

# Full Bridge DC-DC converter as input stage for fuel cell based inverter system

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**Abstract-Telkom and other critical service companies use batteries as the main source of energy for their inverters and uninterruptible power supplies (UPS). An alternative to the battery run inverter or UPS systems would be the use of a fuel cell as the source of energy. Fuel cells provide the main advantage of refuelability over battery operated systems. They can also be used in places where there is no grid connectivity, provided that fuel is available to run the fuel cell. Fuel cells though have the distinct technical drawbacks of slow start startup times, drop in line voltage when the cell is loaded and slow response to transients in the load. In addition, low to medium power fuel cells deliver lower voltage with respect to the grid voltage at high currents. Therefore a higher DC link voltage is required at the input of DC-AC converters to produce the mains level voltage of 240 V AC. Various DC-DC converter schemes can be employed to regulate the varying fuel cell voltage to a required DC-link voltage.**

**This paper presents the development of current fed fullbridge converter prototype as the input stage to a fuel cell inverter system in the 1 – 1.5 kW range. The purpose of this power converter is to boost the 30 -50 V produced by a commercial PEM fuel cell to 100 V for conversion to 240 V 50 Hz used to run domestic loads. The preliminary results of the experimental measurements of the prototype are given.**

## 1. INTRODUCTION

The fuel cell generates electrical energy from a chemical reaction, similar to a battery but fuel cell technology provides the added advantages of refuelability, little maintenance and no problems with disposal as is faced by batteries and other power solutions. In spite of this the cost of this technology still remains its main disadvantage. Nonetheless power electronic converters are required to utilize power generated by fuel cells for running domestic appliances [2].

An inverter system is proposed which will incorporate a PEM fuel cell stack as the DC power source and generate a 240 V 50 Hz single phase alternating current capable of running loads up to 1.25 kVA.

Figure 1, presents the overall block diagram of the system. The system consists of two stages which are the current fed fullbridge converter and the boosted DC to AC inverter. The

DC-DC full bridge converter boosts the variable input voltage generated by the stack to a DC-link voltage of 100 V DC.

The gain of the converter is achieved through a high frequency transformer, which also galvanically isolates the load and inverter from the fuel cell [3] and [6].

The next stage, which is the DC-AC boosted converter, comprises of 2 buck boost converters that are supplied from the 100 V DC-link bus of the DC-DC converter. Each buck-boost converter uses a different duty cycle to produce a DC-biased sine wave output. The resultant output voltage across the load is thus a sine wave. This strategy differs from those that require a 400 V DC-link voltage such as [3] and [6] to generate 240 V 50 Hz.

The two stage design for the complete inverter system was chosen to limit the losses to the first stage of the converter i.e. the DC-DC conversion stage, and still achieve a total efficiency above 75 %.

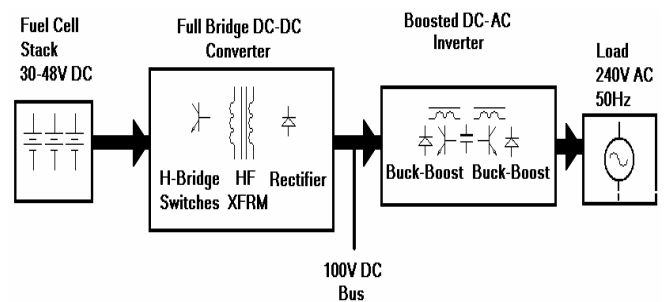


Figure 1: Inverter system block diagram

## 2.1 FULL BRIDGE DC-DC CONVERTER: OPERATING PRINCIPLE

The full bridge converter is a versatile regulation topology that can be used for various power conversions. It provides high power handling, stability and all round symmetry. When a high frequency transformer is used with this topology it not only saves weight but also provides an efficient way of stepping up voltage and transferring large amounts of power.

The full bridge DC-DC converter comprises of four semiconductor switches, a high frequency transformer that feeds into a rectifier circuit as shown in Figure 2.

