69.3% of those of the Δ - Δ and Y-Y configurations. Therefore, the Δ -Y configuration should be a topology of choice for the step-up application.

Fig. 2 shows key waveforms of the proposed converter for illustration of operating principle. Upper and lower switches of each leg are operated with asymmetrical complementary switching to regulate the output voltage. Three legs at the low-voltage side are interleaved with 120° phase shift, which results in increased effective switching frequency.

The converter has seven operating states within each operating cycle per phase, and equivalent circuits of each state are shown in Fig. 3. It is assumed that the output filter inductance is large enough so that it can be treated as a constant current source during a switching period. It is also assumed that the clamp capacitance is large enough so that there is no ripple on the clamp voltage during a switching period.

- State 1 $[t_1 t_2]$: S_1, S_2 , and S_6 are conducting, and lower switches S_2 and S_6 are carrying half of upper switch S_1 current since two transformer primary currents become equal due to the current flow at the secondary. Since voltage across transformer leakage inductor V_{lk1} is a small negative value, which is a difference between the input voltage and half of the clamp capacitor voltage referred to the primary, transformer primary current I_{p1} is slowly decreasing. The transformer secondary winding current is also decreasing but larger than load current I_o during this mode. Therefore, clamp capacitor C_c is being charged through the body diode of S_c by the decreasing current.
- State 2 $[t_2 t_3]$: When clamp current I_{Sc} decreases to zero, the clamp branch is completely disconnected from the circuit. The input power is still being delivered to the output. Diodes D_1 and D_2 carry load current I_0 through the transformer secondary windings. The voltages across the leakage inductors V_{lk1} is zero.
- State 3 $[t_3 t_4]$: S_1 is turned off at t_3 . External capacitor C_{ext} across S_1 is charged and parasitic capacitor C_{oss} of S_4 is discharged by reflected load current to the primary $2nI_0$. Switch voltage V_{S1} increases linearly with a slope of $2nI_0/(C_{\text{ext}} + 2C_{\text{oss}})$. The upper switch is almost turned off with ZVS if external capacitor C_{ext} is chosen large enough to hold the switch voltage at near zero at the switching instant. At the end of this mode, the body diode of S_4 is turned on.
- State 4 $[t_4 t_5]$: Lower switch S_4 is turned on with ZVS since V_{S4} became already zero at State 3. Turning on of the clamp switch at t_4 causes the rectifier voltage referred to the primary to be applied to the leakage inductor resulting in rapid decrease of the transformer primary current to zero, and this causes the clamp capacitor to discharge to supply the load. This reset operation eliminates the circulating current through



	Y - Y	Δ - Δ	Δ - Υ	Υ - Δ
Circuit				
Primary Winding Voltage	$ \begin{array}{c c} & 2 \\ \hline & 7 \\ \hline & V_{in}/3 \\ \hline & T \\ \hline \end{array} $	$ \begin{array}{c c} & & & \\ &$	$ \begin{array}{c c} & & & \\ &$	$ \begin{array}{c c} & 2 \\ \hline & 7 \\ \hline & V_{in}/3 \\ \hline & T \\ \hline \end{array} $
Secondary Winding Current		$ \begin{array}{c c} & & & \\ &$	$ \begin{array}{c c} & & & \\ & & & \\ \hline & & & \\ \hline & & & \\ 0 \leftarrow & & \\ DT \end{array} \xrightarrow{DT} & & \\ \hline & & & \\ 0 \leftarrow & & \\ DT \end{array} \xrightarrow{DT} & \\ \hline \end{array} $	$ \begin{array}{c c} & 2 \\ \hline & 1_{0}/3 \\ \hline & 1_{0}/3 \\ \hline \end{array} $
kVA Rating	$0.384 \cdot V_{in} \cdot I_o \cdot n$	$0.408 \cdot V_{in} \cdot I_o \cdot n$	$0.333 \cdot V_{in} \cdot I_o \cdot n$	$0.333 \cdot V_{in} \cdot I_o \cdot n$
Switch Current Rating	Upper: $0.577 \cdot I_o \cdot n$	Lower: $0.577 \cdot I_o \cdot n$	Upper : $0.577 \cdot I_o \cdot n$	Lower: $0.4 \cdot I_o \cdot n$

 TABLE I

 COMPONENT RATING ACCORDING TO VARIOUS TRANSFORMER CONNECTIONS

the transformer and switches, resulting in significantly reduced conduction losses. Note that the clamp is turned on with ZVS.

