A ZVS-PWM THREE-PHASE CURRENT-FED PUSH–PULL DC–DC CONVERTER WITH FUEL CELL INPUT

B. Mallikarjuna Reddy¹, Ch. Narendra Kumar², Ch. Rambabu³

Post graduate Scholar¹, Assistant Professor², Professor and HOD¹,²,³ Department of Electrical and Electronics Engineering, Sri Vasavi Engineering College, Tadepalligudem, West Godavari District, Andhra Pradesh, Pin-Code-534101, INDIA.

Abstract: In this paper, a ZVS-PWM three-phase current-fed push–pull dc–dc converter is proposed. When compared to single-phase topologies, the three-phase dc–dc conversion increases the power density, uses the magnetic core of the transformer more efficiently, reduces the stress on switches, and requires smaller filters since the frequency for its design is higher. The proposed converter employs an active clamping technique by connecting the primary side of the transformer to a three-phase full bridge of switches and a clamping capacitor. This circuit allows the energy from the leakage inductances to be reused, increasing the efficiency of the converter. If appropriate parameters are chosen, soft-commutation of the switches (ZVS) can also be achieved.

Key words: Active clamping, dc–dc power conversion, multiphase, soft-commutation, fuel cell.

INTRODUCTION

The association of high efficiency and high current is the major problem related to low-voltage high-power applications, particularly when they require isolation at high frequency, resulting in high conduction losses.

Distributed power generation, when fully implemented, can provide reliable, high-quality, and low-cost electric power. As a modular electric power generation close to the end user, it offers savings in the cost of grid expansion and line losses. If connected to the power grid, the bidirectional transactions between the grid and the local generation result in grid capacity enhancement, virtually uninterrupted power supply, and optimum energy cost due to the availability of use/purchase/sales options.

However, depending on the topology, the voltage across the switches is not naturally clamped requiring passive voltage clamps that dissipate energy stored in the leakage inductances to prevent overvoltage [3–5]. This energy loss reduces the efficiency of the converter. In order to avoid this problem, active clamping techniques have already been presented for single-phase converters and have successfully reused the energy that would be dissipated both in non-isolated and isolated topologies. To sum up, soft-commutation (ZVS) was also achieved with a correct parametric combination.

ZVS-PWM THREE-PHASE DC–DC CONVERTER

Circuit Description: The circuit of the proposed ZVS-PWM three-phase current-fed push–pull dc–dc converter is shown in Fig. 1. Switches S’1, S’2, and S’3 and the capacitor Cg were added to the converter in order to achieve active clamping. Inductances Ls1, Ls2, and Ls3 are responsible for maintaining the current during the commutation intervals.

Modulation: The gate signals are generated by the comparison of the modulating signal VM and three saw-tooth carriers 120° out of phase from each other. Fig. 2 shows the resulting gate signals. VG1, VG2, and VG3 are the gate signals of S1, S2, and S3, respectively, and VG’1, VG’2, and VG’3 are the gate signals of switches S’1, S’2, and S’3, respectively.

Three regions defined by Table I differently from the converter which could not operate in region R1 due to the absence of a demagnetizing path for the inductor. The converter proposed in this paper can transfer energy stored in the input inductor to the clamping capacitor if operation in region R1 is desired.

Fig-1: Circuit of the proposed ZVS-PWM Current-fed push–pull dc–dc converter.

Principle of Operation: Operating in region R3, the proposed converter has nine topological stages per switching period that can be described as follows.

Before the first stage, S’1, S2, and S3 are already conducting.

First stage (t0, t1): Starts when switch S1 is turned on. Before this stage, S’1 was conducting, and capacitor Cg was delivering energy. Current iLd1(t), initially negative and equal to −I1/3, increases linearly through the intrinsic diode of S1, as shown in Fig. 3(a), becoming positive and increasing its value though S1 until reaching I1/3, as shown in Fig. 3(b). Currents iLd1(t) and iLd2(t) decrease linearly from 2I1/3 to I1/3 through switches S2 and S3, respectively. The load receives energy from the commutation inductances through diodes D1, D3, and D6. The source does not transfer energy to the load during this stage.

Second stage (t1, t2): Starts when currents iLd1(t), iLd2(t), and iLd3(t) are equal to I1/3. Currents iLd1(t), iLd2(t), and iLd3(t) remain at I1/3, and the diodes of the rectifier bridge remain off. This stage can be seen in Fig. 3(c). The source does not transfer energy to the load during this stage.

