Voltage Fed and Current Fed Full Bridge Converter for the Use in Three Phase Grid Connected Fuel Cell Systems

M. Mohr1 and F.-W. Fuchs2
Christian-Albrechts-University of Kiel / Institute of Power Electronics and Electrical Drives; Kiel, Germany
1mam@tf.uni-kiel.de 2fwf@tf.uni-kiel.de

Abstract—Fuel cells for low or medium power deliver comparatively low voltages compared to the mains voltage at high currents. A high dc-link voltage is needed to feed in electrical energy from fuel cells to the mains via a voltage source inverter. Several well known dc/dc converters can be used to transform the varying fuel cell voltage to the requested amplitude of the dc-link-voltage. Besides transformerless converters like the boost converter, converters with high frequency transformers can be used. In the considered higher power range, the full-bridge converter circuit is the appropriate solution. Depending on their input circuit, the converters are classified between voltage fed and current fed full bridge converter. In this paper, full bridge converters of the voltage type and of the current type as active front end for fuel cell inverters in the power range of 20 kW and higher are analysed and compared to each other. The focus is set on the operating behavior, the system complexity and the efficiency of the different converters.

Keywords—fuel cells, DC-DC power conversion, distributed energy

I. INTRODUCTION

Fuel cells can be an important component of future energy systems, enabling electricity and heat generation from hydrogen or similar substances with high efficiency and low or nearly zero emission. Their introduction is in the stage of beginning as their development has not yet been finished.

Fuel cells provide a variable dc current at variable fuel cell voltage. For feeding 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.

Several converters for fuel cell systems have been discussed in publications, see for example [1]-[3]. A very common solution to feed in electrical energy into the three phase mains is a voltage source inverter. 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.

For low ratios (i.e. 1:1 to 1:3) between fuel cell stack voltage and dc link voltage, a boost converter shows some advantages like high efficiency and low component quantity [3], [4]. For higher ratios between fuel cell stack voltage and dc link voltage, transformerless converters become less applicable [4]. Dc/dc converters with high frequency transformers overcome these problems. They achieve the capability of high voltage ratios due to the magnetic coupling of the transformer and the different number of turns on the primary and the secondary side of the transformer. In addition they provide galvanic isolation between the fuel cell and the mains.

The proposed application is the feed in of electrical energy into the mains; therefore unidirectional converters are appropriate and an additional energy storage to supply peak power is not needed.

Many fuel cell inverters which have been published are designed for a power range of about 1 kW [1], [5]. In this power range, converters like push-pull converters or half bridge converters are suitable converter topologies utilizing high frequency transformers. For a power range of 20 kW and higher, the full bridge converter is an appropriate solution for dc/dc converters with controllable voltage ratio [1], [2]. Depending on their input circuit full bridge converters can be classified into voltage fed and current fed full bridge converters. Both types are used as converters for fuel cell applications.

In this paper, full bridge converters of the voltage type and of the current type are analysed and compared to each other with respect to their suitability as converters for fuel cell inverter systems in the mid power range. In addition to the general behaviour of the converters, the semiconductor losses and the complexity of the converter is investigated. Effects of the transformer’s stray inductances and the dimensioning of the transformer’s turns ratio are part of the analysis.

In chapter II, the basic performance of the fuel cell and the complete inverter system are introduced. Chapter III presents the operating principle of the voltage fed full bridge converter and chapter IV shows the operating principle of the current fed full bridge inverter. In chapter V, the results of the power loss calculation are shown. In chapter VI the two converters are compared to each other. In chapter VII experimental results of a laboratory setup of a current fed full bridge converter are presented. Finally chapter VIII presents the conclusion.
II. BASIC SYSTEM PERFORMANCE

