

Development of a Push-pull Converter for Fuel Cell Applications

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Abstract—Fuel cells have the advantage that they can be used in remote telecommunication sites with no grid connectivity as the majority of telecommunication equipment operates from a DC voltage supply. However, a fuel cell's output power is highly unregulated resulting in a drastic drop in the output voltage with increasing load. Therefore, various DC–DC converter topologies with a wide range of input voltages can be used to regulate the fuel cell voltage to a required DC load. This paper presents the design and development of a push-pull converter with a wide voltage input in the 40 W range. The aim of this DC–DC converter is to convert the 22 - 46 V generated by a commercial proton exchange membrane fuel cell to a 13.8 V used to supply portable telecommunication equipment. The preliminary results of the experimental measurements of the prototype design are presented.

Index Terms—Push-pull converter, fuel cell.

I. INTRODUCTION

The obstacles for integrating fuel cells (FCs) with modern electronics are the low output voltage of the cell combined with its instability over the range of electrical loading. Significant cell voltage variation during a no load period has also been observed. Thus, power conditioning circuitry to accommodate cell to cell inconsistencies and load-driven output voltage variation is a critical component of any FC system [1]. A DC–DC converter with a wide range of input voltages is therefore required to regulate the FC voltage [2].

There are multiple topologies of switched mode DC–DC converter followed by DC–AC inverter proposed so far. A conventional FC network has a switched mode DC–DC converter to limit the size and cost of the system followed by an inverter [3].

Recent comprehensive studies have shown that power-electronics, which interfaces directly to the FC stacks, has a significant impact on the long-term durability and reliable energy efficiency of the FC. Energy conversion efficiency for FC is of significant importance. Today, the efficiencies of power-electronics conversion technology have exceeded 90 %; however, under severe cost constraints, most of these technologies are not economically viable. As such, achieving high power-conversion efficiency at significantly low cost for the viability of FC power systems is a daunting challenge [4].

DC–DC converter design for FC is slightly different from conventional converters, as the electric characteristics of the

converter should match that of the FC. This is particularly important for three reasons [5]:

- The input side current/voltage ripple of the DC–DC converter should be minimum, so as to reduce the ripple current/voltage of the FC;
- When the FC is working under load current pulses, the DC–DC converter must apply a suitable strategy to adjust the output power of the FC, so as to ensure high-efficiency and reliable operation; and
- The DC–DC converter should be able to adjust the power distribution.

These reasons constitute the criterion for this research.

A step-down converter is proposed which will incorporate a proton exchange membrane (PEM) FC stack as the DC power source with a load of 40 W.

Figure 1 shows a block diagram of a 40 W DC–DC regulator using a pulse width modulated (PWM) push-pull power converter. It consists of an Electromagnetic Interference (EMI) filter which protects the source from the switching harmonics of the input current. The latter is fed into a PWM push-pull converter power stage which transforms the unregulated input DC to an AC square wave at the output of the push-pull transformer to lessen the voltage level. This AC square wave voltage is rectified and filtered using a two stage LC filter to obtain a regulated DC component. The output voltage is sampled and compared with a constant reference voltage (V_{ref}). The error voltage is then amplified and compensated for stable operation of the converter before being applied to a pulse width modulator (PWM). The PWM output is used to generate out of phase pulses which are processed in dual drive circuit to provide isolation. Afterward these pulses are amplified to drive the gates of power switching MOSFETs. In this way, the converter output voltage is regulated at the desired level.

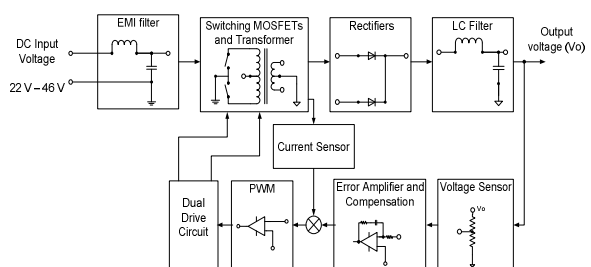


Figure1 Converter system block diagram

The push-pull topology was chosen for the DC–DC converter for the following reasons [6]:

- The output must be isolated. This feature is made possible by the transformer;
- The output voltage can be made either higher or lower depending on the turns ratio of the high frequency (HF) transformer;
- The transformer is relatively small;
- The topology uses relatively low power devices; and
- This topology reduces the output ripple by doubling the current ripple frequency to the output filter.

