High Efficiency Full Bridge Current-Fed DC-DC Converter for a Fuel Cell Power System

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Abstract. A new active clamp current-fed full bridge isolated DC-DC converter topology for fuel cell applications is presented. Comparison results show that this topology improves the efficiency over a wide load range. Using small signal analysis the AC equivalent circuit and transfer functions have been derived. These show that the dynamic response for the proposed converter is more benign than that of other configurations, which will be beneficial when operating a fuel cell on a common DC bus system.

Keywords
Fuel cell, current-fed converter, small-signal analysis, zero voltage switching (ZVS).

1. Introduction

In general, DC-DC converter can be classified as non-isolating and isolating. When a fuel cell (FC) generator is interfaced with a high voltage DC busbar, galvanic isolation from the busbar or the grid is required. Also floating electrodes of the FC may cause problems especially if cells are connected in series in the stack. 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). CFC can be categorized into two configurations: the full bridge current-fed converter (FBCFC) [1] and the L-type current-fed converter (LTCFC) [2]. For fuel cell applications, the CFC has significant advantages over the VFC due to the lower turns ratio, higher efficiency and lower switching losses [3]. However, a CFC can cause high voltage stresses for the switching devices. Additional circuitry must be added to limit this. While the LTCFC requires less switching devices and has a lower turns ratio, it is not as the efficient as the FBCFC since it uses more passive components, requires a more complex control circuit and contains a higher input inductor ripple current.

In this paper, a new FBCFC using a voltage-doubling rectifier with untapped secondary winding and an active clamp soft switching technique is proposed. The proposed converter is described and compared with other full bridge and L-type current-fed converters in terms of efficiency and switching losses. An analysis of the proposed converter is performed to identify the periodical behaviour of the new configuration during the different modes of operation. From this a small-signal equivalent circuit has been derived which is then used to find the dynamic transfer functions.

2. Steady State Analysis and Operational Modes of the Proposed Converter

The proposed CFC, shown in Fig.1a, uses a full bridge, an HF transformer with untapped secondary winding and a voltage-doubling rectifier. Using a single switch active clamp circuit, the converter alleviates the usual voltage ringing across the bridge switches. The working of this converter can be understood from analysis of the voltage and current waveforms, depicted in Fig.1b, where eight operational modes per half cycle can be distinguished:

Mode 1 ($t_0 < t < t_1$) zero voltage switching (ZVS) for $S_1$ and $S_2$: In this interval the anti-parallel diodes of $S_1$ and $S_2$ conduct and therefore $S_1$ and $S_2$ can be turned on with zero voltage. At this moment, the voltage across clamp branch $v_{CB}(t)$ is zero and the blocked voltage for $S_c$ equal to clamp capacitor voltage $V_{ca}$. Parasitic capacitances $C_{pi}$ and $C_{pi}$ will be discharged at this instant. In this mode, the leakage inductance current $i_{LK}(t)$ and the anti-parallel diode current $i_{DST}(t)$ can be described by the following equations:

$$i_{LK}(t) = i_{LK}(t_0) - \frac{V_{ca} - V_o/2n}{L_{LK}}(t - t_0)$$

$$i_{DST}(t) = i_{LK}(t_0) - \frac{V_{ca} - V_o/2n}{L_{LK}}(t - t_0) - i_L(t)$$
branch voltage \( v_{BB}(t) \) and the voltage across \( C_{pe} \) can be described by the following equations:

\[
\begin{align*}
v_{BB}(t) &= v_{Cp3}(t) = V_{Ca}(t - t_3) \\
v_{Cpe}(t) &= V_{Ca} - V_{Ca}(t - t_3)
\end{align*}
\]

Mode 5 \((t_4 < t < t_5)\) anti-parallel diode of \( S_c \) conducts: At \( t = t_4 \) the current \( i_{Ca}(t) \) will be equal to \( I_{Lmax} \) and the leakage current is given by the following equation:

\[
i_{Lk}(t) = \frac{V_{fe} - V_{Ca}}{L} - \frac{V_{fe} - V_{Ca}}{L} \cos (\omega_o(t - t_4))
\]

\[
v_{Ca}(t) = V_{Ca} + I_{Lmax}Z_o \sin (\omega_o(t - t_4))
\]

where \( \omega_o = 1/(L_{LK}C_a) \) is the resonant frequency and \( Z_o = \sqrt{(L_{LK}C_a)} \).