A. Fuel Cell characteristics

Figure 1 shows an example of the characteristic curve, of a single fuel cell [6]. Recommended operation of the cell is in the ohmic region (about a current density of 0.2 to 1 A/cm² in the curve below). Operation in the concentration region (declining section at about a current density of 1.1 to 1.2 A/cm² in the shown curve) of the fuel cell yields on the one hand to a bad efficiency of the fuel cell, on the other hand it may damage the fuel cell and has to be avoided. The fuel cell voltage typically specified in fig. 1 refers to one single fuel cell with a typical current density J. For a nominal operating point of 200 A at 100 V i.e. one has to take a series connection of 168 cells with a cell area of 200 cm² for the examplarily characteristic shown above. In general, there are curves that show a less stiff characteristic than the example shown in fig. 1. Due to the distinctive fuel cell characteristic curve, the voltage at nearly no load can reach values of much more than the nominal voltage, i.e. 168 V in the example above. Due to degradation effects of the fuel cell during its lifetime the voltage decreases. A degradation of 10 % corresponding to a lowest voltage of 90 V is assumed for the dimensioning of the converters. Thus, the converters have to be able to operate at input voltages from $V_1 = 90\, \text{V} \ldots 200\, \text{V}$.

B. Fuel cell inverter system

Fig. 2 shows the whole schematic of the fuel cell inverter. The dc/dc converter elevates the fuel cell voltage $V_1$ to the the voltage source inverter’s dc link voltage $V_2$ which has to be greater than the rectified line to line voltage [3]. The dc link capacitor decouples the voltage source inverter and the dc/dc converter and keeps the dc link voltage ripple at an adequate level. A feasible power flow control method could be keeping the dc link voltage constant via the dc/dc converter. An additional energy storage is not required due to the fact that the inverter is connected in parallel to the mains and peak power is delivered from the mains. Tab. 1 shows the voltage levels of the inverter system taken for this analysis. Nominal operating point of the fuel cell is $V_1 = 100\, \text{V}$ at $I_1 = 200\, \text{A}$.

III. VOLTAGE FED FULL BRIDGE CONVERTER

A. Operating principle

Voltage fed full bridge converters are well-known circuits for high power switch mode power supplies to convert high voltages at the input to low voltages at the output. They are used in fuel cell or photovoltaic inverters as well [1][2]. Fig. 3 shows the circuit diagram of the voltage fed full bridge converter. The transistors $T_1\ldots T_4$ at the input can be MOSFETs due to the low input voltage $V_1$ of the fuel cell. The high frequency transformer is modelled by the following: the transformer has the turns ratio $n$, its total stray inductance $L_\sigma$ is the sum of the primary stray inductance and the secondary stray inductance reflected across the transformer to the primary. The magnetizing inductance $L_m$ is much bigger than the leakage inductance [7]. The rectification on the secondary side is realized with a full bridge rectifier consisting of the diodes $D_1\ldots D_4$.

The waveforms and characteristic time instants are shown in fig. 4. The periods of time are described in the following.

$t_0 - t_1$: At $t_0$ transistors $T_1$ and $T_2$ are switched on. The diodes $D_1\ldots D_4$ are conducting, the secondary voltage of the transformer $V_{sec}$ equals zero. The slope of the rising transformer current is determined by the transformer’s leakage inductance $L_\sigma$ and the Voltage $V_1$.

$t_1 - t_2$: At $t_1$ the primary current $i_{pri}$ reflected over the transformer to the secondary has reached the output current $i_2$. The commutation of the diodes has finished, now only $D_1$ and $D_4$ are conducting. Energy is transferred via the transformer to the secondary. The voltage at the secondary is $V_1\cdot n$ minus the voltage drop over the leakage inductance $L_\sigma$. The current $i_{pri}$ is furthermore rising due to the fact that the voltage at the transformer’s secondary is higher than $V_2$. 

![Fig. 3. Circuit diagram of voltage fed full bridge dc/dc converter](image-url)

**TABLE I**

VOLTAGES OF THE FUEL CELL INVERTER SYSTEM FOR THE ANALYSIS

<table>
<thead>
<tr>
<th>Fuel cell voltage</th>
<th>Dc-link voltage</th>
<th>Line to line voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1 = 90-200, \text{V}$</td>
<td>$V_2 = 700, \text{V}$</td>
<td>$V_{line} = 400, \text{V}$</td>
</tr>
</tbody>
</table>

+10% / - 15%
At t₂ the transistors T₁ and T₂ are switched off. There is a freewheeling path of the primary transformer current through the body diodes of T₃ and T₄. The transformer’s primary voltage is negative (−V₁). The rectifier diodes D₂ and D₃ start to conduct in addition to D₁ and D₄ the secondary voltage of the transformer vsec equals zero.