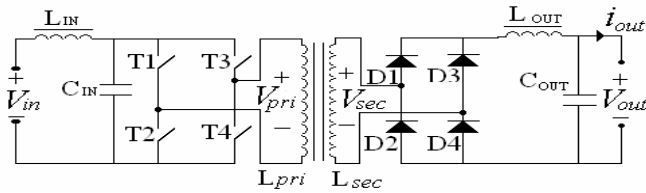


Figure 2: Full bridge converter component layout

To achieve the transfer of power from the input to the output, switches T1-T4 are switched at a high frequency. The switching sequence is in four modes described by Figures 3, 4, 5 and 6.

Mode 1: When switches T2 and T3 are turned ON while switches T1 and T4 are OFF; the primary voltage is positive and the diodes D1 and D4 carry the current through to the output.

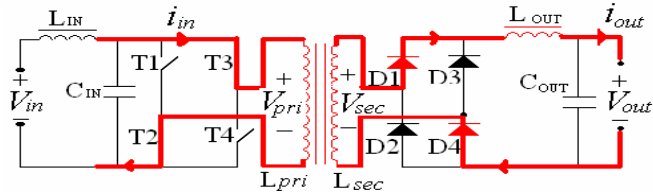


Figure 3: Mode 1 current flow

Mode 2: When all switches are OFF and during this first dead time the output current continues to flow through all 4 diodes.

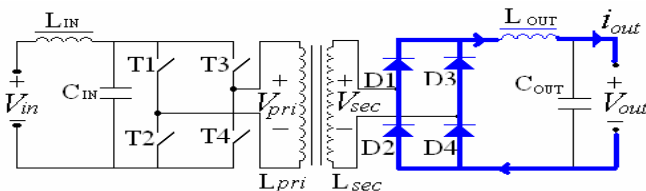


Figure 4: Mode 2 current flow.

Mode 3: When switches T1 and T4 are ON, while T2 and T3 are OFF. The primary voltage is reversed and diodes D4 and D1 are reverse biased this causes the output current to flow through diodes D2 and D3.

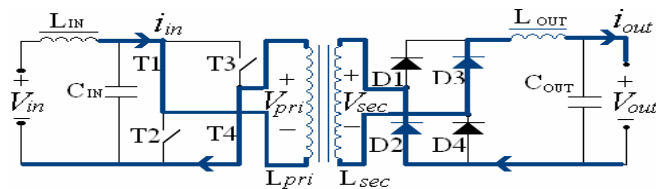


Figure 5: Mode 3 current flow

Mode 4: When all switches are OFF; similar to mode 2, this is the second dead time. Again in this mode the current is carried through to the output by all four diodes.

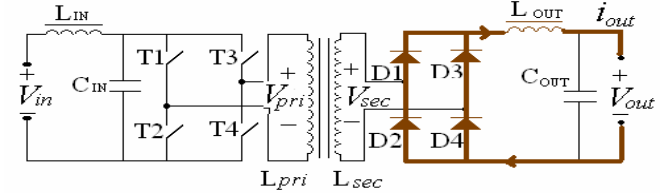


Figure 6: Mode 4 current flow.

This switching sequence described in the modes above will cause a square ac wave at the primary of the transformer. This ac wave is then stepped up by the transformer. The transformer output voltage is stepped up rectified and then filtered to produce the DC output. The steady state waveforms, of this type of converter operating in continuous conduction mode are shown in Figure 7.

