Abstract – This paper presents the results of a research project dealing with the development of an adjustable converter for the injection of power generated by low voltage energy sources (primarily fuel cells used for decentral cogeneration of electric and thermal energy) into the public grid. The converters principle of operation is explained; measurements demonstrate the performance of the converter interfacing to the fuel cell (e.g. current ripple) and the grid (islanding detection, grid power quality impact).

INTRODUCTION

Employing fuel cells, the cogeneration of electric and thermal energy in private houses offers an efficient way of primary energy (i.e. fuels) utilization. The decentral generation of thermal energy for heating renders heat transmission unnecessary while grid injection of the generated electric energy eliminates the need to store electric energy if the generated amount of energy does not meet the current level of local electric energy consumption.

In order to convert the direct current that can be drawn from the fuel cell at a low voltage level (in this case 40-80VDC) to an alternating current that can be injected into the grid (typically 230VAC/50Hz or 110VAC/60Hz), a power converter is necessary that accounts for the requirements of the fuel cell (low current ripple) and the grid (islanding detection, impact on grid power quality).

As the power drawn from the fuel cell is adapted to account for the varying amounts of required heating, the converter needs to maintain a high efficiency over a wide operating range. Considering the relatively high internal resistance of a fuel cell, this applies to the input voltage range as well as to the power level range. Often, the grid voltage shape is distorted by the harmonic currents drawn by nonlinear loads (e.g. input rectifiers of switched mode power supplies). In order to prevent a further degradation of the grids voltage quality, the converter needs to be able to inject a current with a defined shape (e.g. purely sinusoidal) despite the grid voltage shape being distorted. It may also desirable to improve the grid voltage shape by a directed injection of current harmonics with a phase angle opposite to the grid voltage harmonics, so that the voltage harmonics are (partially) compensated by the accumulated effect of a larger number of converters performing this kind of compensation. Similary, the converter can vary its active power output and an additional fundamental frequency reactive power component can be injected to counteract load/generation imbalances in the grid (voltage amplitude and frequency variations); the setpoints are determined by a voltage/frequency droop control or by commands issued by a centralised control system of the electric utility (virtual power plant).

When the local low voltage distribution grid is disconnected from the higher voltage level network due to a fault or for maintainance, converters operate in the islanded grid segment together with a number of loads. As the amount of power drawn by the loads may be balanced with the power output of the converters, islanding can not be detected reliably by only monitoring the (single phase) phase-to-neutral voltage in amplitude and frequency.

An additional detection method favoured by the grid connection regulations of several countries is the detection of sudden changes in the grid impedance. This is archived by injecting a test current and measuring the resulting alteration of the grid voltage. Employing a subharmonic (noncharacteristic to the grids fundamental frequency) test current run that is added to the setpoint run of the converters current control and using the converters digital signal processor for detecting the respective frequency component of the grid voltage, this method can be integrated
into a converter without increasing costs for additional circuit components. In case of an interruption of the public grid, it may be desirable to continue the power supply for local loads. This requires the converter to be operated in an voltage controlled 'island' mode after disconnection from the grid.

**PRINCIPLE OF OPERATION**

The two stage conversion circuit with an DC link energy buffer (Fig. 1) allows the injection of arbitrary current waveforms into the grid without an increase of low frequency input (fuel cell) current ripple (e.g. caused by the 100Hz pulsation of the fundamental frequency momentary power - switching frequency 100kHz pulses are buffered by an input capacitance). A DC/DC stage converts the input voltage of 40-80V to a DC link voltage of 360V. Due to the high voltage level ratio (factor 9 for minimum input voltage), the DC/DC stage employs a low voltage MOSFET full bridge, a high frequency transformer and a SiC rectifier to maintain high efficiency. The DC/AC conversion is performed by a CoolMOS full bridge controlled by the current (current mode control loop allowing arbitrary current waveforms) in the output filter inductance.

The converter is controlled by a digital signal processor (DSP) that performs all control and monitoring functions:

- DC link voltage regulation
- grid current regulation and grid synchronisation (phase angle in relation to grid voltage); output voltage control and overcurrent protection (overload, short circuit) in island mode
- fuel cell voltage monitoring (e.g. overload)
- DC link charge current monitoring
- grid voltage monitoring (islanding detection) and grid (dis-)connection
- MOSFET and high frequency transformer temperature monitoring
- optional higher level control functions modifying the grid current run: voltage/frequency droop, harmonic compensation

The DSP provides interfaces to a local temperature control (varying the amount of generated heat by adapting the active power) and optionally to a remote control system of the electric utility (modifying the active power setpoint, specifying setpoints for fundamental frequency reactive power and harmonic current components to improve voltage quality).