Third stage (t2, t3): Starts when switch S2 is turned off. Current iLd2(t) decreases linearly from I1/3 through the intrinsic diode of S’2, as shown in Fig. 3(d), and then, it is equal to zero.
and starts to increase negatively, as shown in Fig. 3(e), until it reaches $-I_{L}/3$. In Fig. 3(d), the clamping capacitor $C_g$ receives energy from the commutation inductance, and in Fig. 3(e), the capacitor $C_g$ returns this energy. Currents $i_{Ld1}(t)$ and $i_{Ld3}(t)$ increase linearly from $I_{L}/3$ to $2I_{L}/3$ through switches $S_1$ and $S_3$, respectively. The load receives energy from the source through diodes $D_2$, $D_4$, and $D_6$.

The fourth and seventh topological stages are similar to the first stage, the fifth and eighth topological stages are similar to the second stage, and the sixth and ninth stages are similar to the third stage. The only difference is that other switches are on. After the ninth stage, the switching period is complete, and a new period starts with the first stage.

The main voltages of the circuit during the described stages are shown in Table 3. Whose time intervals are described by equations as presented in Table 2 and the voltages presented in Table-2 correspond to the symbols presented previously in Figs. 1.

Nevertheless, that architecture is prone to voltage and current stresses on the semiconductors and a substantial increase of the reactive element dimensions. Afterward, in order to provide a ZVS commutation of all switches, the use of an asymmetrical duty cycle was proposed with a notable high efficiency, even if higher conduction losses in the rectifier stage were present. Consequently, a three phase dc–dc converter that is capable of achieving a soft commutation requires a high-efficiency rectifier to attain the optimal arrangement for low-voltage high-current applications.

Nowadays, the main topology used in high power dc/dc conversion is the zero-voltage switching (ZVS) pulse-width modulation (PWM) full-bridge converter. It is characterized by four switches operating in high frequency. The soft commutation can be obtained by using phase shift modulation, which preserves the simplicity and achieves high power density.
components or even converters can be applied. The former choice increases the complexity of the compromise between the layout circuit and the thermal design. Besides that, one should consider that the dynamic and static current sharing problem limits its application. The other alternative causes redundancy in the control circuits as well as in the number of power components and drivers, increasing the global cost and size of the equipment.

<table>
<thead>
<tr>
<th>Region</th>
<th>Duty cycle</th>
<th>Switches simultaneously ON</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>0&lt;D&lt;0.33</td>
<td>None</td>
</tr>
<tr>
<td>R2</td>
<td>0.33&lt;D&lt;0.66</td>
<td>Two</td>
</tr>
<tr>
<td>R3</td>
<td>0.66&lt;D&lt;1</td>
<td>Three</td>
</tr>
</tbody>
</table>

### Table-1: Operating regions of the circuit

#### First stage

\[ \Delta t_1 = \frac{n \times Ld \times I_l}{V_o} \]

#### Second stage

\[ \Delta t_2 = \frac{T_s}{3} - \Delta t_1 - \Delta t_3 \]

#### Third stage

\[ \Delta t_3 = (1 - D)T_s \]

### Table-2: time intervals of operation

Since 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.

### Voltage gain:

Equation (1) is the average current through the clamping capacitor \( C_g \)

\[ \frac{3}{T_s} \int_0^{(1-D)T_s} \left( \frac{n \times Vld2}{Ld} \times t \right) dt = 0 \]  

Substituting \( V_l \) during the third stage from Table II in (1) and solving the integral yield

\[ V_{cg} - \frac{V_o}{n} = \frac{V_d \times F_s \times I_o}{1 - D} \]  

(2)

Considering the analysis that there are no losses in the converter, the following is valid

\[ V_i \times I_l = V_o \times I_o \]  

(3)

Substituting \( I_l \) from (3) in (2), the following is found

\[ V_{cg} = \frac{V_o}{n} + \frac{1}{n} \]  

(4)

Where \( I_o \) is given by

\[ I_o = \frac{Ld \times F_s \times I_o}{V_i} \]  

(5)

As the average voltage across the inductors is zero, the average voltage across the switches \( S_1 \), \( S_2 \), and \( S_3 \) is the input voltage \( V_i \), and the following can be written

\[ V_i = (1 - D)V_{cg} \]  

(6)

Equation (6) leads to the input–clamping capacitor voltage gain shown in

\[ \frac{V_{cg}}{V_i} = \frac{1}{(1-D)} \]  

(7)

Substituting (4) in (7) leads to the input–output voltage gain

\[ q = \frac{V_o}{V_i} = \frac{n}{(1-D) + n \times \frac{I_o}{V_d}} \]  

(8)

Equation (8) represents the voltage gain of the proposed three-phase current-fed push–pull dc–dc converter with active clamping in region R3.