- State 5 $[t_5 t_6]$: At t_5 , the main switch current, transformer winding current, and diode current become zero, and the clamp capacitor fully supplies the load.
- State 6 $[t_6 t_7]$: Clamp switch S_c is turned off at t_6 , and the load current freewheels through all the diodes. The clamp switch can also be turned off with ZVS if capacitance across the clamp switch is properly chosen. The gate signal for lower switch S_6 is removed during this mode, and S_6 is turned off with ZCS.
- State 7 $[t_7 t_8]$: Upper switch S_3 is turned on at t_7 and S_2 , S_3 , and S_4 start conducting. Note that S_3 is turned on with ZCS since S_3 current linearly increases with a slope of V_{in}/L_{k1} . This causes commutation of diode currents, that is, increase of diode currents I_{D3} and I_{D4} and decrease of other diode currents. At the end of the commutation, the rectifier voltage is clamped by V_c through the body diode of S_c . This is the end of one-third of the cycle. The second part of the cycle is repeated in the same fashion.

III. FEATURES OF THE PROPOSED CONVERTER

In a low-voltage, high-current application such as fuel cells, conduction loss at high-current side of the converter is a dominant loss factor. Generally, in the phase-shifted full-bridge converter conduction losses associated with the circulating current generated during the nonpowering mode are of great concern. In the proposed converter, the conduction loss is significantly reduced due to the reset operation mentioned in State 4. That is, the energy stored in the leakage inductance located at highcurrent primary side, which is the circulating current through the transformer winding and lower switch, is transferred to the clamp capacitor located at the low-current secondary side resulting in significantly reduced total conduction losses and kVA rating of the transformer (see the shaded area in Fig. 2).

In the phase-shifted, full-bridge converter ZVS can inherently be achieved using transformer leakage inductance. However, in order to achieve ZVS over wide load range, the leakage inductance should be increased. In the proposed three-phase converter, the ZVZCS operation can be achieved over wide load range for all switches (ZVS turn on and ZCS turn off for lower switches and ZCS turn on and ZVS turn off for upper switches) *without* increasing leakage inductance.

In order to achieve the ZVZCS operation, appropriate dead times are required for both upper and lower switches. In the ZVZCS full-bridge converter [7], dead times required for both leading and lagging leg switches actually *limit* effective duty cycle, which may cause increased conduction losses. The effect of the duty limit on efficiency is considerable especially in the low-voltage high-current application such as fuel cells. However, in the proposed three-phase converter required dead times do not affect the effective duty cycle of upper switch by which energy is delivered to the load. That is, required dead times do not impose duty cycle limit on operating range of the duty cycle.

In order to achieve ZVS turn-ON of a lower switch, the lower switch should completely be discharged before the lower switch turns on. Therefore, the required dead time for lower switches is determined by

$$t_{\rm dead,L} \ge (2C_{\rm oss} + C_1) \frac{V_{\rm in}}{2nI_{\rm o,ZVS}} \tag{1}$$

where $I_{o,ZVS}$ is a minimum load current to which ZVS turn-OFF can be achieved from the full load. Since there is no duty limit, the proposed converter can achieve ZVS turn-OFF over *wider* load range compared to the ZVZCS full-bridge converter [7].

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Fig. 2. Key waveforms of the proposed converter ($V_c > 2nV_{in}$).

In order to achieve ZCS turn-OFF of a lower switch, the primary circulating current should completely be reset before the upper switch turns on. Therefore, the required dead time for upper switches is determined by

$$t_{\rm dead,U} \ge L_{\rm k} \frac{4n^2 I_{\rm o}}{V_{\rm c}}.$$
 (2)

ZCS turn-OFF range of the ZVZCS full-bridge converter [7] is actually *restricted* by the maximum duty cycle since the required dead time of lagging leg switches is considerable in this lowvoltage, high-current application. However, ZCS turn-OFF of the



Fig. 3. Operation states ($V_{\rm c} > 2nV_{\rm in}$).



