A New High-Power DC/DC Converter for Residential Fuel Cell Power Systems

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1. Introduction

Fuel cells have been considered as a highly promising alternative for environmentally friendly renewable energy generation due to their high efficiency, modularity, and cleanness [1]. A possible fuel cell application is the residential power systems, where the special two-stage interface converter with galvanic isolation is required for interconnection of low DC voltage generating fuel cell and single- or three-phase residential loads.

A typical structure of the two-stage interface converter is presented in Fig. 1. Due to safety and dynamic performance requirements, the interface converter must be realized within the DC/DC/AC concept. This means that low voltage from the fuel-cell first passes through the first stage step-up DC/DC converter with the galvanic isolation; afterwards the output DC voltage is inverted in the three-phase inverter and filtered to comply with the imposed standards and requirements (second DC/AC stage).

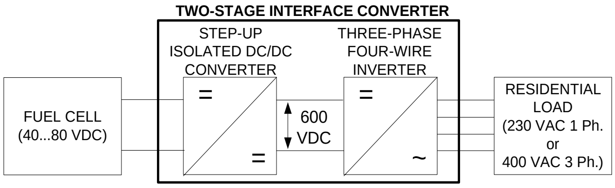


Fig. 1. Typical structure of the interface converter for the residential fuel cell power systems.

The design of the first stage isolated DC/DC converter is most challenging, because this stage is the main contributor of an interface converter efficiency, weight and overall dimensions. The low-voltage provided by the fuel cell is always associated with the high currents in the primary part of the DC/DC converter (switching transistors and primary winding of the isolation transformer). These high currents lead to high conduction and switching losses in the semiconductors, and therefore reduce the efficiency.

Moreover, the large voltage boost factor requirement presents a unique challenge to the DC/DC converter design [1]. This specific requirement could be fulfilled in different ways: by the implementation of an auxiliary boost converter before the isolated DC/DC converter [2] or by use of an isolation transformer with a large turns ratio [3] for effective voltage step-up. In the first case, the auxiliary boost converter steps up the varying fuel cell voltage to a certain constant voltage level (80...100 V DC) and supplies the input terminal of the isolated DC/DC converter. In that case the primary inverter within a DC/DC converter operates with a fixed duty cycle, thus ensuring better utilization of an isolation transformer.

A direct step-up DC/DC converter without input voltage preregulation is simpler in control and protection. The varying voltage from the fuel cell passes through the high-frequency inverter to the step-up isolation transformer. The magnitude of the primary winding voltage is controlled by the duty cycle variation of inverter switches in accordance with the fuel cell output voltage and converter load conditions. The choice of DC/DC converter topology in that case can be broadly categorized as a push-pull [4] or a single-phase full-bridge [3] topology. Because of the symmetrical transformer flux and minimized stress of primary inverter switches, the full-bridge topology has been found to be most useful in terms of cost and efficiency, especially when implemented for power levels higher than 3 kW [3].

In the case of a direct step-up DC/DC converter, an interesting solution was proposed in [5], where the single-phase auxiliary AC link was replaced by the three-phase one. The advantages of such three-phase isolated DC/DC converters over classical topologies are the reduction of volumes of input and output filters, lower rms currents through the semiconductors, improved power density and efficiency. The topology was verified experimentally on 6.8 kW prototype demonstrating small input current ripple, good regulation margin and efficiency close to 90%.

2. Proposed DC/DC Converter Topology

This paper proposes a new high power (≥10 kW) DC/DC converter for residential fuel cell power systems. The converter utilizes the three-phase auxiliary AC link discussed above, which is supplied from the Z-source (impedance source) inverter (Fig. 2).

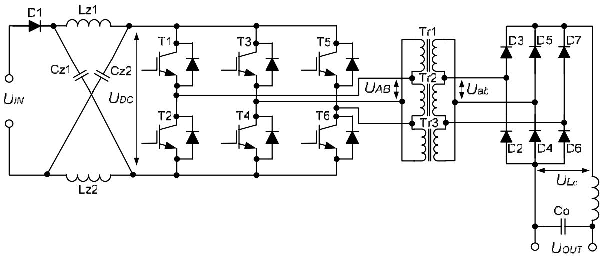


Fig. 2. Topology of the proposed DC/DC converter.