Another deciding factor is the simplicity of the switching. Only one switch is turned on at a time. This results in timing issues becoming less critical.

II. PUSH-PULL CONVERTER OPERATION AND ANALYSIS

The circuit arrangement for a push–pull DC–DC converter is shown in Figure 2. This converter topology produces pulses of opposite polarity on the primary and the secondary windings of the transformer by switching transistors Q_1 and Q_2 . The diodes on the secondary windings rectify the pulse waveform before applying them to the input of the low-pass filter (LC) [7].

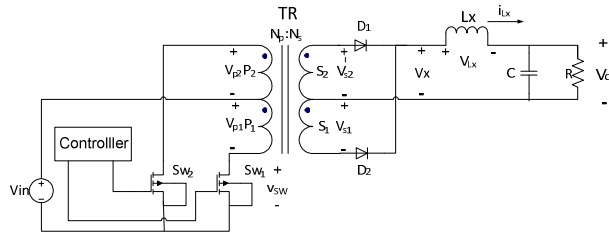


Figure 2 Basic push-pull converter topology

According to Hart [7], the push-pull converter circuit is analysed with one switch on and with both switches off. Mathematical expressions for the four modes of operation over one switching cycle are as follows:

Mode 1: As depicted in Figure 3, during this mode, Q_1 closes and establishes the voltage across the primary winding P_1 , thus:

$$v_{p1} = V_{in} \quad (1)$$

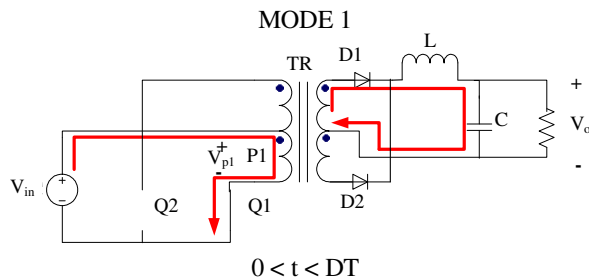


Figure 3 Mode 1 Q_1 closed

Diode D_1 is forward biased, D_2 is reverse biased, and assuming a constant output voltage V_o , the voltage across the inductor (L) is a constant, resulting in a linearly increasing current in the inductor. In the interval when Q_1 is closed, the change in current in the inductor is given by:

$$\Delta iL_{closed} = \left(\frac{V_{in} \left(\frac{N_s}{N_p} \right) - V_o}{L} \right) DT \quad (2)$$

Mode 2: Figure 4 shows the sequence when both switches are open. The current in each of the primary windings is zero. The current in the filter inductor (L) must maintain continuity, resulting in both D_1 and D_2 becoming forward biased. The inductor current divides evenly between the transformer's secondary windings.

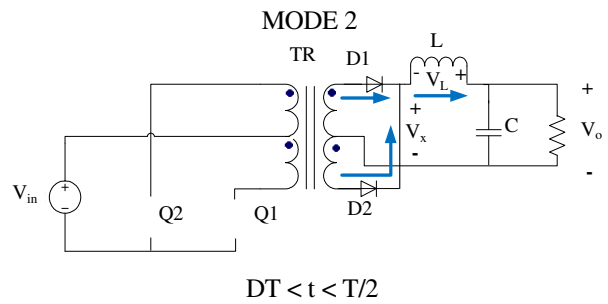


Figure 4 Mode 2 with both Q_1 and Q_2 open

The voltage across each secondary winding is zero, and

$$v_L = v_x - V_o = -V_o \quad (3)$$

where $v_x = 0$

Mode 3: As illustrated in Figure 5, Q_2 is closed and the voltage established across the primary winding P_2 is

$$v_{p2} = -V_{in} \quad (4)$$

Diode D_2 is forward biased while D_1 is reverse biased. The current in the inductor increases linearly while Q_2 is closed, and Equation 2 applies.

