A Novel Isolated DC/DC Converter With Improved Efficiency
For Fuel Cell based DC Power Supply Systems

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Abstract—For fuel cells based power supplies, necessity for operation for a wide input range presents a problem for realizing synchronous rectification for achieving higher converter efficiency. A novel design scheme that allows synchronous rectification with isolated interleaved active clamp converter is introduced in this paper. It involves a pre-regulating buck converter for part of the fuel cell output range. Interleaving helps achieve higher efficiency due to reduced rms current per phase; allows higher power transfer and reduces the input ripple current. Input current is accurately limited to protect fuel cell stacks from damage during overload. The converter PWM strategy is analyzed and verified experimentally on a 500 W prototype.

I. INTRODUCTION

Fuel cells are electrochemical power sources [1] that directly convert hydrogen fuel to electricity, having waste heat and water vapour as its by-products. Different types of fuel cells are currently under research, among them the proton exchange fuel cell (PEM) is increasingly gaining acceptance for both transportation and residential power generation. Fuel cells are widely viewed as the technology of the future to replace the batteries in transportation systems and generate or store electrical power [2]. Some of the advantages of fuel cells include potential flexibility in fuel, low acoustic noise, higher power density and being more cost effective than batteries. Moreover, the waste heat generated by the fuel cell can usually be used for cogeneration such as steam, air conditioning, hot air and heating and consequently the overall efficiency of such a system could be increased up to 80%.

The basic fuel-cell concept involves converting chemical energy directly into electrical energy. It produces electricity by electrochemically combining fuel (hydrogen) and oxidant (oxygen from the air) gases through electrodes and across an ion-conducting electrolyte. Since increasing fuel cells’ surface area results in higher current capability and consequently higher power, it is much cheaper and less complex to have cells with medium low output voltage and high current. Moreover a fuel cells’ output voltage drops nonlinearly from a no-load voltage of about 1.24 V DC to below 0.5 V DC at full load with an approximation of a voltage source with series resistance. Further a fuel cell stack could be catastrophically damaged if overloaded due to cell reversal and membrane rupture.

The above requirements and the cost of generating power require that some kind of fuel cell power conditioners like a dc-dc converter, dc-ac inverter, storage energy element, etc be always used with a fuel cell. This paper presents an integrated dc-ac inverter topology suitable for fuel cell technology. The aim of this integrated topology is to convert in a single processing stage the variable dc output from the fuel cell into a single regulated dc output with high conversion efficiency, when compared with a other solutions. The dc-dc converter connected to the fuel cell must have high efficiency, accurate input current limit for protecting the fuel cell from overload and work for a wide range of input voltage.

II. PROBLEMS WITH EXISTING SYSTEMS

The output voltage variation of a typical fuel cell stack with respect to the load current demand is shown in Fig. 1.

Further the slow fuel cell supply regulation and hydration control of the energy transformation process results in fuel cells having a long time constant. This long time constant (30 – 60 sec) creates more control difficulties to the downstream power conversion stages as overloading can particularly cause irreversible damage to the fuel cell. Therefore, some type of supplementary energy storage is typically required (batteries and/or super capacitors).

It is are common for practical power systems to often have hybrid power generation and storage systems using PV arrays, as another input power source. A downstream DC-DC converter is always necessary for providing isolation and power conditioning. For DC power systems, as common in telecom applications, the output voltage is usually 24 V or 48 V with high output current capability. This high current output can cause significant conduction losses in the output circuit of the DC-DC converter resulting in lower efficiency.
For AC power systems the output voltage is usually 360 V with a much lower output current capability followed by an inverter stage that is able to interface the fuel cell stack to an external load and/or to the utility grid. Fig. 2 shows the block diagram of a hybrid power generation and storage system and the power electronics processing stages, which are needed to supply various types of loads.

In order to effectively apply fuel cells in power supply systems, the downstream power conditioner should overcome the fuel cell’s inherent restrictions described above. In general, the most important requirements needed in the fuel cell power conditioning design are; galvanic isolation of fuel cell, operation for wide input voltage variation, boosting and regulation action, compensates fuel cell slow dynamics and high efficiency. While an isolated DC-DC Converter can meet most of the above requirements, the high output currents of DC-DC Converters in DC power systems cause significant conduction losses and reduces efficiency. The wide voltage variation at the input makes synchronous rectification less practical, as the large input voltage variation results in a high voltage at the isolating transformer secondary requiring a corresponding high voltage device for rectification. The inherently a poor $R_{DS(ON)}$ and poor body diode recovery time of high voltage MOSFETs, makes achieving higher efficiency by synchronous rectification difficult. For example a converter operating from a fuel cell whose output varies between 32 V to 78 V, generates a 48 V DC output and has maximum converter PWM duty cycle of 76% at 32 V input - will generate at least 154 V in the transformer secondary at 78 V input requiring at least a 200 V MOSFET.