If communication with the control system of the electric utility is realised via a bidirectional communication channel, actual values of the local grid voltage amplitude and shape (in form of the voltages frequency spectrum) are reported to the electric utility to provide additional information about the present condition of the low voltage grid.

![Fig. 1. Simplified schematic of converter](image1)

![Fig. 2. Demonstration model](image2)
Figure 2 shows a front side view of the 1kW converter prototype designed for wall fastening. The circuit parts on the main printed circuit board (PCB) are arranged according to the respective ground potentials to separate fuel cell input and control electronics (1), DC link (2), and grid interface (3). The supply voltage for the control electronics is generated from the input (fuel cell) voltage to allow grid independent operation and to prevent the converter from drawing power from the grid. Thus, the electronics supply is placed on an exchangeable board (4) to adapt to different input (fuel cell) voltage ranges. Due to their size and to allow changes of their type of construction, the chokes of the DC link (5) and output filter (6) are not integrated on the main PCB. Next to the DC link choke, an optional freewheeling diode (7) is placed to increase efficiency: Connected in parallel to the SiC rectifier, the chokes current commutates to the freewheeling diode instead of a series of two rectifier diodes at the end of the duty cycle. The power semiconductors (a) i.e. low voltage MOSFETs, SiC diodes and CoolMOS are placed on the bottom side of the main PCB (b). Mounted on a right angle bracket (c), they are thermally connected to a heatsink (d) attached to the rear panel of the casing (e) as indicated in figure 3.

Fig. 3. Power semiconductor cooling

**FUEL CELL INTERFACE**

A. Fuel cell current ripple

Figure 4 shows a measurement of the converters input (fuel cell) current $I_{FC}$ and DC link voltage $U_{DC}$ ($I_{FC,AC}$ and $U_{DC,AC}$ represent the alternating current components with an increased resolution). The output (grid) current $I_{inj}$ indicates the phase angle of the AC components in relation to the output power pulsating at 100Hz. Calculating the rms-value of the 100Hz frequency component of the current run (approx. 0.6A) to filter out high frequency noise and dividing it by the currents average value (approx. 14A), the low frequency fuel cell current ripple amounts to approximately 4.3%. This value remains below the maximum permissable current ripple values specified by fuel cell manufacturers (typically 10-15%) to prevent a reduction of fuel cell lifetime.

![Fig. 4. Fuel cell current ripple measurement](image)

While the voltage control loops response time is parametrised not to compensate the DC link voltage ripple caused by the pulsating output power, a remaining current ripple is caused by the varying driving voltage at the DC link inductor.

If a further decrease of the input (fuel cell) current ripple is required, the DC link charging current variations caused by the DC link voltage varying from its nominal value due to low frequency DC link voltage ripple can be compensated by incorporating a charging current control loop into the DC link voltage control loop; a charging current control loop also allows current limiting and an optional modulation of the input current waveform.

B. Input bridge efficiency optimisation

At the end of each input bridge duty cycle, the transformer current commutates from the formerly conducting MOSFET diagonal to the body diodes of the opposite diagonal, causing increased losses due to the body diodes higher voltage drop. These losses can be decreased if the body diodes are bypassed by freewheeling of the current through one leg of the input side. Figure 5 shows the switching states of the input bridge and the waveforms of transformer input
voltage $U_v$, transformer input current $I_{tr}$ and drain source voltages of one half bridge $U_{dsT1}$ (highside) resp. $U_{dsB1}$ (lowside). Additionally, the gate drive schemes are drawn into the plot.

Without freewheeling, the transformer current decreases rapidly at the end of the duty cycle while the transformer voltage reverses its polarity, causing a large voltage-time area. Current and voltage oscillations occur before the drain-source voltages of the highside and lowside MOSFETs are balanced to approximately half of the input voltage. Freewheeling eliminates the voltage reversal and oscillation while current-time area is increased.

Due to the higher voltage drop of the MOSFETs body diodes when conducting the same initial transformer current, the initial power loss is higher without freewheeling. As the current decreases at a higher rate because of the counteracting input voltage, the overall power loss depends on the present point of operation.

In this application, freewheeling decreases the power losses for higher power levels, while an increase of the losses can be detected for low power output as indicated in figure 6. Thus, the converters DSP control performs an on-the-fly change of the input stages gate drive method depending on the current level of power output. A hysteresis function ensures the proper operation of the DC link voltage regulation by preventing a perpetual change of the switching method.