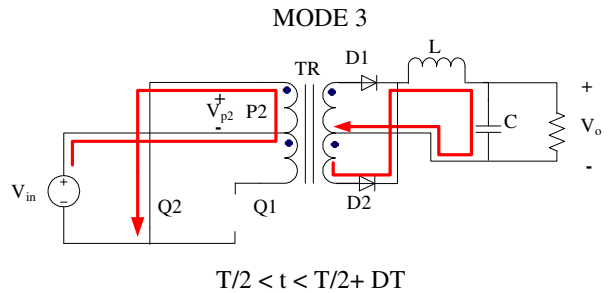


Figure 5 Mode 3 with Q_2 closed and Q_1 open

Mode 4: Figure 6 again illustrates that both switches are off. This mode is identical to mode 2.

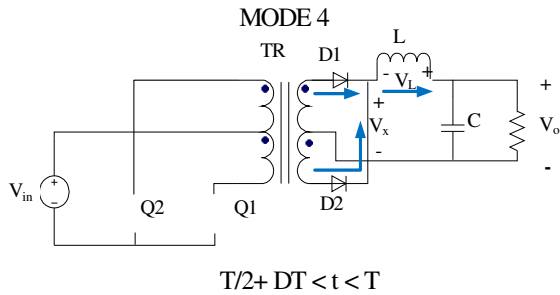


Figure 6 Mode 4 with both switches are open

The modes described earlier result in the following steady state theoretical waveforms as shown in Figure 7 for the push-pull converter operating in continuous conduction mode.

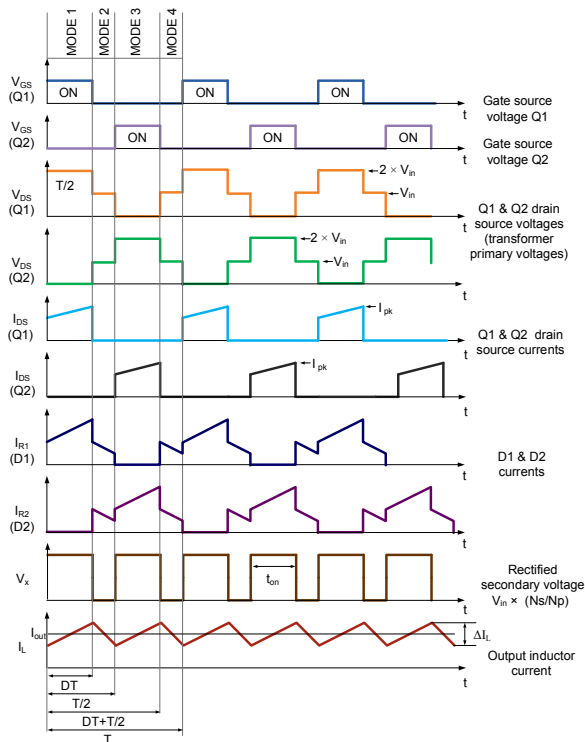


Figure 7 Waveforms of a push-pull converter

III. DESIGN ASPECTS OF THE CONVERTER

Based on the analysis in the previous section, the specifications set for the design are as follows:

- Input voltage range: 22 - 46 V
- Output voltage: 13.8 V
- Output current: 3 A
- Output power: 40 W
- Switching frequency: 50 kHz

A. Computer Aided Design of the Push-pull Converter

Computer aided design of power electronic converter systems have become indispensable before practical hardware implementation is done [8]. The need to further reduce design time and effort, as well as reduce cost and

improve quality, have spurred many efforts to use the computer in the design cycle [9]. This approach has been applied for the prototype design.

Power Stage Designer Tool™, a software package from Texas Instruments, was used for the design of the power stage. Commonly used switch-mode power supplies can be designed using this tool. It is a useful tool in order to visualise voltage and current waveforms inside critical components of the converter, such as the MOSFET switches, HF transformer, power diodes and inductor. Figure 8 shows a screenshot of the Power Stage Designer Tool™.

Regarding the HF transformer and the output inductor, the transformer's primary and secondary inductance, turns ratio and output inductance were obtained from Power Stage Designer Tool™ and were used for building the magnetic components.