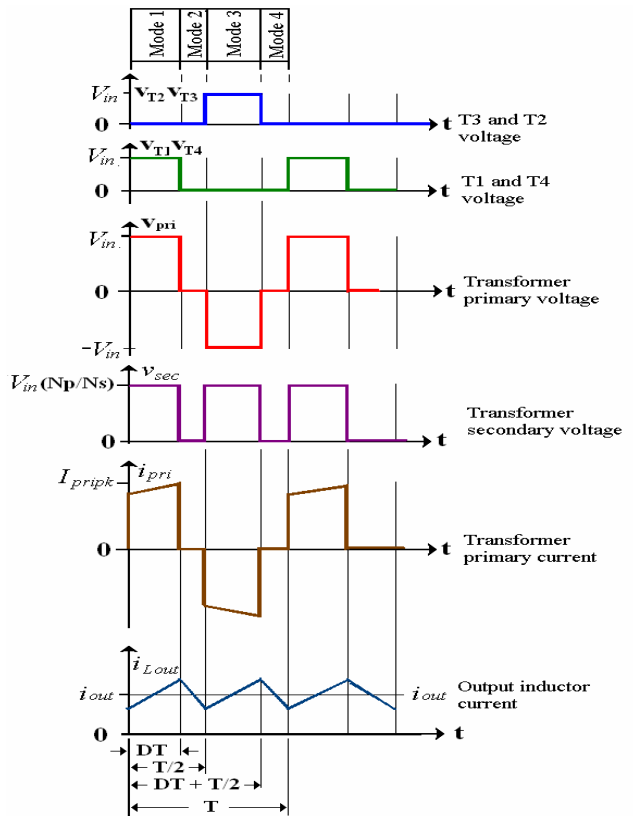


Figure 7: Waveforms for a full bridge converter.

## 2.2 FULL BRIDGE CONVERTER SYSTEM ANALYSIS

According to [5], mathematical expressions for the four modes of operation over one switching cycle to obtained as follows:

Mode 1: This mode is valid for the time period  $0 < t < DT$ . During this mode switches T2 and T3 are turned ON while T1 and T4 are OFF, the voltage across the secondary is calculated according to (1). The plot for the secondary voltage  $V_{sec}$  is shown on Figure 3,

$$V_{sec} = \frac{N_s}{N_p} V_{in} \quad (1)$$

The voltage across the output inductor  $L_{out}$  is given by

$$v_{Lout} = \frac{N_s}{N_p} V_{in} - V_{out} \quad (2)$$

The output inductor current increases linearly at a rate of

$$\frac{di_{Lout}}{dt} = \frac{v_{Lout}}{L_{out}} = \frac{1}{L_{out}} \left[ \frac{N_s}{N_p} V_{in} - V_{out} \right] \quad (3)$$

This gives the peak inductor current  $I_{Lout(pk)}$  at the end of this mode with  $t = DT$  as:

$$I_{Lout(pk)} = I_{Lout}(0) + \frac{1}{L_{out}} \left[ \frac{N_s}{N_p} V_{in} - V_{out} \right] \quad (4)$$

Mode 2: This mode is valid for the time period for  $DT < t < T/2$ . During this time all switches are OFF, while diodes D1 and D2 are forward biased and conduct the magnetizing current generated at the end of mode 1. Redefining the time origin at the start of this mode, the rate of fall of the output inductor current  $i_{Lout}$  is given by;

$$\frac{di_{Lout}}{dt} = \frac{V_{out}}{L_{out}} \quad \text{For } 0 < t \leq (0.5 - D)T \quad (5)$$

This gives;

$$\begin{aligned} I_{Lout}(0) &= i_{Lout} [t = (0.5 - D)T] \\ &= I_{Lout(pk)} - V_{out}(0.5 - D) \frac{T}{L_{out}} \quad (6) \end{aligned}$$

Mode 3: This mode is valid for the time period  $T/2 < t < DT + T/2$ . During mode 3, T1 and T4 are ON while T2 and T3 are OFF. Diode D1 is reverse biased and D2 conducts. The voltage across the primary  $V_{pri}$  is  $V_{in}$ . The circuit operates similar to mode 1.

Mode 4: This mode is valid for the time period  $DT + T/2 < t < T$ . During this second dead time all switches are OFF and the output current flows through all four diodes as in mode 2.

The output voltage  $V_{out}$  is obtained by taking the time integral of the output inductor voltage  $v_{Lout}$  over the switching period  $T$  that is:

$$\begin{aligned} V_{out} &= 2 \times \frac{1}{T} \int_0^{DT} \left( \frac{N_s}{N_p} V_{in} - V_{out} \right) dt + \\ &\quad \int_{T/2}^{T/2+Dt} -V_{out} dt \quad (6) \end{aligned}$$

This gives  $V_{out}$  as;

$$V_{out} = 2 \frac{N_s}{N_p} V_{in} D \quad (7)$$

The output power  $P_{out}$  for this type of converter is given by

$$P_{out} = \eta P_{in} = \eta V_{in} I_{pri(avg)} D \quad (8)$$

This gives the average primary current  $I_{pri(avg)}$  as;

$$I_{pri(avg)} = \frac{P_{out}}{\eta V_{in} D} \quad (9)$$

### 3.1 FULL BRIDGE CONVERTER PROTOTYPE DESCRIPTION

The specifications set for the design based on the analysis in section 2 are shown as follows:

|                |           |
|----------------|-----------|
| Supply voltage | 30 – 48 V |
| Efficiency     | 75 %      |
| Output Power   | 1000 W    |
| Output Voltage | 100 V     |

The functional block diagram of the full converter system prototype is shown in Figure 8. The fuel cell which is the power source of the converter, feeds into the full bridge converter circuit as described in section 2.1, which then feeds into the DC-AC inverter (load). The control of the system is by means of a UC3825 IC from Texas instruments.