### Clamping Voltage and Duty Cycle:

The duty cycle was chosen to guarantee operation in region R3 and to generate an acceptable clamping voltage

Choosing a clamping voltage of \( V_{cg} \), the duty cycle is calculated as follows:

\[ D = 1 - \frac{V_i}{V_{cg}} \]

### Turns Ratio of the Transformer, Effective Duty Cycle, and Commutation Inductance:

The turns ratio of the transformer is calculated to achieve the desired output voltage considering the effective duty cycle Reduction (nIo). If an effective duty cycle reduction of 5% is chosen, the turn’s ratio of the transformer is calculated as follows:

\[ n = \frac{V_o}{V_i} (1 - D + n \times \frac{I_o}{V_d}) \]

The turn’s ratio n was defined as the number of turns of the secondary winding divided by the number of turns of the primary winding.

After this, the commutation inductance is calculated as

\[ Ld = \frac{n \times V_i \times I_o}{F_s \times I_o \times n} \]

### Boost Inductance:

operating in region R3, the boost inductance can be calculated as

\[ L = \frac{V_i}{\Delta I_l \times F_s} (D - \frac{2}{3}) \]

Boost inductance is critical value for the selection of the input inductance

<table>
<thead>
<tr>
<th>voltage</th>
<th>1st stage</th>
<th>2nd stage</th>
<th>3rd stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{i1} ) (t)</td>
<td>( \frac{2}{3} \frac{V_o}{n} )</td>
<td>0</td>
<td>( -\frac{1}{3} \frac{V_o}{n} )</td>
</tr>
<tr>
<td>( V_{i2} ) (t)</td>
<td>( \frac{1}{3} \frac{V_o}{n} )</td>
<td>0</td>
<td>( \frac{2}{3} \frac{V_o}{n} )</td>
</tr>
<tr>
<td>( V_{lr} ) (t)</td>
<td>( \frac{1}{3} \frac{V_o}{n} )</td>
<td>0</td>
<td>( -\frac{1}{3} \frac{V_o}{n} )</td>
</tr>
<tr>
<td>( V_{ld} ) (t)</td>
<td>( \frac{2}{3} \frac{V_o}{n} )</td>
<td>0</td>
<td>( \frac{1}{3} (V_{cg} - \frac{V_o}{n}) )</td>
</tr>
<tr>
<td>( V_{ld} ) (t)</td>
<td>( \frac{1}{3} \frac{V_o}{n} )</td>
<td>0</td>
<td>( \frac{2}{3} (V_{cg} - \frac{V_o}{n}) )</td>
</tr>
<tr>
<td>( V_{x} ) (t)</td>
<td>0</td>
<td>0</td>
<td>( \frac{V_{cg}}{3} )</td>
</tr>
</tbody>
</table>

### Table-3: Main voltages during each topological stage

### Simulation diagrams:

Simulation diagrams of proposed a ZVS-PWM three phase current-fed push-pull technology: A ZVS-PWM three phase
current-fed push-pull dc-dc converter technology is proposed in the simulation diagram. In this diagram, the effect of electromagnetic interference is more effect on operation with this effective operation of the converter and efficiency are decreases.

Fig-4: A ZVS-PWM three phase current-fed Push-pull dc-dc converter

Fig-5: Output voltage of the dc-dc converter

Fig-6: Input current of the dc-dc converter

Fig-7: current through Ls1, Ls2 and Ls3

three currents are changes \( -I_L/3 \) to \( 2I_L/3 \) due change of the duty cycle.

Fig-8: saw-tooth wave forms

Fig-8 shows mat lab graph of zvs-pwm three phase current-fed push-pull dc-dc converter with fuel cell input. These saw-tooth wave forms are produced by the pulse generator. The dc-dc converter required pulse for ON/OFF of the switching devices in dc-dc converter. The pulse width modulation is done by the dc source and saw-tooth wave form and generate the pulse for dc-dc converter switching operation.