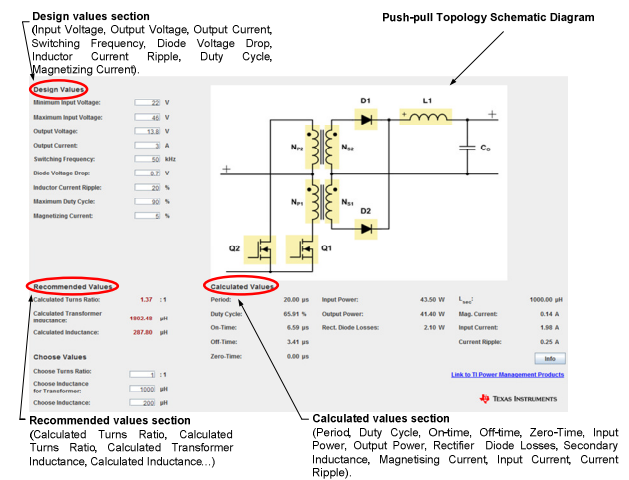
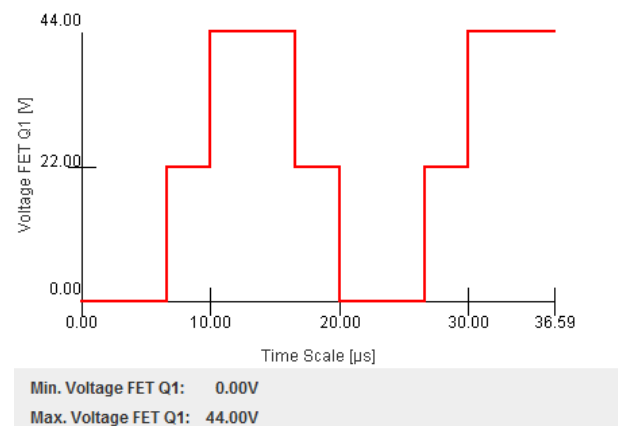
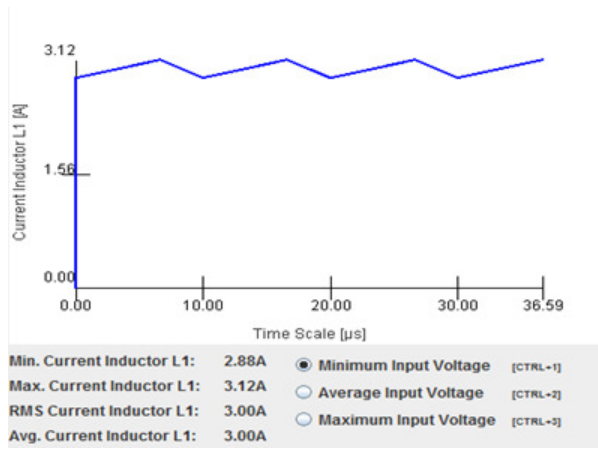


Figure 8 Power Stage Designer Tool™ screenshot

Figure 9 (a) and (b) illustrate some of the voltage and current waveforms obtained using this software. This is significant because Power Stage Designer Tool™ is useful for further analysis of the waveforms of the converter's components especially at minimum, average and maximum input voltage.



(a)



(b)

Figure 9 a) MOSFET drain voltage of 44 V with a V_{in} of 22 V, b) Output inductor current of 3.12 A with a V_{in} of 22 V.

B. High Frequency Push-pull Transformer

Designing magnetic components form the backbone of a good switching power supply. Their proper electrical and physical design have a large effect on the reliable operation of every switching power supply [10]. Furthermore, the design of magnetic components take considerable time as there are many decisions to be made: core material, core shape and type of conductor, to mention a few [11]. A specific method was followed for the design of the HF transformer [12]. The design incorporates a N87 Mn-Zn ferrite core material while the core shape is the EPCOS ETD 49. It comprises a center tap primary winding and a secondary center tap winding. The primary and secondary are each divided into two 3-turn windings and the transformer's turns ratio is 1:1. The primary was wound using copper foil in order to achieve good coupling and minimize leakage inductance and skin effect that is prevalent in cylindrical copper conductors.