A resonant energy exchange now takes place between \( L_{LK} \) and \( C_a \) until \( t = t_5 \). From \( t_5 \) to \( t_6 \) the difference between \( i_{Lk}(t) \) and \( i_{L}(t) \) flows into \( C_a \) via the anti-parallel diode, until the current reverses sign.

Mode 6 \((t_5 < t < t_6)\) \( S_c \) turned on: Due to the discharge of \( C_{pe} \) the anti-parallel diode of \( S_c \) is conducting in zero voltage across \( S_a \) at \( t = t_5 \). This allows \( S_c \) to turn on under ZVS. The same equations as for Mode 5 will hold.

Mode 7 \((t_6 < t < t_7)\) transfer energy: At \( t_6 \) the \( i_{Ca}(t) \) reduced to zero and then energy stored in it starts to transfer into the primary winding in a resonant fashion started in mode 5. At \( t = t_7 \), \( i_{Ca}(t) \) will have the same value as \( i_{L}(t) \) but with the opposite sign. The currents in \( S_1 \), \( S_2 \) and \( I_{Lk} \) will have an equal to approximately twice the input current at \( t_7 \). \( S_c \) is now turned off.

Modes 8, 9 & 10 \((t_7 < t < t_9)\) \( L_{LK} \) discharging period: At \( t_7 \) the \( i_{Ca}(t) \) equal to zero and then energy stored in it starts to transfer into the primary winding in a resonant fashion started in mode 5. At \( t = t_9 \), \( i_{Lk}(t) \) will have the same value as \( i_{L}(t) \) but with the opposite sign. The currents in \( S_1 \), \( S_2 \) and \( L_{LK} \) are equal to approximately twice the input current at \( t_9 \). \( S_c \) is now turned off.

Some discharging of \( C_a \) continues until the voltage across \( C_{pe} \) becomes negative, but \( C_{pe} \) and \( C_{pe} \) are being reverse-charged by the leakage inductance energy until the anti-parallel diodes of \( S_a \) and \( S_b \) start to conduct \( t_9 \). This creates a ZVS condition for these devices, which then switched on at \( t_9 \). At \( t_9 \), \( i_{Lk}(t) \) has fallen to zero and the switch currents are again equal to 1/2 of the input current. Modes 9 to 16 are similar to modes 1 to 8 but differ in the way the output capacitors \( C_1 \) and \( C_2 \) are being charged.
3. Comparison of the proposed CFC with other CFC topologies

Operation of different current-fed converters configurations, suitable for fuel cell power systems, has been analyzed and compared with the proposed FBCFC. To achieve a fair comparison, all converters topologies are designed to the same specifications as listed below.

Fuel cells stack characteristics:
- Maximum output power = 1.2kW
- FC voltage = 26-50 V
- Maximum FC ripple current ≤35%.

Converter characteristics:
- Switching frequency = 50kHz
- DC bus voltage = 650V

The calculated components values are listed in Table1.

Table 1 Calculated component values for four CFC topologies

<table>
<thead>
<tr>
<th>Topology</th>
<th>Cα, µF</th>
<th>Lα, µH</th>
<th>L1, µH</th>
<th>L2, µH</th>
<th>n</th>
<th>Cα, µF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tapped-transformer FBCFC[4]</td>
<td>----</td>
<td>2.5</td>
<td>500</td>
<td>------</td>
<td>1:6</td>
<td>250</td>
</tr>
<tr>
<td>Proposed FBCFC</td>
<td>1.92</td>
<td>1.5</td>
<td>500</td>
<td>500</td>
<td>1:6</td>
<td>100</td>
</tr>
<tr>
<td>Active clamp LTCFC[5]</td>
<td>1.92</td>
<td>1.5</td>
<td>500</td>
<td>500</td>
<td>1:6</td>
<td>100</td>
</tr>
<tr>
<td>Voltage doubler LTCFC</td>
<td>2.88</td>
<td>1</td>
<td>500</td>
<td>500</td>
<td>1:3</td>
<td>100</td>
</tr>
</tbody>
</table>

The main waveforms of the hard switched voltage doubler FBCFC using a tapped transformer [4] are shown in Fig. 2.

From this figure, it is noted that there is severe ringing of the voltages across the switches to twice the reflected output voltage. On the other hand, as can be seen from the analysis results of the proposed converter in Fig.3, the voltage across the switches is clamped by clamp circuit.

