ZVS Boost Converter for Grid connected Fuel Cell Systems

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Abstract—A new zero voltage switching current fed zero-voltage switching isolated boost converter topology for fuel cell applications is presented. L-type half-bridge is more suitable to low voltage, high current applications such as front-end dc–dc converters for the fuel cell applications. It has larger switch voltage rating and also suffers from high voltage across the switches. Clamping methods are needed to reduce the voltage spikes but they require additional components and losses. In this paper, an improved current-fed zero-voltage switching (ZVS) isolated boost converter is proposed for fuel cell applications. The voltage ratings of the primary switches and secondary diodes of the proposed converter are significantly reduced. It does not require any clamping circuits like conventional current fed converters. These advantages make the new converter promising for fuel cell applications. A simulation is carried out using MATLAB/Simulink to verify the proposed DC-DC converter.

Keywords—Zero Voltage switching (ZVS), current fed, isolated boost converter, fuel cell.

I. INTRODUCTION

Fuel cells for low or medium power deliver fuel cells for low or medium power deliver. A high dc-link voltage is needed to feed in electrical energy from fuel cells to the mains via a voltage source inverter. Fuel cells provide a variable dc current at variable fuel cell voltage. To feed into the mains they have to be connected to the ac mains by means of inverters. Because of the comparatively low voltage of a fuel cell stack for low and medium power compared to the mains voltage, the inverter has to increase the voltage when feeding into the mains. To attain the high dc-link voltage necessary for the voltage source inverter, a dc/dc converter is used between the fuel cell stack and the inverter. Compared to the DC bus voltage level (650-700V), the Proton Exchange Membrane (PEM) FC output voltage is only about 26-48V and hence the DC-DC converter must achieve by high boost ratio which may be difficult to accomplish by non-isolated converters. Therefore, the DC-DC converter usually incorporates a high frequency (HF) transformer. DC-DC converters with a HF transformer can be divided into two topologies: voltage-fed converters (VFC) and current-fed converters (CFC) [1]&[2]. CFC can be categorized into two configurations: the full bridge current-fed converter (FBCFC) [3] and the L-type current-fed converter (LTCFC) [4]. Fig.1 shows conventional L-type half bridge converter. For fuel cell applications, the CFC has significant advantages over the VFC due to the lower turn’s ratio, higher efficiency and lower switching losses [5].

II. PROPOSED ISOLATED BOOST CONVERTER

In this paper, an improved current-fed zero-voltage switching (ZVS) isolated interleaved boost DC-DC converter is proposed for the fuel cell applications. Performance of the interleaved boost converter with dynamic evolution controller is analysed [7]. It has the advantages of current-fed converter which include smaller input current ripple, lower diode voltage rating, and lower transformer turns-ratio, the voltage ratings of the primary switches and secondary diodes of the proposed converter are reduced to half of those of the L-type half bridge converter. Also it does not require any clamping [8] and start-up circuits unlike most of the conventional current-fed converter based on full-bridge, push–pull, or half-bridge topologies in which duty ratio is restricted to greater than 0.5, resulting in need of an additional start-up circuitry to prevent the inrush current during start up [9].
II. OPERATING PRINCIPLE

The proposed isolated boost converter consists of two input filter inductors, four MOSFET switches, two auxiliary capacitors at the low voltage side, and two series connected voltage-doubler rectifiers [10] at the high-voltage side. The topology is basically two high-frequency transformers and two voltage-doubler rectifiers, which are employed for isolation, step-up, and rectification, are connected in series so that the diode-voltage rating becomes half of the output voltage. The voltage-transfer ratio of the proposed converter is twice that of the conventional L-type half-bridge converter meaning that the required transformer turn ratio for step-up is reduced to half. This reduces the number of turns of the transformer winding resulting in reduced copper losses and leakage inductance of the transformer. Also, the proposed converter does not require clamping and start-up circuits unlike most of the conventional current-fed converter. A single phase current-fed full bridge converter with high voltage gain for fuel cell applications is implemented in [11] where clamping circuit is implemented by an auxiliary buck converter[12]. A active clamping current-fed half-bridge converter is proposed in [13].

A. Operating Modes

Fig.4 shows six operating states. Input inductance is large so that it can be treated as a constant current source.

a) Mode 1 (t1-t2): Switches S1 and S2 are conducting and each switch carries both the input-inductor current and the leakage-inductor current. The voltage across the leakage inductor of the transformer is a difference between an auxiliary capacitor voltage (Vc1, Vc2) and an output-capacitor voltage (Vc3, Vc4, Vc5, or Vc6) referred to the primary.

b) Mode 2 (t2-t3): Switch S1 is turned OFF at t2, and then parasitic capacitors of switches S1 and S4 are charged to \( V_n/(1 - D) \) and discharged to 0V, respectively, by current I_L2. Main channel of S4 starts conducting at the time the gate signal is applied to S4. This state ends when current I_Lk2 reaches 0A.

c) Mode 3 (t3-t4): Since current I_Lk2 reverses its direction, the diode D3 is turned ON, and then current I_Lk2 starts slowly increasing due to the small positive value applied across the leakage inductance L_Lk2. This state ends when current I_Lk2 becomes equal to I_L2, i.e., switch current I_s3 reaches 0.

