A Three-Phase Current-Fed Push-Pull DC-DC Converter with Active Clamp for Fuel Cell Applications

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Abstract - In this paper a new active-clamped three-phase current-fed push-pull DC-DC converter is proposed for high power applications where low voltage high current input sources such as fuel cells are used. The proposed converter has the following features: active clamping of the transient surge voltage caused by transformer leakage inductances, natural ZVS turn-on of main switches using energy stored in transformer leakage inductor, small current rating and ZVZCS of clamp switches, no additional start-up circuitry for soft starting due to the operating duty cycle range between 0 and 1, ZCS turn-off of rectifier diodes leading to negligible voltage surge associated with the diode reverse recovery. Experimental results on a 5kW laboratory prototype are provided to validate the proposed concept.

I. INTRODUCTION

The step-up DC-DC converter with high frequency transformer has increasingly been used in high power applications such as fuel cell systems, photovoltaic systems, hybrid electric vehicles, and UPS where voltage step-up and galvanic isolation are required. The step-up DC-DC converter with high frequency transformer could be either voltage-fed or current-fed type. The advantages and disadvantages of the two types are detailed in [1]. Compared to the voltage-fed topology, the current-fed topology exhibits smaller input current ripple, lower diode voltage rating, lower transformer turns ratio and negligible reverse recovery problem at the rectifier side, in general [2]. Especially, lower transformer turns ratio leads to smaller duty cycle loss and transformer copper losses, which are important for efficient operation at high power levels. Direct and precise control of the input current is also possible with the current-fed topology. Therefore, the current-fed DC-DC converter is better suited to low voltage high current input application such as fuel cells [1].

Three-phase DC-DC converters have presented good performance in the high power applications where high device stresses are faced when implemented with the single-phase DC-DC converter[3-8]. Generally, the three-phase DC-DC converter has several advantages over its single-phase counterpart; easy MOSFETs selection due to reduced current rating, reduction of the input and output filters’ volume due to increased effective switching frequency by a factor of three, reduction in transformer size due to better transformer utilization. The isolated current-fed dc-dc converters can be classified by primary side configuration into three basic topologies; full-bridge[3, 4], L-type half bridge[5, 6, 7], and push-pull [8]. Among them, the current-fed push-pull converter [8] has the simplest structure in its gate drive circuits and power circuits. However, their active switches are hard switched, and the dissipative losses associated with passive clamp circuit for suppressing the voltage spikes caused by leakage inductance of the high frequency transformer are considerable. Therefore, it is not easy to achieve high efficiency and high power density at high power level.

In this paper, an active clamped three-phase current-fed push-pull DC-DC converter is proposed for high power applications where low voltage high current input sources such as fuel cells are used. In addition to the above mentioned advantages of the three-phase and current-fed topologies, the proposed converter has the following features:

- Active clamping of the transient surge voltage caused by transformer leakage inductances
- Natural ZVS turn-on of main switches using energy stored in transformer leakage inductor
- Small current rating and ZVZCS of clamp switches
- No additional start-up circuitry for soft starting due to the operating duty cycle range between 0 and 1
- ZCS turn-off of rectifier diodes leading to negligible voltage surge associated with the diode reverse recovery

II. OPERATING PRINCIPLES

The circuit topology of the proposed converter is basically a three-phase, current-fed, push-pull converter with an active clamp circuit, as shown in Fig. 1. The proposed converter includes an input filter inductor, three main switches $S_{M1}$, $S_{M2}$, and $S_{M3}$, and a clamp circuit consisting of three clamp switches $S_{C1}$, $S_{C2}$, and $S_{C3}$ and a clamp capacitor $C_c$ at the low voltage primary side, and a three-phase diode bridge at the high voltage secondary side. Note that a three-leg core must be used for proper operation of the proposed converter. The three-phase windings are configured in Y-Y connection. The neutral point of the three-phase primary winding is connected to input...
source through the input inductor. The proposed active clamping method not only limits the transient surge voltage caused by transformer leakage inductances, but helps improve the efficiency by enabling soft switching of the main switches.