The layer sequencing in Figure 10 shows how the layers have been arranged in the HF push-pull transformer. When interleaving windings in a push-pull circuit with two primary layers and two secondary layers, the simultaneously conducting half primary and secondary should be adjacent to each other. This reduces eddy current losses [13].

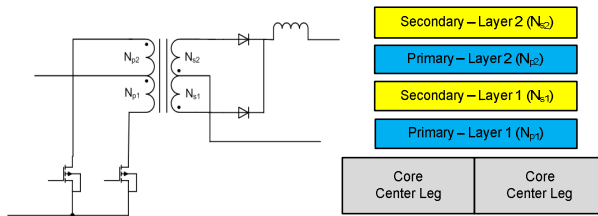


Figure 10 Push-pull transformer layer sequencing

C. Selection of Power Switches and Rectifiers

As for other topologies, voltage and current stresses in power switches and rectifiers of the push-pull converter can be predicted [10]. These estimates have about a 90 % percent confidence factor. The equations used to determine the stresses are the following:

- For MOSFET switches

$$V_{DS} = 2V_{in} \quad (5)$$

where V_{DS} is the drain source voltage.

$$I_D = \frac{1.2 \times P_{out}}{V_{in(min)}} \quad (6)$$

where I_D is the drain current.

Based on these equations, the IRF540N MOSFETs from International Rectifier was chosen.

- For the rectifiers

$$V_R = 2V_{out} \quad (7)$$

where V_R is the DC reverse voltage.

$$I_F = I_{out} \quad (8)$$

where I_F is forward current.

The results of these equations were used to select the 30CPQ150 schottky rectifier diodes which are readily available.

D. Control Stage

The control scheme is built around a PWM IC UC3825 from Texas Instruments which drives the gates of the two MOSFET switches. The UC3825 chip maintains the regulated output voltage.

As depicted in figure 11, current mode control has been implemented to regulate the converter output. The PWM IC generates low and high MOSFET drive signals that are varied to give an output of 13.8 V. This voltage is sampled into the IC, which compares this voltage with its own internal reference. If the error is positive, then the output pins of the control IC are shutdown, therefore providing overvoltage protection for the load. If the error is negative, the duty cycle is adjusted to give the desired output voltage [14].

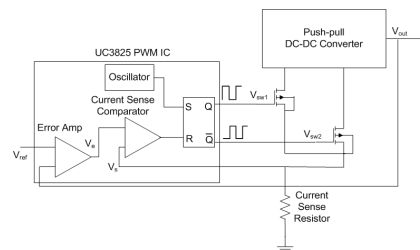


Figure 11 Concept of current mode control

The input current is also monitored and its equivalent voltage is fed to the current limit pin of the control IC. If the current exceeds the set current limit, the output pins of the control IC are shutdown providing short-circuit protection as well.

IV. EXPERIMENTAL RESULTS

The 40 W converter was constructed on a bread board and tested to evaluate its performance. The push-pull converter prototype consists of an EMI filter, two paralleled IRF540N MOSFETs, the HF transformer, rectifying circuit and LC output filter. Figure 12 shows the converter under test.

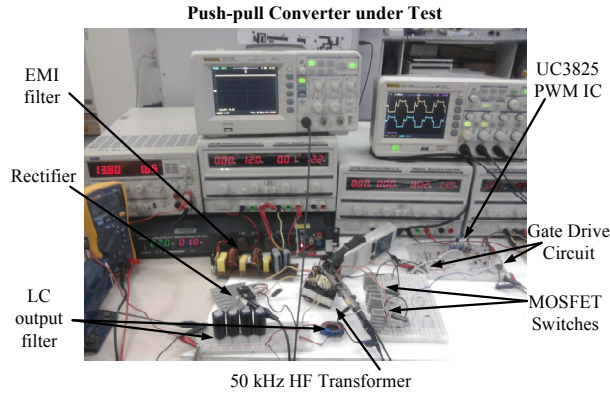


Figure 12 Push-pull converter built in laboratory

The efficiency of the converter for different load currents has been determined and plotted in Figure 13. The overall estimated efficiency of a push-pull converter has been around 72 % [10]. The highest efficiency at this stage of the development has been 63% at an input voltage of 28 V which is the nominal operating voltage of the commercial PEM FC intended to be used in conjunction with this prototype.