The slope of the falling current ipri is determined by the voltage -U₁ and the leakage inductance Lσ.

At t₃ the current ipri has become zero. Primary voltage and secondary voltage of the transformer are zero, too. The diodes D₁–D₄ are conducting, the transistors T₁–T₄ are off.

At t₄ the transistors T₃ and T₄ are switched on. The behavior and the waveforms in the second half period are like the ones shown above due to the symmetrical circuit of the converter.

### B. Analysis

The duty cycle D* of the voltage fed full bridge converter is defined here as follows:

\[
D^* = \frac{2T_E^*}{T} \quad \text{with } T_E^* \text{ as shown in fig. 4.} \tag{1}
\]

The ratio between the input voltage V₁ and the output voltage V₂ can be derived to:

\[
V_2 = L_2 D^* n \frac{V_1}{(L_2 + L_\sigma n^2 - D^* L_\sigma n^2)} \tag{2}
\]

It depends on L₂, L₀, the transformer turns ratio n and the duty cycle as defined above.

The maximum possible duty cycle depends on the leakage inductance L₀, the period T and the transformer turns ratio n. For a well smoothed output current i₂ it can be derived to:

\[
D_{\text{max}}^* = 1 - \frac{4L_\sigma I_2 n}{V_1 T} \tag{3}
\]

Eq. (2) inserted in eq. (1) yields to the maximum achievable output voltage V₂, max for given system parameters. From this it can be seen that the leakage inductance of the transformer L₀ has a great influence on the dimensioning of the converter. The leakage inductance limits the maximum output to input voltage ratio V₂/V₁ or the operation frequency f = 1/T of the converter.

The blocking voltage of the rectifier diodes is V₁n. It is very high at low load due to the high voltage at the fuel cell and the high turns ratio of the transformer.

### IV. CURRENT FED FULL BRIDGE CONVERTER

#### A. Operating principle

The circuit of a current fed full bridge converter is shown in fig. 5. At the input there is the filter inductance L₁. As will be shown in the following, a clamping circuit is needed. This circuit consists of the diode D₁Cl and the capacitance with assumed constant voltage V₁Cl. The maximum blocking voltage of transistors T₁–T₄ is the voltage of the clamping circuit V₁Cl. The transformer Tr has the turn ratio n. The rectification on the secondary side is realized with a full bridge rectifier consisting of the diodes D₁–D₄ directly connected to the output voltage V₂.

At t₅ the transistors T₃ and T₄ are switched on. The behavior and the waveforms in the second half period are like the ones shown above due to the symmetrical circuit of the converter.

#### B. Analysis

The duty cycle D* of the voltage fed full bridge converter is defined here as follows:

\[
D^* = \frac{2T_E^*}{T} \quad \text{with } T_E^* \text{ as shown in fig. 4.} \tag{1}
\]

The ratio between the input voltage V₁ and the output voltage V₂ can be derived to:

\[
V_2 = L_2 D^* n \frac{V_1}{(L_2 + L_\sigma n^2 - D^* L_\sigma n^2)} \tag{2}
\]

It depends on L₂, L₀, the transformer turns ratio n and the duty cycle as defined above.
switched off. The primary current $i_1$ is impressed into the transformer with its leakage inductance $L_\sigma$. Due to the fast current slope at $L_\sigma$, the voltage across the transformer’s primary is rising so the clamping diode $D_{Cl}$ starts to conduct. The primary voltage of the transformer is clamped to $V_{Cl}$ which will be kept to a constant value. The falling slope of the input current $i_1$ is determined by the voltage $V_1-V_{Cl}$ across the inductance $L_1$. The slope of the primary current $i_{pri}$ is determined by the voltage $(V_{Cl}-V_2/n)$ across the leakage inductance $L_\sigma$.

$t_4 - t_3$: At $t_3$ the transformer’s primary current $i_{pri}$ has reached the input current $i_1$. Energy is transferred via the transformer to the secondary. The current $i_1$ and $i_{pri}$ are equal. The current slope is determined by the voltage $(V_{1}-V_{2}/n)$ across $(L_1+L_\sigma)$.