Output voltage control is achieved by applying the asymmetrical PWM switching to each main and clamp switch pair. The three switch pairs are interleaved with 120° phase shift, which leads to increased effective switching frequency resulting in smaller input current ripple. The duty cycle of each main switch is in the whole range between 0 and 1. The ideal voltage ratio of the proposed converter can be expressed as,

\[ \frac{V_o}{V_i} = \frac{n}{1 - D} \quad (0 < D < 1) \]  

where \( n = N_S/N_P \). Also, the voltage across the clamp capacitor \( C_c \) can be obtained by,

\[ V_C = \frac{1}{1 - D} V_i \]  

In order to simplify the analysis of the steady-state operation several assumptions are made as follows,

- Input inductor \( L_i \) is sufficiently large so that it can be considered as a constant current source.
- Output capacitor \( C_o \) is sufficiently large so that it can be considered as a constant voltage source.
- Dead time between main and clamp switch pair is ignored.
- Magnetizing inductance is assumed to be infinity.
- All leakage inductance values are equal \( (L_{k1} = L_{k2} = L_{k3} = L_{k}) \).

A. Principle of operation

The proposed converter operates under three different regions based on the duty cycle; \( D > 0.66, 0.33 < D < 0.66, \) and \( D < 0.33 \). The number of switches that simultaneously turn on is shown in Table I. The operating modes of the proposed converter are analyzed based on the three regions. In any case total number of switches that simultaneously turn on is three.

![Fig. 1 Proposed three-phase push-pull converter with active clamp](image)

Table I. Operation modes based on duty cycle

<table>
<thead>
<tr>
<th>Duty cycle</th>
<th>No. of main switches simultaneously on</th>
<th>No. of clamp switches simultaneously on</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D &lt; 0.33 )</td>
<td>up to 1</td>
<td>up to 3</td>
</tr>
<tr>
<td>( 0.33 &lt; D &lt; 0.66 )</td>
<td>up to 2</td>
<td>up to 2</td>
</tr>
<tr>
<td>( D &gt; 0.66 )</td>
<td>up to 3</td>
<td>up to 1</td>
</tr>
</tbody>
</table>

1) Operation in \( D > 0.66 \)

Fig. 2 shows key waveforms of the proposed converter in the case of \( D > 0.66 \). The converter has five operating modes within each operating cycle per phase, and the equivalent circuits of the five operating modes are shown in Fig. 3.

Mode I \([t_0, t_1]\): At time \( t_0 \), all the diode currents become zero, and therefore the winding voltages become zero. Each of the primary winding current becomes identical.

\[ i_{pri1} = i_{pri2} = i_{pri3} = \frac{1}{3} I_i \]  

The output capacitor supplies the load during this mode.

Mode II \([t_1, t_2]\): At time \( t_1 \), main switch \( S_{M2} \) is turned off and current \( i_{pri2} \) is commutated to body diode of clamp switch \( S_{C2} \). This causes current \( i_{pri2} \) to decrease and currents \( i_{pri1} \) and \( i_{pri3} \) to increase, leading to conducting of upper diode \( D_{U2} \) and lower diodes \( D_{L1} \) and \( D_{L3} \), respectively, at the secondary. The voltages of the windings become,

\[ V_{pri2} = \frac{1}{n} V_{sec2} = \frac{1}{n} \frac{2}{3} V_o \]  

Then, the voltages across \( L_{k2} \) can then be obtained by,

\[ V_{Lk,n} = \frac{2}{3} \left( V_C - \frac{V_o}{n} \right) \]  

The current \( i_{pri2} \) is decreasing with the slope determined by \( V_{Lk,n}/L_k \). It is seen that clamp switch \( S_{C2} \) is turned on with ZVS when the gate signal for \( S_{C2} \) is applied during this mode.