The Z-source inverter [6] implemented at the converter input side has a unique feature: it can boost the output voltage of the fuel cell by the introducing a shoot through operation mode, which is forbidden in traditional voltage source inverters. Thus, the varying output voltage of the fuel cell is first preregulated by adjusting the shoot through duty cycle;

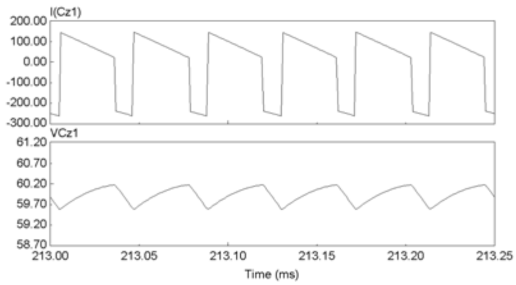
afterwards the isolation transformers are being supplied with the voltage with a certain magnitude from the inverter operating with the constant duty cycle. Such a feature provides the proposed three-phase isolated DC/DC topology with a Z-source inverter with a cheaper, more powerful, reliable and efficient approach to be used for fuel cell powered systems.

3. Simulation Results

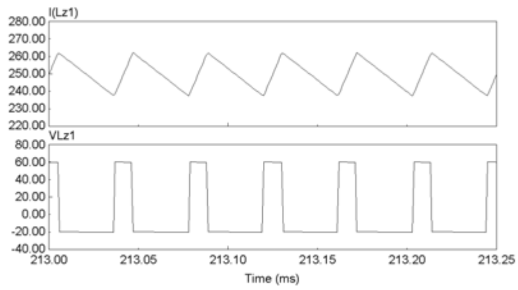
A 10 kW three-phase isolated DC/DC converter was considered for the simulations to confirm the above presented assumptions. To control the Z-source inverter, simple control was implemented, which utilizes two straight lines to control the shoot-through states and generally operates as a traditional carrier-based PWM. The switching frequency implemented was 24 kHz.

To provide the required galvanic insulation, the proposed converter utilizes three single-phase “delta-delta” connected transformers, which in real design could be replaced by the single-core three-phase transformer. The primary-secondary turns ratio was set as 1:10. The Z-source network parameters (L_{Z1}=L_{Z2}=25 uH and C_{Z1}=C_{Z2}=4.34 mF) were estimated for the operating voltage of the fuel cell at the rated load conditions (U_{IN} = 40V @ 10 kW). A 10% peak-to-peak current ripple was assumed through the Z-source inductors during the maximum power operation.

The simulations were performed for both, the minimum and maximum input voltages and at the rated load conditions. In first case the shoot-through mode (D_Z=0.25) was used to boost the input voltage by factor of 2. In the second case the shoot-through mode was eliminated and the duty cycle of the inverter output voltage was controlled by the utilization of the zero vector (classical zero state, D_0=0.25). The voltage and current ripple values obtained from simulations were consistent with the results predicted by the theoretical analysis (Figs. 3 and 4).



(a)



(b)

Fig. 3. Simulated waveforms of the Z-source network at the maximal boost mode of the input voltage (duration of the shoot-through state is t_Z=10.42 us): operating current and voltage of Z-capacitors (a) and operating current and voltage of Z-inductors (b).

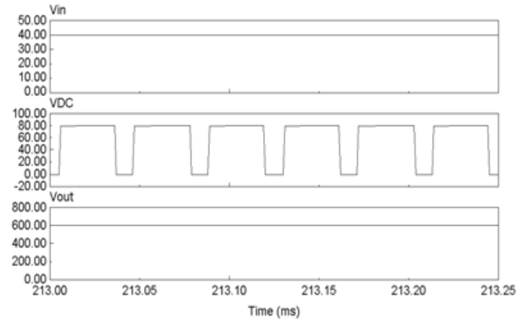


Fig. 4. Input, DC-link and output voltage waveforms of the proposed DC/DC converter operating at minimal input voltage (duration of the shoot-through state is t_Z=10.42 us).

4. Conclusion

This paper has presented a new isolated step-up DC/DC converter with an impedance-source inverter. The topology is intended for applications with widely varying input voltage and stabilized output voltage. The three-phase high-frequency transformer stack is responsible for providing the input/output galvanic isolation demanded in many applications. The paper is focused on an example of the 10 kW step-up DC/DC converter with high-frequency isolation for residential fuel cell power systems. The operating principle, converter design methodology and simulation results are presented and analyzed. Moreover, to improve the control flexibility and minimize the dimensions of isolation transformer stack, the updated converter topology with the voltage doubler rectifier was proposed.

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