At $t_4$ transistors $T_3$ and $T_4$ are switched on, all transistors are conducting. Due to the symmetrical circuit of the converter the waveforms in the second half period are equal to the waveforms shown above.

**B. Analysis**

The duty cycle $D$ of the current fed full bridge converter is here defined as follows:

$$D = \frac{2T_E}{T} \text{ with } T_E \text{ as shown in fig. 6}$$

The ratio between output and input voltage $V_2/V_1$ depends on the mean input current $I_1$, $L_1$, $n$ and the duty cycle $D$. It does not depend on stray inductance $L_\sigma$. The expression of the ratio between output and input voltage $V_1/V_2 = f(D, I_1, L_1, n)$ is rather huge. Showing it will go beyond the scope of this paper.

Due to the boost principle of the current fed full bridge converter, the input voltage is limited to a maximum amplitude. This yields to the maximum transformer turns ratio $n_{max}$ depending on maximum input voltage $V_{1,max}$ and output voltage $V_2$:

$$n_{max} = \frac{V_2}{V_{1,max}}$$

As shown in chapter IV, section A, the current fed full bridge converter needs a clamping circuit for the energy stored in the transformer’s leakage inductance. The power, which has to be dissipated through the clamping circuit, is given in eq. (6):

$$P_{Cl} = V_{Cl} I_1^2 T_\sigma \frac{n}{(n V_{Cl}-V_2)}$$

It depends inter alia on the clamping voltage $V_{Cl}$ and the leakage inductance $L_\sigma$.

In contrast to the voltage fed converter the duty cycle is not influenced by the leakage inductance, but the power in the clamping circuit is higher for a larger leakage inductance. In addition the blocking voltage of the rectifier diodes is $V_2$ at every operating condition.

**V. SEMICONDUCTOR LOSSES**

**A. Semiconductor losses of the voltage fed full bridge converter**

In this section the calculation of the semiconductor losses is shown. The following simplifications have been assumed: the output current $i_2$ is assumed to be well smoothed. The output characteristic of the MOSFETs ($T_1$ – $T_4$) is modelled with the drain source resistance $R_{DSon}$, the output characteristic of the MOSFET’s body diodes and the rectifier diodes are modelled with a forward threshold voltage $V_{F0}$ and a differential resistance $r_F$ ($V(1) = V_{F0} + r_F \cdot I$). The switching losses of the body diodes and the rectifier diodes are calculated [7] using their reverse recovery charge $Q_{rr}$, which depends on the slope of the falling diode current. Due to the slow current slopes the switching losses of the diodes are comparatively low. MOSFET’s switching losses are estimated by multiplying idealized current and voltage waveforms (with rise time $t_r$ and fall time $t_f$ as defined in the respective datasheet) and integrating the product [7]. Due to the fact that the transistor current rises very slow, caused by the leakage inductance of the transformer, turn on losses are very small. The semiconductor losses in detail are as follows:

MOSFET conduction losses:

$$P_{C,MOS} = R_{DSon} \frac{n^2 I_2^2}{3} \frac{L_1 I_2^2}{V_{Cl} T_\sigma} + R_{DSon} \frac{n^2 I_2^2 D^*}{2}$$

MOSFET switching losses:
Conduction losses of MOSFET’s body diode:
\[ P_{C,Body} = V_{F0} n_2 I_2 L_{\alpha} + \frac{r_p n_2 I_2 L_{\alpha}}{3 V_1 T} \] (9)

Switching losses of MOSFET’s body diode:
\[ P_{S,Body} = \frac{Q_n V_1}{4 T} \] (10)

Conduction losses of one rectifier diode:
\[ P_{C,RF} = \frac{r_p n_2 I_2 L_{\alpha} + r_p n_2 I_2 L_{\alpha}}{4 V_1 T} \]
\[ + \frac{r_p n_2 I_2 L_{\alpha}}{2} \left( \frac{D^T}{2} + \frac{n_2 I_2 L_{\alpha}}{V_1} \right) \] (11)

Switching losses of one rectifier diode:
\[ P_{S,RF} = \frac{Q_n V_1 n}{2 T} \] (12)

B. Semiconductor losses of the current fed full bridge converter

For the loss calculation of the current fed full bridge converter the simplified conditions shown in the section above have been assumed, too. In contrast to the voltage fed converter, the input current \( i_1 \) is here well smoothed. In the current fed full bridge converter with the proposed modulation the body diodes are not used, but there are conduction and switching losses in the clamping diode.