Mode III \([t_2, t_3]\): The current \( i_{pri2} \) reverses its direction of flow at \( t_2 \) and increases its magnitude while current \( i_{pri1} \) and \( i_{pri3} \) keep increasing linearly. Since the average current through each clamp switch is zero, \( i_{pri2(t3)} \) is the magnitude of the current \( i_{pri2} \) at the end of Mode III can be obtained by,

\[ I_{pri2(t3)} = -\frac{1}{3} I_i \]  

Then, current magnitudes \( i_{pri2(t3)} \) and \( i_{pri3(t3)} \) at \( t_3 \) can be obtained by,

\[ i_{pri3(t3)} = I_{pri3(t3)} = \frac{2}{3} I_i \]  

Mode IV \([t_3, t_4]\): At time \( t_3 \) clamp switch \( S_{C2} \) is turned off, and current \( i_{pri2} \) is commutated to body diode of main switch \( S_{M2} \). This causes all primary currents \( i_{pri1}, i_{pri2}, \) and \( i_{pri3} \) to decrease. The voltages across \( L_{k2} \) can then be obtained by,
\[ V_{lk,p} = \frac{2V_o}{3n} \]  

The decreasing rate of current \( i_{pri2} \) is determined by \( V_{lk,p}/L_k \). It should be noted that main switch \( S_{M2} \) can be turned on with ZVS at this mode.

Mode \( V \left[ t_4, t_5 \right] \): The current \( i_{pri2} \) reverses its direction of flow at time \( t_4 \) and increases its magnitude while currents \( i_{pri1} \) and \( i_{pri3} \) keep decreasing linearly until each of the primary winding current becomes identical, as shown in equation (1). It is also noted that the rectifier diodes \( D_{U2}, D_{L1}, \) and \( D_{L3} \) are turned off with ZCS. This is the end of one third of the cycle. The other parts of the cycle are repeated in the same fashion.

2) Operation in \( 0.33 < D < 0.66 \)

Fig. 4 shows key waveforms of the proposed converter in the case of \( 0.33 < D < 0.66 \). The converter has four operating modes within each operating cycle per phase, and their equivalent circuits are shown in Fig. 5. At Modes I and IV two main switches and one clamp switch are conducting together while at Modes II and III one main switch and two clamp switches are conducting together.

3) Operation in \( D < 0.33 \)

Fig. 6 shows key waveforms of the proposed converter in the case of \( D < 0.33 \). The converter has five operating modes within each operating cycle per phase, and their equivalent circuits are shown in Fig. 7.

At Mode I all the main switches are being turned off, and all the clamp switches are conducting. At time \( t_1 \) clamp switch \( S_{C2} \) is turned off, and the current that was flowing through main channel of \( S_{C2} \) is commutated to its body diode as we can see in Mode II. When the gating signal is applied to main switch \( S_{M2} \) the current that was flowing through body diode of \( S_{C2} \) is commutated to main channel of main switch \( S_{M2} \), resulting in...
Fig. 4 Key waveforms of the proposed converter ($0.33 < D < 0.66$)

Fig. 5 Operation states of the proposed converter ($0.33 < D < 0.66$)

hard switching of main switch $S_{M2}$. Instead, clamp switch $S_{C2}$ is turned off with ZCS.

Owing to the operation of clamp switches, the proposed converter can be operated with duty cycle less than 0.33, and therefore, no additional start-up circuit is required. In addition, this could improve dynamic characteristics of the closed-loop control system. Table II summarizes the soft switching condition for the proposed converter.

B. Voltage conversion ratio

The actual voltage conversion ratio of the proposed converter is derived in $D > 0.66$ case, considering the effect of voltage drop across the leakage inductor of the transformer.

Applying the voltage-second balance principle to leakage inductor $L_{k2}$ from Mode I to Mode V, the following equation can be obtained (See waveforms of $v_{Lk2}$ and $i_{pr12}$ in Fig. 2),

$$V_{Lk,n} \cdot (1-D) \cdot T = V_{Lk,p} \cdot D \cdot T$$

From the waveforms of $v_{Lk2}$ and $i_{pr12}$, it can be seen,

$$\frac{V_{Lk,p}}{I_k} = \frac{1}{D \cdot T} \left( \frac{1}{3} I_{1} - I_{pr12 (t3)} \right)$$