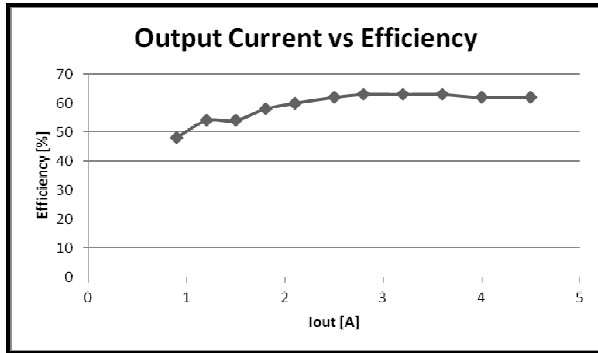


Figure 13 Plot of current vs efficiency of the push-pull converter

Other results are shown below showing the voltages and currents at a minimum input voltage of 22 V and a current of 1.8 A. The output voltage was 13.8 V with an output current of 1.6 A. Calculating the efficiency:

$$P_{in} = V_{in} \times I_{in} = 22 \text{ V} \times 1.8 \text{ A} = 39.6 \text{ W} \quad (9)$$

$$P_{out} = V_{out} \times I_{out} = 13.8 \text{ V} \times 1.6 \text{ A} = 22 \text{ W} \quad (10)$$

The efficiency is

$$\eta = \frac{P_{out}}{P_{in}} = \frac{22 \text{ W}}{39.6 \text{ W}} = 0.55 = 55\% \quad (11)$$

Figure 14 shows the gate voltages of each MOSFET as well as the dead time which exists between them.

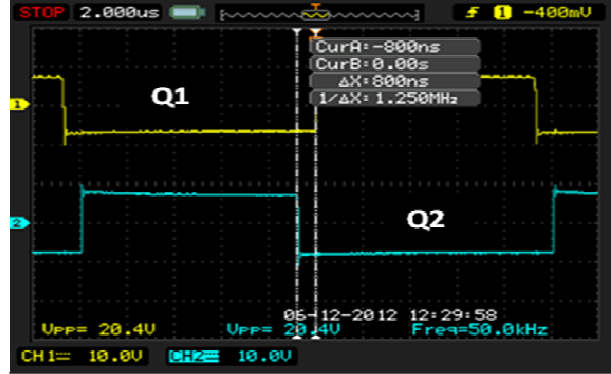


Figure 14 $Q1$ and $Q2$ MOSFET gate voltages

The top trace in Figure 15 represents the voltage across one half of the primary windings of the transformer and the lower one the voltage across the other half.

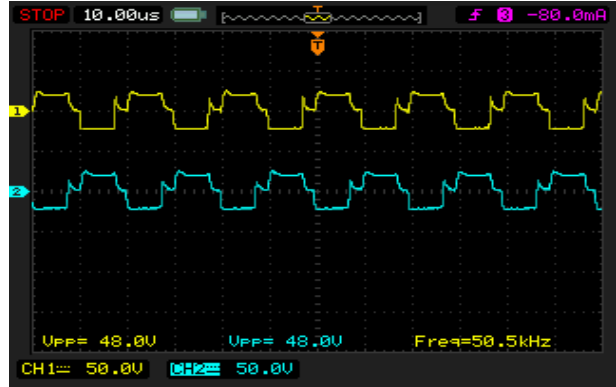


Figure 15 Transformer primary waveforms or drain source voltages of $Q1$ and $Q2$

Figure 16 shows the current waveforms in MOSFET $Q1$, which is the same for $Q2$.