The losses in detail are as follows:

MOSFET conduction losses:
\[ P_{C,MOS} = R_{DSS} \frac{I_r^2}{2} \left[ \frac{8}{12} \left( \frac{n_1 I_1 L_{\sigma}}{V_2} \right) + \frac{1}{2} \left( \frac{D^T}{2} \right) \right] \]
\[ \frac{n_1 I_1 L_{\sigma}}{V_2} \]...

MOSFET switching losses:
\[ P_{S,MOS} = \left( V_{F0} \frac{I_1 L_{\sigma}}{2 n^2} + V_{Cl} \frac{I_1 L_{\sigma}}{2 n^2} + \frac{I_1 L_{\sigma}}{2 n^2} \left( V_{Cl} + \frac{L_{stop} I_1}{2 V_2} \right) \right) \frac{1}{2} T \] (14)

Conduction losses of one rectifier diode:
\[ P_{C,RF} = \left( V_{F0} \frac{I_1 L_{\sigma}}{2 n^2} + r_p \frac{I_1 L_{\sigma}}{3 n^2} \left( \frac{I_1 L_{\sigma}}{V_1} \right) + \frac{n_1 I_1 L_{\sigma}}{2 V_2} \right) \frac{1}{2} T \]
\[ + \left( V_{F0} \frac{I_1 L_{\sigma}}{2 n^2} + \frac{r_p L_{\sigma}}{3 V_1 T} + \frac{I_1 L_{\sigma}}{2 V_2} \right) \frac{D^T}{2} \frac{1}{2} T \] (15)

Switching losses of one rectifier diode:
\[ P_{S,RF} = \frac{Q_n V_1}{4 T} \] (16)

Conduction losses of the clamping diode:
\[ P_{C,Cl} = V_{F0} \frac{I_1 L_{\sigma}}{2} \frac{1}{T} + \frac{2 I_1 L_{\sigma}}{3 V_1} \frac{1}{T} \] (17)

Switching losses of the clamping diode:
\[ P_{S,Cl} = Q_n \frac{V_{Cl} - V_2}{4 T} \] (18)

VI. COMPARISON

A. Converter’s dimensioning and operating conditions

In the following semiconductor losses for the voltage fed and the current fed full bridge converter are calculated for a certain dimensioning. Starting from the operating conditions shown in chapter II section B the converter’s components are rated as follows. The projected MOSFETs on the voltage fed converter are calculated for the worst case (maximum losses) by using the loss equations shown above for different numbers of semiconductors. The numbers of semiconductors is optimal dimensioned if the junction temperature of the used semiconductors is near to and does not exceed 125°C in the worst case. The assumed transformer leakage inductance is \( L_{in} = 0.75 \mu H \).

Fig. 7 shows the efficiency based on semiconductor losses for the current fed and the voltage fed full bridge converter depending on the input current \( I_1 \). The current fed converter has significantly lower semiconductor

![Fig. 7. Efficiency of voltage fed (dotted line) and current fed full bridge converter (solid line) connected to the fuel cell depending on fuel cell current. Optimal rating of semiconductors.](image)
conducting losses because the left and the right leg are connected in parallel during $T_E$. The efficiency of the current fed converter is about 1-2\% better than the efficiency of the voltage fed converter.

More than 80\% of the semiconductor losses are conducting losses. From this, losses can be easily reduced by connecting more MOSFETs in parallel. Fig. 8. shows the efficiency of the two converters with an overdimensioning of the MOSFETs. It can be seen that even with more than twice as many MOSFETs per switch in parallel than the current fed converter, the voltage fed converter reaches just the efficiency of the optimal utilized current fed converter.

C. Evaluation

This section gives a short outline of the characteristics of the voltage fed and current fed full bridge converter.