Using equations (2), (5), (6), (8), (9) and (10), the voltage conversion ratio in $D > 0.66$ case can be obtained by,

$$V_o = \eta \left( \frac{V_i \cdot P_o \cdot f_i}{(1-D) \cdot V_i \cdot (1-D) \cdot \eta} \right)$$

where $\eta$ is the converter efficiency, and $P_o \cdot f_i = P_i$. In the similar way, the voltage conversion ratios in $0.33 < D < 0.66$ and $D < 0.33$ cases can be obtained by, respectively,
From equations (11) to (13), the actual voltage conversion ratio of the proposed converter is plotted in Fig. 8 as a function of duty ratio \( D \) with different leakage inductances. It is shown in Fig. 8 that at low duty cycle range the duty loss caused by leakage inductance of the transformer is significant, but at the duty cycle greater than 0.5, which is usually chosen to be the main operating range, the duty loss is negligible.

C. ZVS current and range

As shown in Fig. 2, the ZVS current of the main switch \( I_{SM,ZVS} \) is the clamp switch current at turning off that is commutated to the main switch and used to discharge the output capacitance of the main switch and is determined by,

\[
I_{SM,ZVS} = I_{pri2,1} = \frac{1}{3} I_i
\]

To ensure the ZVS turn on of main switch the following condition should be satisfied,

\[
\frac{1}{2} L_q \cdot I_{SM,ZVS}^2 > \frac{1}{2} \left( C_{out,M} + C_{out,C} \right) V_c^2
\]

where \( C_{out,M} \) and \( C_{out,C} \) are the output capacitances of main switch and clamp switch, respectively.
The ZVS current of the clamp switch $I_{SC,ZVS}$ is the main switch current at turning off that is commutated to the clamp switch and used to discharge the output capacitance of the clamp switch and is determined by,

$$ I_{SC,ZVS} = \frac{1}{3} I_i $$

(16)

To ensure the ZVS turn on of clamp switch $S_{C2}$ the following condition should be satisfied,

$$ \frac{1}{2} L_k \cdot I_{SM,ZVS}^2 > \frac{1}{2} \left( C_{os,M} + C_{os,C} \right) V_C^2 $$

(17)

Using equations (14)-(17), the ZVS currents and ZVS ranges of main and clamp switches as the function of duty cycle and output power are plotted, respectively, as shown in Fig. 9. As shown in Fig. 9(a), the ZVS current of the main switch tends to increase as the output power increases and/or the input voltage decreases (as the duty cycle increases). This means that the ZVS turn-on of the main switch can be more easily achieved under the condition of higher output power and lower input voltage. It is noted that the ZVS range of the main switch becomes broader for smaller total output capacitance $C_{os,M} + C_{os,C}$ of MOSFETs. For example, if MOSFETs with total output capacitance $C_{os,M}$ of 10nF are selected in this example, the ZVS turn-on of the main switch can be achieved with output power which is greater than 1000W at duty cycle of 0.5 (See Fig. 9(a)).

The ZVS current of the clamp switch tends to increase as the output power and input voltage decrease. It should be noted from Fig. 9(b) that the ZVS turn-on of the clamp switch can be achieved in the overall input voltage and output power ranges.

D. Summary of the features

Main characteristics of the proposed converter are compared to the conventional converter and are summarized in Table III. Compared to the conventional converter, number of switches and circuit complexity of the proposed converter are increased.

<table>
<thead>
<tr>
<th></th>
<th>Conventional converter</th>
<th>Proposed converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of switches</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Clamping Method</td>
<td>Passive</td>
<td>Active</td>
</tr>
<tr>
<td>Switching Method</td>
<td>Hard switching</td>
<td>Soft switching</td>
</tr>
<tr>
<td>Operating Duty</td>
<td>0.33 – 1</td>
<td>0 – 1</td>
</tr>
<tr>
<td>Startup Circuit</td>
<td>Required</td>
<td>None</td>
</tr>
<tr>
<td>Diode Reverse Recovery Loss</td>
<td>Large</td>
<td>Negligible due to ZCS Turn Off</td>
</tr>
</tbody>
</table>
Nevertheless, lossless clamping of the surge caused by transformer leakage inductor, soft switching of both main and clamp switches and elimination of diode losses associated with reverse recovery characteristic by the active clamping technique result in an improvement of overall power conversion efficiency of the proposed converter. Further, the extended operating duty cycle not only improves the dynamic characteristics of the closed-loop system, but does not necessitate additional start-up circuit.