Fig.3 Voltage and current waveforms of the proposed FBCFC

Fig.4 illustrates that the proposed converter exhibits a much improved efficiency over the entire load range (up to 97% at 60 percent of the full load) compared with other topologies.

Table.2 gives a detailed comparison of the power losses incurred in the different topologies and also demonstrates the lower device stresses for the proposed converter.

2. Small Signal Equivalent Circuit and Transfer Functions of the Converter

The dynamic equations for the boost inductor voltage \( v_L(t) \), leakage inductor voltage \( v_{Lk}(t) \), clamp capacitor current \( i_{Ck}(t) \), output capacitor currents \( i_{C1}(t) \) and \( i_{C2}(t) \) have been derived for each mode. After that, the small signal approximation is achieved by replacing the voltage and currents with their average values, while averaging voltages and currents over one switching cycle. The nonlinear set of differential equations is then perturbed and linearized to construct the small signal equations. These equations contain DC terms, 1st order linear AC terms and 2nd order nonlinear AC terms. By neglecting...
the first term and the third term and then taking the Laplace Transform, the following small signal state space equations are obtained:

\[
\begin{bmatrix}
  sL & D' \\
  -D' & sC_a + g_3
\end{bmatrix}
\begin{bmatrix}
  0 \\
  -g_2
\end{bmatrix}
\begin{bmatrix}
  \bar{L}_L(s) \\
  \bar{V}_{Ca}(s)
\end{bmatrix}
\begin{bmatrix}
  \bar{\theta}_o(s)
\end{bmatrix}
\begin{bmatrix}
  \bar{d}(s)
\end{bmatrix}
\begin{bmatrix}
  g_1 \\
  -p_3
\end{bmatrix}
\begin{bmatrix}
  V_{Ca} \\
  0
\end{bmatrix}
\begin{bmatrix}
  1 \\
  0
\end{bmatrix}
\begin{bmatrix}
  \bar{v}_{fe}(s)
\end{bmatrix}
\]

\[ (10) \]

where

\[ g_1 = \frac{D' \left( \frac{V_{Ca}}{2n} - V_o \right)}{2L_{LLK}fs} - I_L \]

\[ J = \frac{2(D' + D'')}{n} \]

\[ p_2 = \frac{jI_L}{V_o} + \frac{1}{R_o} \]

\[ (13) \]

\[ D', g_2, g_3, p_1 \text{ and } p_2 \text{ are equal to \((1-D), D''/(8nL_{LLK} f_s), D''/(4L_{LLK} f_s), (4L_V_{Ca})/V_o\), and \((4L_I D'')/V_o\) respectively and \(D''\) is a period of energy transfer from \(L_{LLK}\) to the load.}

From (10) the Control-to-output voltage transfer function and small-signal transfer function for duty cycle-to-
boost inductor current can be derived as shown in (14) and (15) respectively:

\[ G_{vd}(s) = \frac{\bar{\theta}_o(s)}{\bar{d}(s)} \bigg|_{\bar{v}_{fe}(s)=0} \]

\[ G_{gd}(s) = \frac{\bar{L}_L(s)}{\bar{d}(s)} \bigg|_{\bar{v}_{fe}(s)=0} = G_{g0} \frac{m_1 s^2 + m_2 s + 1}{q_1 s^3 + q_2 s^2 + q_3 s + 1} \]

\[ (15) \]

where

\[ b_1 \text{ and } b_2 \text{ are equal to \((1-D), D''/(8nL_{LLK} f_s)\) and \((4L_I D'')/V_o\) respectively.}

A small signal equivalent circuit that corresponds to the above state-space equations is depicted in Fig.5.
The Bode plots of $G_{vd}$ and $G_{id}$ are shown in Fig.6 for the standard FBCFC without active clamp [4] and the proposed FBCFC, where it can be seen that the output voltage and input current do not longer contain an oscillatory mode.

### 3. Conclusion

The results of the comparison and dynamic modelling analysis described above show that the proposed converter operates at a very high efficiency (up to 97%), has low switch stresses, and has a higher voltage ratio compared with other CFC topologies. The latter simplifies the HF transformer construction, improves window utilization and reduces the leakage inductance. The transient response shows that the new configuration has a more benign behaviour, simplifying the design of closed loop controller and protecting the fuel cell from damaging overcurrents.

### References