The working principle of the voltage fed full bridge converter could be characterized as “buck” principle. The series connected transformer generates the high voltages which will be averaged using the inductor $L$. Therefore the voltage fed converter needs a transformer with high turns ratio. The leakage inductance $L_\sigma$ has a strong influence on the converter’s dimensioning. The blocking voltage at the rectifier diodes is very high, particularly at low duty cycles (high input voltages at low fuel cell load). The start up of the converter from $V_2 = 0$ V can be easily obtained by the voltage fed converter. Due to the voltage fed input, the input current becomes temporarily negative. In order to provide negative currents from the fuel cell, additional filter elements are required. The transformer of the voltage fed converter is well utilized at nominal load due to high duty cycles. The voltage fed full bridge converter shows much higher losses and a higher amount of semiconductors compared to the current type converter. Switching losses of the MOSFETs contribute less than 4\% to the total losses and, in addition, turn on losses are low due to the slow current slope caused by the transformer’s leakage inductance. Therefore phase shift modulation of the voltage fed full bridge converter [8] does not significantly reduce semiconductor losses.

The working principle of the current fed full bridge converter could be described as “boost” principle. The inductance $L$ at the input of the converter boosts the input voltage to a higher level. In addition this voltage is increased by the transformer. Hence, the current fed converter needs a transformer with a comparatively low turns ratio. The value of the transformer’s stray inductance influences the energy dissipated from the clamping circuit. The rectifier diode’s blocking voltage is always the output voltage $U_2$. The current fed converter is not able to work with output voltages near zero. Thus starting-up the converter has to be done by loading the dc link from the mains voltage source inverter or using the additional converter at the clamping circuit. Due to the input inductance at the converter, the input current is well smoothed; no additional filtering towards the fuel cell is needed [9]. Semiconductor losses of the current fed converter are lower than for the voltage fed converter, hence the current fed converter needs less power semiconductors than the voltage fed converter. Another possibility to recycle the clamping energy could be to use an active clamp circuit [10] instead of the passive clamp circuit as described above.

VII. EXPERIMENTAL RESULTS

Fig. 9 shows the laboratory setup of a 20 kW current fed full bridge converter. CoolMOS® semiconductor bridge with gate drive circuits and fast clamping diodes with heat sink on the left, high frequency transformer with $n = 3.25$ consisting of two transformers in “power link” connection to reduce the stray inductances of the transformer (parallel connection of the primary windings, series connection of the secondary windings) in the middle. On the right hand side there is the full bridge rectifier. The MOSFETs $T_1$-$T_4$ and the clamping unit consisting of $D_{C1}$ and $C_{C1}$ are linked by copper busbars to reduce the stray inductance of the clamping path. Below the heatsink of the MOSFETs there is the input inductance $L_1 = 10$ $\mu$H.

Fig. 10 and 11 show experimental waveforms of the current fed full bridge converter. The energy stored in the clamping unit is here dissipated by a resistor. Fig. 10 shows the gate signals of the transistors, the input current of the converter $i_1$ and the transformer’s primary current.
The operating performance of the converters is shown, and their semiconductor losses have been calculated and compared. The effects of the transformer’s leakage inductance on the dimensioning of the converters and the dimensioning of the transformer turns ratio have been shown. The analysis has been done by analytical calculation in steady state by average models.

The comparison between the two converter topologies is based on a converter design for a rated nominal input load of 20 kW at 100 V, 200 A, including standard fuel cell performance, and a dc link voltage of 700 V for an inverter at the three phase mains with a line to line voltage of 400 V. Standard power semiconductors have been selected.

The analysis shows that for this application the current fed converter has lower losses compared to the voltage fed converter. This is due to the fact that input MOSFETs are connected in parallel for the proposed modulation strategy. Due to the lower losses of the current fed full bridge converter, it can operate with less installed semiconductors compared to the voltage fed full bridge converter. However, the current fed converter needs an additional clamping circuit and for further improving the performance an additional auxiliary converter to transfer the energy dissipated in the clamping circuit to the dc link of the inverter.

Regarding this analysis it can be concluded that current fed full bridge converters combine most advantages. Thus they are the favored solution for dc/dc converters with high frequency transformers for fuel cell applications in the medium power range.

**REFERENCES**