III. EXPERIMENTAL RESULTS

A 5kW laboratory prototype has been constructed, and the experimental results are presented to verify the operating principles of the proposed converter. The system specifications used in the experiment are given in the following,

\[
\begin{align*}
\bullet P_o &= 5kW \quad \bullet V_i &= 60-110V \\
\bullet \Delta I_i &= 10\% \quad \bullet \Delta V_o &= 3\% \\
\bullet f_s &= 50 \text{ kHz}
\end{align*}
\]

The operating duty cycle for output voltage regulation is shown to be in the range 0.42<D<0.7. The component ratings for the given specification and the respective selected devices from the manufactures are provided in Table IV. The voltage ratings of both the main and clamp switches and the clamp capacitor are 200V. A film capacitor was used for the clamp capacitor since the rms ripple current was 18A.

An off-the-shelf EI core of ferrite material was used for the three-phase transformer. Since the cross sectional area of the center leg of the off-the-shelf E core is twice them of the both side legs, the center leg is cut out so as to have equal width, as shown in Fig. 10. Even though the widths of all three legs are equal the magnetizing inductance of the center leg is still larger than them of the both side legs since the magnetic path length of the center leg is longer than them of the both side legs. This may cause more than 20% of unbalance in magnetizing inductions of the three legs[4]. In order to further decrease the unbalance in magnetizing inductions a small air gap was added in the center leg of the transformer. This led to less than 5% of unbalance in magnetizing inductions of the three legs.

Fig. 11 shows the photograph of the prototype. Experimental waveforms at three different duty cycles are shown in Fig. 12 to Fig. 14, respectively. It can be seen from Fig. 12 that the main switch is hard switched while the clamp switch is being turned on with ZVS and off with ZCS. Figs. 13 and 14 show that both the main and clamp switches are being turned on with ZVS.

IV. CONCLUSIONS

A new three-phase current-fed push-pull DC-DC converter featuring active clamping of the transient surge voltage, natural ZVS turn-on of main switches and clamp switches, unrestricted operating duty cycle range between 0 and 1, ZCS turn-off of rectifier diodes is proposed. The proposed three-phase converter could be a viable solution for high current high power application such as fuel cells. Experimental results on a 5kW laboratory prototype are provided to validate the proposed concept.

<table>
<thead>
<tr>
<th>Design item</th>
<th>Rating</th>
<th>Selected devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Switches</td>
<td>( V_{pk} )</td>
<td>200 V</td>
</tr>
<tr>
<td></td>
<td>( I_{rms} )</td>
<td>33 A</td>
</tr>
<tr>
<td>Clamp Switches</td>
<td>( V_{pk} )</td>
<td>200 V</td>
</tr>
<tr>
<td></td>
<td>( I_{rms} )</td>
<td>9.5 A</td>
</tr>
<tr>
<td>Diodes</td>
<td>( V_{pk} )</td>
<td>380 V</td>
</tr>
<tr>
<td></td>
<td>( I_{rms} )</td>
<td>9.5 A</td>
</tr>
<tr>
<td>Clamp Capacitor</td>
<td>Capacitance</td>
<td>5 uF</td>
</tr>
<tr>
<td>Transformer</td>
<td>Number of Turns</td>
<td>10 : 20</td>
</tr>
<tr>
<td></td>
<td>Primary ( V_{rms}, I_{rms} )</td>
<td>70 V, 37 A</td>
</tr>
<tr>
<td></td>
<td>Secondary ( V_{rms}, I_{rms} )</td>
<td>178 V, 10 A</td>
</tr>
<tr>
<td></td>
<td>kVA</td>
<td>6540VA</td>
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<tr>
<td>Input Inductor</td>
<td>Inductance</td>
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<tr>
<td></td>
<td>( I_{rms} )</td>
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<td>Output Capacitor</td>
<td>Capacitance</td>
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<tr>
<td></td>
<td>( V_{dc} )</td>
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REFERENCES