Fig. 4. Effect of clamp duty cycle on various waveforms.

proposed converter can be achieved over whole load range since the dead time for upper switches does *not* affect the effective duty cycle.

Neglecting the transformer leakage inductance, the voltage– second balance on the output filter inductor L_f gives

$$(V_{\rm c} - V_{\rm o})(D + D_{\rm c})T = V_{\rm o}\left(\frac{1}{3} - (D + D_{\rm c})\right)T.$$
 (3)

This leads to

$$V_{\rm o} = 3V_{\rm c}(D+D_{\rm c}).$$
 (4)

Since the leakage inductance is neglected, the voltage across the clamp capacitor becomes

$$V_{\rm c} = 2nV_{\rm in}.\tag{5}$$

Then, from (4) and (5), the voltage transfer ratio can be obtained by

$$\frac{V_{\rm o}}{V_{\rm in}} = 6n(D+D_{\rm c}) \tag{6}$$

where D is duty cycle of the main switch and D_c is duty cycle of the clamp switch. The voltage-fed converter for step-up application such as fuel cells, in general, has larger transformer leakage inductance due to higher turn ratio, which causes a relatively large duty cycle loss. In the proposed converter, the duty cycle loss can be compensated by operation of the clamp switch in a way that rectifier voltage V_R would maintain high during turn-ON period of the clamp switch. The output voltage compensated for duty loss D_L is as follows:

$$V_{\rm o} = 3V_{\rm c}(D + D_{\rm c} - D_{\rm L}).$$
 (7)

As shown in Fig. 4, there are two modes of operation depending on the clamp voltage, which is an important design parameter: $V_c > 2nV_{in}$ and $V_c < 2nV_{in}$. The magnitude of the primary current is determined by voltage across the leakage inductor $V_{in} - V_c/(2n)$. Clamp capacitor voltage V_c , which is determined by D_c , affects voltage ratings of the clamp switch and capacitor and current ratings of the converter. Making D_c large decreases clamp voltage V_c (and therefore decreases the

TABLE II Design Example of the Proposed Converter

Parts	Design items	Rating	Components	
Switch	V_{pk} , I_{rms}	35V, 48A	IRFP4410Z (Two in parallel)	
Diode	V_{pk} , I_{rms}	600V, 2.6A	IDP4E120G	
Auxiliary Switch	V_{pk} , I_{rms}	600V, 2A	IXFH14N80	
Auxiliary Capacitor	Cc	10uF	Film 3.9uF (Three in parallel)	
Transformer	Number of Turns	2:16	El Ferrite	
Transformer	Total kVA	1.7kVA		
Output	Lf	120 uH	CM270125(MPP)	
Filter	Co	400 uF	Electrolyte (Two in series)	

voltage rating of the clamp switch and capacitor) but increases current ratings resulting in increased conduction losses. On the other hand, making D_c small increases clamp voltage V_c resulting in increased switching losses associated with the clamp switch. Tradeoff of switching losses associated with the clamp circuit and conduction losses at high-current primary side should be considered.

The switching loss of the clamp switch could be of concern since the clamp switch is operated with three times the switching frequency of the main switch and located at the high-voltage side in this step-up application. In the proposed converter, the clamp switch is inherently turned on with ZVS over whole load range. The turn-OFF loss can also be eliminated by adding an external capacitor across the clamp switch. Therefore, in this low-voltage high-current application where conduction losses are dominant, the duty cycle D_c is kept small as long as both required dead time t_{dead-U} for complete reset of the circulating current and the predetermined duty boost compensation are fulfilled so that the conduction losses are minimized. The clamp duty cycle D_c can be obtained within the range determined by

$$\frac{2n^2 L_{\rm k} I_{\rm o}}{V_{\rm c} T} \leq D_{\rm c} \leq \frac{1}{3} - D.$$
 (8)

IV. EXPERIMENTAL RESULTS

A 1.5 kW prototype of the proposed converter has been built and tested to verify the operating principle and the experimental results are provided. The system specification used in the experiment is as follows:

• $P_{\rm o} = 1.5 \text{ kW}$ • $V_{\rm in} = 22 \sim 35 \text{ V}$ • $V_{\rm o} = 400 \text{ V}$ • $\Delta I_{\rm in} = 10\%$ • $V_{\rm o} = 3\%$ • $f_{\rm s} = 50 \text{ kHz}$.