Fig-9: pulse generating signals

Fig-9 shows mat lab/semolina graph of the zvs-pwm three phase current-fed push-pull dc-dc converter. These signals are developed by the pulse width generator. Three signals are produced by the comparison of the saw-tooth and dc source. These signals are fed to the gated signals of the converter.

Simulation diagram of a ZVS-PWM three phase current-fed push-pull dc-dc converter with fuel cell input: with this concept, the output voltage is increases and efficiency also improves. In the fuel cell, in put voltage and current are variable and output voltage and current are maintained constant.

Fig-10: a zvs-pwm three phase current-fed push-pull dc-dc converter with fuel cell input
Fig-11: input voltage

Fig-11 shows mat lab/semolina graph of zvs-pwm three phase current-fed push-pull dc-dc converter with fuel cell input. The above graph is input voltage of the zvs-pwm three phase current-fed push-pull dc-dc converters with fuel cell input. By using fuel cell, input voltage is variable. Because; it is process of the combination of hydrogen and oxygen. The zvs-pwm three phase current-fed push-pull dc-dc converter with fuel cell input mat lab diagram is shown in the above fig. It is operated above 0.66 duty ratio. Because, in the above 0.66 duty cycle active clamping technique is excellently work. Exactly, duty ratio is 0.791 and effective duty cycle is 0.008 in the zvs-pwm three phase current-fed push-pull dc-dc converter with fuel cell is input.

Fig-12: current through Lp1

Fig-12 shows mat lab graph of zvs-pwm three phase current-fed push-pull dc-dc converter with fuel cell input. Current through Lp1 is present in above graph. This current is present in region 1 and 3 only .the primary side inductance means leakage inductance of the transformer and extra inductance in region 3 for active clamping technique.

Fig-13: current through primary winding

Fig-13 shows the mat lab/semolina graph of the zvs-pwm three phase current-fed push-pull dc-dc converters with fuel cell input. It is switching current for the active clamping technique for the betterment of electromagnetic effect.

Fig-14: output voltage

Fig-14 shows mat lab graph of zvs-pwm three phase current-fed push-pull dc-dc converter with fuel cell input. In this project, output voltage is maintained constant due to the dc-dc converter with the active clamping technique. Here input voltage is 120 volts and output voltage is 570 at duty cycle is 0.791 with effective duty cycle is 0.008.

**Simulation results comparison:**

<table>
<thead>
<tr>
<th>particulars</th>
<th>A ZVS with basic dc source</th>
<th>A ZVS with fuel cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage</td>
<td>450 volts</td>
<td>570 volts</td>
</tr>
<tr>
<td>Input voltage</td>
<td>120 volts</td>
<td>120 volts</td>
</tr>
<tr>
<td>Input voltage constant</td>
<td>variable</td>
<td>constant</td>
</tr>
<tr>
<td>Output voltage constant</td>
<td>constant</td>
<td>constant</td>
</tr>
<tr>
<td>EMI(EMI)</td>
<td>More effect</td>
<td>Less effect</td>
</tr>
<tr>
<td>performance</td>
<td>Good</td>
<td>Very good</td>
</tr>
<tr>
<td>efficiency</td>
<td>93%</td>
<td>94.5%</td>
</tr>
</tbody>
</table>

**Table-4: simulation diagrams comparison**

**Conclusion:**

A ZVS-PWM three phase current-fed dc-dc converter is basically operated with the renewable energy sources (i.e. d c sources).Because, output of the all renewable energy sources producing the partially dc voltage. In this project, electromagnetic effect is more compare to the single phase concept and effective utilization of the core is more in three phases compare to the single phase. A ZVS-PWM three phase current-fed with fuel cell input is boosting more output voltage compare to the base concept as well as efficiency of the converter is increases some more due effective reutilization of the inductances energy through active clamping technique. A ZVS-PWM three phase current-fed push-pull dc-dc converter is operated on the 0.735 duty cycle and 0.008 effective duty cycles with active clamping. With fuel cell, it is operated duty cycle is...
0.791 and effective duty cycle is 0.008. the output voltage of the project is pure constant for drive of the fuel cell vehicles.

REFERENCES