The PWM IC generates low and high MOSFET drive signals that are adjusted to give an output of 100 V. This voltage is measured by a voltage sensor and then isolated by the isolation amplifier. This isolated voltage is then fed into the control IC, which compares this voltage with its own internal reference.

If the error is positive then the output pins of the control IC are shut off hence providing over voltage protection for the next stage of the system. If the error is negative the duty cycle is adjusted to give the desired output voltage.

The input current is also monitored and its equivalent voltage is feed into the current limit pin of the control IC. If the current exceeds the set current limit the output pins of the control IC are shut off, also providing short circuit protection.

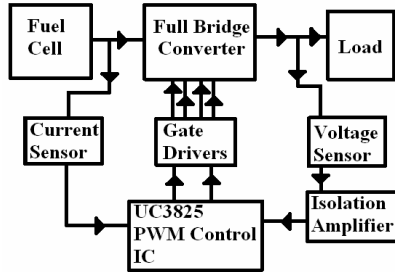


Figure 8: Full Bridge Converter system block diagram

### 3.2 CONVERTER INPUT STAGE HARDWARE

This comprises of the input LC filter and H-bridge switches. The H-Bridge switching stage consists of 4 paralleled 100 V, 40 A MOSFETS (STP40NF10L) that are chosen for their low on resistance ( $R_{dsON}$ ), to carry the input current. Two devices per switch are paralleled together to handle the input current and also reduce the switching losses caused by the MOSFET ON resistance. The paralleling of switching devices leads to ringing and unwanted oscillations from the leakage inductance and capacitance of the switching devices [1], [4]. Two parallel devices are used in this design as a trade off to this shortcoming.

The input and output capacitors are selected based on equivalent series resistance (ESR), ripple current, cost and availability. Four 220  $\mu$ F 100 V electrolytic capacitors (RIFA) are used at the input and six 220  $\mu$ F 100 V capacitors are used at the output. These capacitors in addition to having very low ESR have the advantage of high capacitance per unit volume and long service life which further improves on the robustness of the design.

### 3.3 HIGH FREQUENCY TRANSFORMER DESIGN

The HF transformer is an integral part of the full bridge converter. The design employs a ETD59 core for the HF transformer which operates at 25 kHz. It comprises of a single primary and single secondary windings. The primary winding is divided into two 4-turn sections that are rated to carry 40 A average current supplied by the fuel cell at full load. The primary is wound using copper foil in order to minimize leakage inductance and the skin effect that is prevalent in cylindrical copper conductors.

The secondary winding comprises of 20 turns of copper foil and is sandwiched between the two primary sections so as to achieve good coupling. A cross section of the winding topology showing the primary and secondary terminations are shown Figure 9.

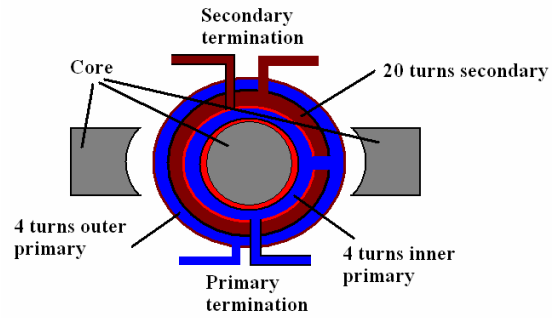


Figure 9: Cross section of HF transformer

## 4. EXPERIMENTAL MEASUREMENTS AND RESULTS

1 kW prototype has been built and tested to evaluate its performance as the input stage to the inverter. Figure 10 shows a picture of the prototype. The switching frequency of the system is set to 25 kHz, with the load varied from 100 W through to the full load of 1 kW. The efficiency of the system under different loads has been determined and shown in Table 1. The plots for the output voltage and current at full load are shown in Figures 11, 12, while Figure 13 illustrates the plot of efficiency against load.