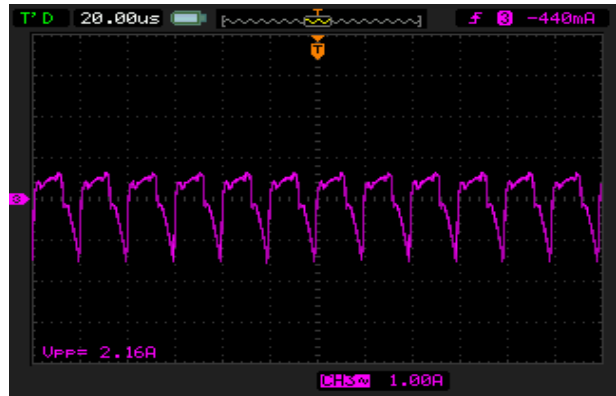


Figure 16 Current carried by each switch

As the HF transformer has a turns ratio of 1:1, the amount of voltage present at the primary is the same on the secondary. Figure 17 presents this rectified voltage.

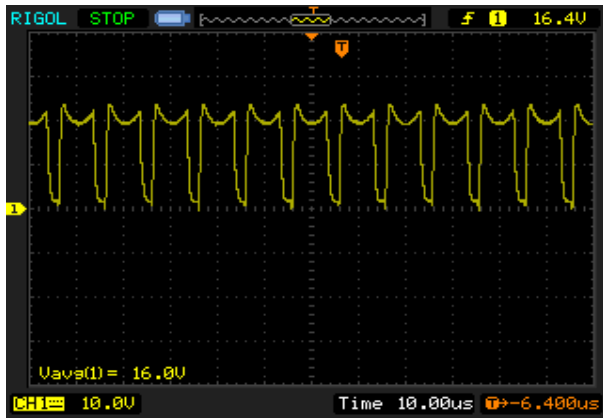


Figure 17 Voltage at the output of the rectifier circuit

Finally, Figure 18 and 19 present respectively the measured output current and voltage. These measurements show that the converter produces a regulated 13.8 V DC from an input voltage of 22 V.

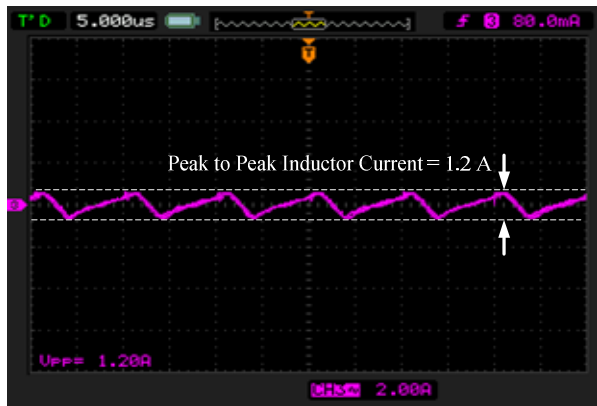


Figure 18 Push-pull converter output current

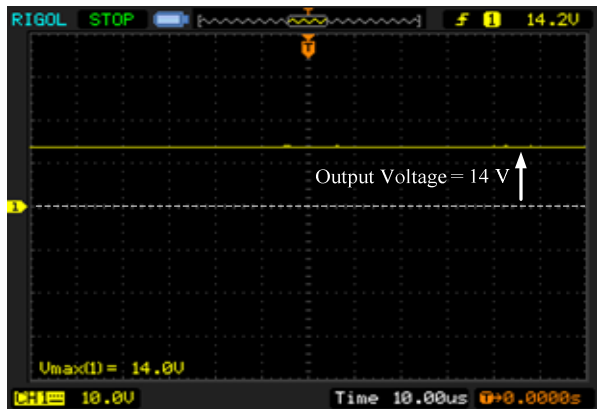


Figure 19 Push-pull converter output voltage

V. CONCLUSION

The design and preliminary development of a push-pull converter with the aim of converting 22 - 46 V DC voltages from a commercial PEM FC to 13.8 V was presented. The experimental results confirm the expected outcome. The highest efficiency of the converter is around 63 % (See Figure 12).

However, for further improvement, the converter will be built on a proper PCB board to negate parasitic effects affecting the prototype which is currently built on breadboard.

Further design considerations will include efficient energy management and control of the power flows in the various system components. This is a key point for converter performance.

Fuel cells need to be integrated with storage elements such as supercapacitors and batteries in order to accommodate rapid changes in load demand. This requires additional converter systems in order to interface the various power sources with each other and with the load.

VI. ACKNOWLEDGEMENT

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