GRID INTERFACE

A. Current shape

As the current loop utilizes current mode (hysteresis) control, arbitrary current waveforms can be generated independent of the grid's voltage shape as well as a purely fundamental frequency current (a small amount of current shape distortion is caused by the current loop during polarity change) despite the grid voltage shape being distorted e.g. by nonlinear loads. The current run is determined by the requested amounts of active and reactive power. As shown in figure 7, the full power factor range from 0 to 1 can be accomplished (reactive power corresponds to a periodic exchange of energy between grid and DC link).

Optionally, grid voltage harmonics can be compensated (assuming a larger number of converters) by injecting current harmonics with an opposite phase angle. Because of the low impedance of the grid, a complete harmonic compensation is not possible with the limited current of only one converter.

To demonstrate the effect that can be expected for a larger number of converters performing harmonic compensation, the grid impedance is
increased by a resistive coupling of the converter to the grid. The resulting grid voltage and injected current shapes are shown in figure 8; to allow a comparison, the voltage and current shapes without harmonic compensation are also included in the diagram.

Fig. 8. Voltage and current shape with harmonics compensation and increased grid impedance

B. Islanding detection

In addition to monitoring the grid voltages amplitude and frequency, the converter optionally performs a measurement of the grid impedance. Employing a subharmonic test current component that is added to the converters current run and determining the resulting subharmonic frequency component of the grid voltage via a digital fourier transformation (DFT), the complex grid impedance at the subharmonic frequency (e.g. 40Hz) is calculated. Assuming a resistive/inductive grid, the inductive component (imaginary part) of the result can be scaled (according to the frequency ratio) to acquire the impedance at the grids fundamental frequency. The measurement result for a given subharmonic frequency will deviate from the correct value when several converters inject subharmonic test currents at the same frequency: Depending on the relative phase angles, the impedance value can vary between the actual value multiplied with the number of converters in the grid segment (all currents adding up) and zero (currents compensating each other). Thus, the conventional impedance measuring method employing subharmonic test currents is extended by an additional modulation/demodulation step as shown in figure

9: To allow a larger number of converters to be operated within a grid segment without interference of their measurements causing unintended grid disconnections, the subharmonic test currents amplitude is modulated with a pulse pattern, assigning each converter an individually detectable "signature" for its test signal.

Fig. 9. Structure and simulated time base run of subharmonic impedance measurement with pulsating amplitude

In figure 10, two converters operate at the same subharmonic frequency without amplitude pulsation (non-filled markings): For the measurements taken while both converters are performing grid impedance measurements, the calculated impedance values deviate from the expected value implied by the measurements that are recorded with only one converter operating. Using different amplitude pulsation frequencies (filled markings), an interference between the impedance measurements of the converters can be prevented: The correct impedance values are recorded during parallel operation.

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1. \( \text{DFT}(I_{inj}) \) is inverse fourier transformation of 50-500Hz current components to eliminate switching noise
Islanding detection deactivates the current injection and disconnects the converters output stage from the grid. After grid disconnection, it is possible to supply local loads connected parallel to the output filters capacitance in an voltage controlled operation mode.

The transition² from grid injection to 'island' mode is shown in figure 11. Markings indicate the points of time for output stage deactivation (1) and output reactivation in voltage control mode (3); the point of time for grid disconnection (2) depends on the response time of the relay. In 'island' mode, the converters output current is equivalent to the load current; with a resistive load, voltage and current shapes are sinusoidal.

REFERENCES


[3] F. Bertling and S. Soter, "Improving grid voltage quality by decetral injection of current harmonics", IECON05 Raleigh, USA, 2005


CONCLUSION

The described converter topology allows the injection of power generated by low voltage energy sources (primarily fuel cells used for decentral cogeneration of electric and thermal energy) into the public grid. Utilising a two stage conversion with a DC link energy buffer, the momentary values of input (fuel cell) and output (grid) power are decoupled, allowing arbitrary input and output current waveforms.

Employing a digital signal processor (DSP) as a central controller, control strategies and monitoring functions can be implemented to provide suitable interfaces to the fuel cell (low current ripple, high efficiency over wide operating range) and the grid (islanding detection, power quality).

To complement the measurements obtained from the prototype as presented in this paper and to obtain information about the converters long-term operating performance and reliability, a field test is planned in cooperation with an industrial partner and an electric utility company.