The component ratings of the proposed converter according to the given specification are calculated, and Table II lists actual devices from manufactures that are selected with appropriate



Fig. 5. Experimental waveform of the primary current.



Fig. 6. Experimental waveforms of the main switch. (a) Lower switch. (b) Upper switch.

safety margin. The Δ -Y transformer has been constructed with three single-phase transformers. The measured leakage inductance is 2 μ H, and the turns ratio of the high-frequency transformer is 1:8, which is only half of the conventional voltage-fed converter. The total kVA rating of the proposed converter is shown to be low owing to the reset operation of the circulating current.

Experimental waveforms obtained at $P_{\rm o} = 1.5$ kW and $V_{\rm in} = 24$ V (nominal duty cycle of 0.308) are shown in Figs. 5–10.

Fig. 5 shows the primary current, which is reset by turn-ON of the clamp switch. Therefore, conduction losses associated with the circulating current through the transformer and switches could be removed.

The waveforms of the main switch are shown in Fig. 6. As shown in Fig. 6(a), the lower switch S_4 is turned on with ZVS and turned off with ZCS. It is noted that ZCS is achieved by the reset operation of the clamp switch. Upper switch S_1 is turned on with ZCS and turned off with ZVS, as shown in Fig. 6(b). ZCS turn-ON is achieved by linearly increasing current with a slope of V_{in}/L_{k1} .



Fig. 7. Experimental waveforms of the clamp switch.



Fig. 8. Experimental waveforms showing the duty boost effect.

ZVS turn-OFF is also achieved by adding small capacitance of 5 nF across the upper switch. Fig. 7 shows the clamp switch voltage and current. The clamp switch is inherently turned on with ZVS.

Turn-OFF process is almost ZVS due to the external capacitor added to the clamp switch. Fig. 8 shows the duty boost effect achieved by the clamp switch. Rectifier voltage V_R is maintained high during the turn-ON period of the clamp switch. It is also seen from the waveform of V_R that surge voltage caused by the reverse recovery characteristic and the ringing phenomenon is nearly eliminated by the clamp circuit. The effect of the proposed active clamping is clearly shown by comparing the waveforms with (the proposed converter) and without (the conventional converter [9]) the clamp circuit, as shown in Figs. 9 and 10. The diode voltage waveforms with and without the clamp circuit are shown in Fig. 9(a) and (b), respectively. It is clearly seen that in the proposed converter the surge voltage due to the reverse recovery current and the ringing phenomenon are significantly reduced by the clamp circuit. Fig. 10(a) and (b) shows the transformer primary current with and without the clamp circuit, respectively. It is also seen that the primary current of the proposed converter is considerably reduced by the reset operation of the clamp switch.

The measured efficiency is shown in Fig. 11. The maximum efficiency of 95.5% was measured at 700 W load. The efficiency decreased sharply as the load increases over 700 W. A large portion of the power losses at medium to heavy load was generated from the parasitic resistance in the PCB pattern and the junction resistance between the PCB and the passive components such as transformers and inductors.



Fig. 9. Experimental waveforms of the diode voltage. (a) With the clamp switch (the proposed converter). (b) Without the clamp switch [9].



Fig. 10. Experimental waveforms of the transformer primary current. (a) With the clamp switch (the proposed converter). (b) Without the clamp switch [9].



Fig. 11. Measured efficiency.

V. CONCLUSION

In this paper, a new three-phase voltage-fed dc–dc converter for a low-voltage, high-current step-up application has been proposed. The proposed converter has the following advantages:

- 1) The required transformer turn ratio is as low as that of the current-fed converter due to the Δ -Y connection.
- 2) ZVZCS for all switches are achieved over wide load range without affecting effective duty cycle.
- Circulating current through high-current side is removed due to the reset operation, resulting in significantly reduced conduction losses.

4) The duty cycle loss is compensated by the clamp switch.

These advantages make the proposed converter attractive for low-voltage, high-current step-up application such as fuel cell power conditioning systems.

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