Now even the best of class of a 200 V MOSFET today like the STY100NS20FD from ST Microelectronics, besides being very expensive, has a poor body diode recovery time of 225 ns and $R_{DS(ON)}$ of 22 mΩ. Comparatively a 100 V part like the IRFB4110 from IR, is much less expensive, has an excellent diode recovery time of 50 ns and $R_{DS(ON)}$ of only 3.7 mΩ. Therefore design strategies that allow use of these low voltage parts, are the best ways to improve converter efficiency and performance.

### III. STRATEGIES FOR IMPROVING EFFICIENCY OF FUEL CELL CONVERTER

Often multiphase DC-DC converters that reduce the rms current per phase, allows current sharing among phases and provides high-frequency ripple cancellation, improves efficiency in low-voltage high-power fuel cell applications. Three-phase DC-DC converters [3] or Six Phase converters operating in ZVS also improves efficiency at the cost of higher complexity.

Further as explained earlier, implementing synchronous rectification for achieving higher efficiency is difficult unless some modified design scheme is used. As can be seen from Fig.1, the DC- DC Converter input voltage drops rapidly to about 50 V when loaded to only about 30%. Thus it is proposed that the converter input is pre-regulated till the fuel cell voltage drops to 50 V. This way the main DC-DC Converter sees a smaller input voltage variation allowing realizing synchronous rectification at the output.

![Figure 2 Hybrid power systems for (a) DC loads (b) AC loads](image)

![Figure 3a. Proposed converter circuit model](image)
In the proposed scheme given in Fig.3a, a dual interleaved active clamp converter is used as the main isolating converter with its input is pre-regulated about 50 V by a buck converter designed around Q1/L1/C2/D1. The two interleaved converters designed around Q2/Q3/TX1/Q5/Q6/L2 and Q9/Q10/TX2/Q7/Q8/L3 operate in a phase-shifted manner to reduce the input ripple current [5] and generate an ORed dc output across C4. The input pre-regulation scheme described below allows the use of low voltage devices for Q5/Q6/Q7/Q8.

Since the fuel cell voltage is higher at lower loads, the buck converter works only for lower load conditions. At higher loads, the buck converter is fully turned (100% Duty cycle) ON resulting in no switching losses. Further use of new generation ultra low RDS(ON) low voltage low cost MOSFETs as the buck converter switch, results in negligible losses in the switch when it is fully turned on. This way the voltage swing for rectifying devices in the transformer secondary circuit is significantly reduced making synchronous rectification practical. Thus higher efficiency is achieved. The input voltage, the PWM strategy of Q1 and the output voltage is shown in Fig.3b.

Moreover as explained earlier, the DC-DC converter must have an accurate and adjustable input current limit for protecting the fuel cell from permanent membrane damage during overload conditions. The proposed buck converter at the input provides this additional function by sensing the input dc current through R1.

IV. EXPERIMENTAL RESULTS

To develop a better understanding about the proposed DC-DC Converter, measurements were made on a 500 W prototype converter loaded to 48 V/10 A. The converter circuit model was similar to that shown in Fig. 3. All waveforms were recorded with and without the front-end pre-regulator buck converter, while the input was varied between 32 V to 78 V for both conditions. Efficiency measurements were also made for these conditions and compared. The synchronous rectification circuit was disabled by removing Q5/Q6/Q7/Q8 when the front-end pre-regulator was absent while the synchronous rectification circuit was active when the front-end pre-regulator was present. Both the pre-regulating buck converter and the downstream interleaved active clamp converters were synchronized to each other with their switching frequency set to about 74 kHz. These are presented in the oscillograms given in Fig. 4, Fig. 5 and Fig. 6. In these oscillograms Channel 1 shows input voltage $V_{IN}$, Channel 2 shows $V_1$ the output of Q1, Channel 3 shows $V_3/V_4$ the drain-source voltage across Q3/Q10, Channel 4 shows the corresponding secondary voltage $V_{s}/V_d$.

Fig. 4 shows these waveforms with and without the pre-regulator buck converter at 32 V input, Fig. 5 shows these waveforms without the pre-regulator buck converter at 78 V input and Fig. 6 shows these waveforms with the pre-regulator buck converter at 78 V input. Efficiency measurements were made without synchronous rectification and without the front-end pre-regulator buck converter with the output loaded to 48 V/10 A at 32 V, 50 V and 78 V input. Efficiency measurements were also made with synchronous rectification and with the front-end pre-regulator buck converter for the above input and load conditions. These are shown in Fig. 7. Efficiency improvements of over 2% were achieved at 50 V input with the synchronous rectification and the front-end pre-regulator buck converter working.

Figure 4. Waveforms with and without the pre-regulator buck converter at 32 V input.

Figure 5. Waveforms without the pre-regulator buck converter at 78 V input.
V. CONCLUSION

In this paper, a new high power active clamp isolated DC-DC Converter that operates for a wide input voltage range common with a fuel cell output, is proposed. The converter has higher efficiency due to reduced conduction losses; has reduced rms current per phase due to interleaved operation; provides increased power transfer and imposes reduced overall ripple current [4] into the fuel; has accurate input current limit for protecting fuel cell stack damage during overload. Experimental verification on a 500W prototype unit demonstrated efficiency improvements of over 2%.

REFERENCES