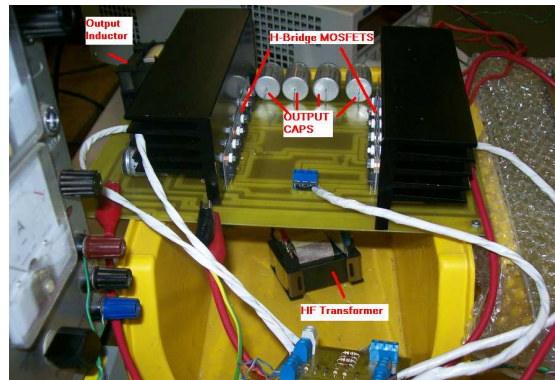


Figure 10: Picture of the 1 kW prototype setup

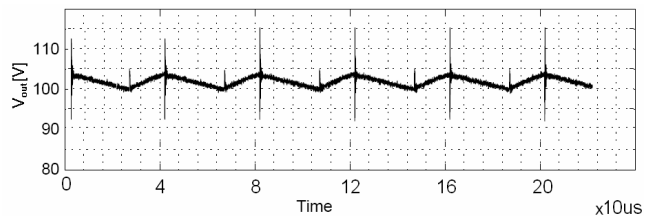


Figure 11: Output voltage plot at 1 kW

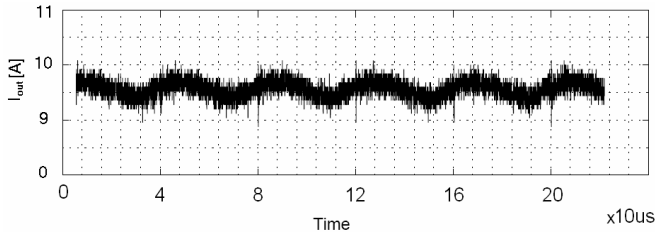


Figure 12: Output current plot at 1 kW

TABLE 1  
POWER OUTPUT AND EFFICIENCY FOR THE FULL  
BRIDGE INVERTER PROTOTYPE

| Power Output<br>[W] | Efficiency [%] |
|---------------------|----------------|
| 100                 | 78             |
| 200                 | 77             |
| 300                 | 77             |
| 400                 | 79             |
| 500                 | 80             |
| 600                 | 82             |
| 700                 | 84             |
| 800                 | 85             |
| 900                 | 84             |
| 1000                | 79             |

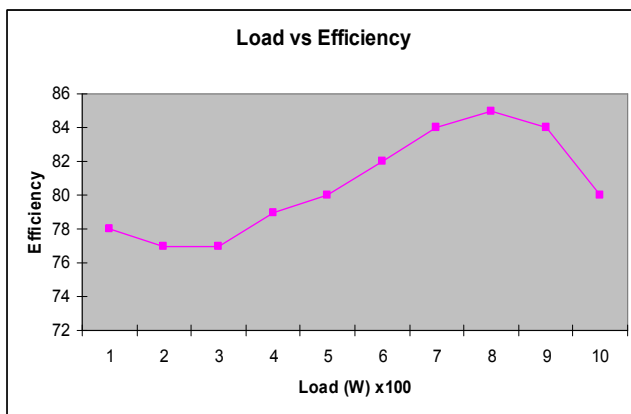


Figure 13: Plot of load vs. efficiency of the full bridge converter system.

## 5. CONCLUSION

The objective of the project was to build a prototype full bridge DC-DC converter as an input stage to DC-AC inverter of a fuel cell inverter system. A prototype was constructed which converts 30 – 48 V DC to 100 V DC with an output power up to 1kW. This 100V DC can be used by a buck - boosted DC-AC to generate 240 V 50 Hz.

From the results obtained it is determined that the full bridge converter prototype has an overall efficiency of greater than 77%. The lowest efficiency was observed at 300 W. The voltage gain of the system was also satisfactory with a voltage

of 100 V for an input of 35 V, which is ideal for next stage of the converter.

It should be noted however that load current was tested only with resistive loads. The impedance of the next stage would have to be taken into consideration to further improve the converter. In addition soft switching techniques can also be investigated to further improve the efficiency of the converter.

## ACKNOWLEDGEMENTS

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