d) Mode 4 (t4-t5): At t4, the current Is4 reverses its direction, and then S3 is turned ON with ZVS. Current I_Lk2 is continuously increasing with the slope determined at state 3.

e) Mode 5 (t5-t6): Switch S1 is turned OFF at t5, and then parasitic capacitors of switches S1 and S4 are discharged to 0V and charged to \( V_n/(1 - D) \), respectively, by current I_L2. After completion of discharge operation, the body diode of S3 is turned ON, and the current flowing through the body diode of S1 rapidly decreases since voltage \( V_n/(1 - D) \) becomes large negative. The main channel of S1 starts conducting at the time the gate signal is applied to S1. This state ends when current I_Lk2 becomes equal to I_L2, i.e., switch current I_s3 reaches 0.

f) Mode 6 (t6-t7): At t6, the current Is4 reverses its direction, and S3 is turned ON with ZVS. Current I_Lk2 is continuously increasing with the slope determined at state 5. This state ends when current I_Lk2 reaches 0A. This is the end of a half cycle. The other half cycle begins at time t7 and is repeated except with the correspondingly opposite set of legs.
B. ZVS conditions

As explained in mode 2, the parasitic capacitor of upper switch \( S_4 \) is discharged by the current magnitude \( I_1 = I_{L2} + I_{lk} \), as shown in Fig. 4. ZVS for upper switches \( S_2 \) and \( S_4 \) is said to be achieved over the whole load range.

As explained in mode 5, the parasitic capacitor of lower switch \( S_3 \) is discharged by current magnitude \( I_2 = I_{lk2} - I_{L2} \) at time \( t_5 \). Increasing transformer leakage inductance to enlarge the ZVS region makes the duty cycle loss large resulting in increased turn ratio. Instead, the input filter inductance can be reduced, and hence current magnitude \( I_2 \) can be increased resulting in enlarged ZVS region. Decreasing the input filter inductance increases the current rating of the power devices, and therefore, the input-filter inductance should be properly chosen considering a trade-off between the ZVS region and the device current ratings. To further enlarge the ZVS region, discontinuous conduction mode (DCM) operation on the input-filter inductor may be employed as shown in Fig. 2 meaning that negative current flows on the input-filter inductor.

III. Simulation results

To verify the proposed control approach simulation study is carried out using MATLAB/Simulink. The block diagram of the designed system is shown in Fig. 5.

Fig. 5 Designed system with isolated boost converter

The Gating signals for the switches are shown in Fig. 5. The upper and lower switches of each leg are operated with asymmetrical complementary switching to regulate the output

The proposed Boost converter has been designed according to the following specifications

\[ \begin{align*}
V_{in} &= 100 \\
V_{out} &= 130 \\
f &= 50Hz \\
L_1 &\text{ and } L_2 = 130\text{mH}
\end{align*} \]
The output voltage of the proposed converter can be regulated by the general voltage such as PI control with output voltage feedback. The transformer-leakage inductance is 1µH.

The interleaved inductor and input current are shown in Fig.7. Current through the leakage inductances $I_{lk1}$ and $I_{lk2}$ are shown in Fig.8. From the graph it is observed that there was no dc offset in magnetizing current.

![Fig.7 Input and Inductor currents](image)

![Fig.8 Current through the leakage inductances](image)

![Fig.9 Voltage across the switches and current through Inductor](image)

Fig.9 shows the drain-source voltage of switched $S_1$ and $S_2$ and current $I_{L1}-I_{lk1}$. It can be seen from the figure that the switches $S_1$ and $S_2$ are being turned on with ZVS and also the voltage spikes are less even without any clamping circuits.

![Fig.9 DC output voltage](image)

Fig.10 shows the zero current switching turn on and off of diode D1. Similarly diode D2 is also turned on and off with Zero current switching.

![Fig.10 ZCS turn on and off of diode D1](image)

It is noted that the proposed converter could have smaller size and weight of the passive components such as input inductors, output capacitors and auxiliary capacitors. The proposed converter employs four output capacitors but total energy volumes of the capacitors are smaller. Since the duty cycle of the proposed converter ranges from 0 to 1, no start up circuitry is required here unlike conventional L-type half bridge converter.

![Fig.10 ZCS turn on and off of diode D1](image)

Thus the input voltage is boosted to a higher value with the help of the proposed boost converter as shown in Fig.9.

IV. CONCLUSION

To feed in electrical energy from fuel cells into the three phase mains via a voltage source inverter, there is the need of a dc/dc converter which increases the fuel cell voltage to the dc link voltage of the inverter. Dc/dc converters with high frequency transformers meet the demands for larger input to output voltage ratios. The proposed converter has the following advantages over the conventional current-fed converter.

1. Reduced voltage ratings of the switches and diodes.
2. Reduced size and weight of the passive components.
3. No clamping or snubber circuits required due to the ZVS operation.
4. No start-up circuitry.

Thus the overall efficiency of the proposed converter is high and is best suited for grid connected fuel cell inverter systems in the medium power range.
V. REFERENCES


