Impedance-Source Inverter-Based High-Power DC/DC Converter for Fuel Cell Applications

Mikhail Egorov(1), Dmitri Vinnikov(1), Ryszard Strzelecki(2), Marek Adamowicz(3)
(1)Tallinn University of Technology, Department of Electrical Drives and Power Electronics
Ehitajate tee 5, 19086 Tallinn, Estonia
(2)Electrotechnical Institute, Pożaryskiego 28, 04-703 Warsaw, Poland
(3)Gdynia Maritime University, Department of Electrical Engineering
Morska 81-87, 81-345 Gdynia, Poland

Abstract- **This paper presents the possibility of implementation of fuel cells with low output voltage range for supplying the high-voltage loads. For matching the different voltage levels and for the providing of galvanic insulation the isolated DC/DC interface converter is required. For increasing of power density, efficiency and flexibility the interface DC/DC converter with three-phase intermediate AC-link is proposed. The one of features of the proposed topology is the impedance source inverter utilized in the input stage of the converter. The paper is devoted to study of theoretical background of the topology proposed, which is verified by the simulations.**

I. INTRODUCTION

Fuel cells (FC) have achieved global attention as alternative power sources due to the environmental concerns. In this paper the possibility of FC interconnection with the high-voltage load is studied. Generally, the FCs are used as power sources with the output voltage variation between 40 V and 80 V. For supplying the high-voltage, high-power loads it is necessary to boost the relatively low output voltage of the FC to certain operating voltage level (for example, 600 V DC), required by the end user. Moreover, for the safety reasons the isolation transformer should be used for decoupling the low-voltage input and the high-voltage output sides of the converter. Thus, the step-up isolated DC/DC converter topology should be used in presented application. Practically, it can be realized by several approaches [1]:

- conventional PWM inverter with the step-up transformer and rectifier,
- combination of boost converter with conventional PWM inverter and step-up transformer with rectifier,
- impedance-source inverter with isolation transformer and rectifier.

The most technically feasible solution is the implementation of impedance-source inverter (ISI) widely known as Z-source inverter. The ISI (Fig. 1) employs impedance network coupled with the main inverter circuit and has unique properties of voltage step-up and DC/AC conversion [1], [2].

For improving the power density, efficiency and flexibility of the system the intermediate AC-link of the proposed converter is realized with the three-phase architecture (Fig. 1). Compared to recently popular single-phase intermediate AC-link (full-bridge single-phase isolated DC/DC converter) the resulting advantages of the three-phase approach are obvious:

1. lower RMS current through the inverter and rectifier switches (higher power transfer through the switch with the same level of switch current and voltage stresses);
2. reduced isolated transformer's volume (and weight) due to reduced overall yoke volume and reduced voltage and magnetic stresses;
3. three-phase transformers and inductors are generally smaller and lighter than their counterpart single phase ones, for the same processed power. As a result, the energy losses in three-phase transformers and inductors will diminish.
4. reduced size of the output filter due to a dramatic increase (by a factor of three) of ripple frequency of the dominant harmonic;

The ISI implemented at the converter input side has the unique feature that it can boost the output voltage of the fuel cell by 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 to a certain value (for example, 600 V) by adjusting the shoot through duty ratio. Afterwards, the isolation transformers are being supplied with the voltage with constant amplitude value and certain duty cycle. With such feature the proposed three-phase isolated DC/DC topology with ISI could provide cheaper, reliable and efficient approach for fuel cell powered systems.

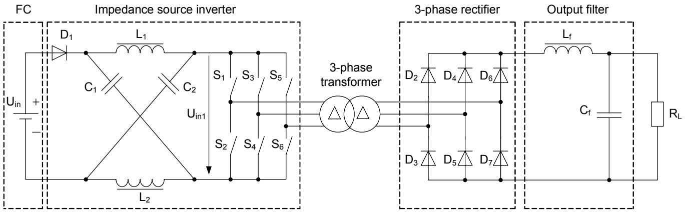

Figure 1. Proposed topology of the step-up isolated DC/DC converter for fuel cell applications.

The given paper provides the design guidelines of the proposed topology. The operation of interface converter will be studied in two boundary operating points - at the minimum and maximum output voltages of the fuel cell. The rated power of the interface converter is 10 kW and the desired output voltage is 600 V DC. The general specifications of the interface converter are submitted in Table I.

TABLE I.
GENERAL SPECIFICATIONS OF THE INTERFACE CONVERTER

Input voltage range, U_{in}	40...80 V DC
Converter output power, P	10 kW
Desired DC-link voltage, U_{in1}	400 V
Output voltage, U_{Load},	600 V DC
Load current, I_{Load}	16.7 A
Switching frequency, f_{sw}	10 kHz
Type of switching devices	IGBT
Peak-to-peak current ripple through Z-source inductors	60%
Desired voltage ripple on the Z-source capacitors	3%

II. DESIGN RECOMMENDATIONS FOR THE ISI

As was reported in previous section, the ISI implemented in proposed topology has unique features compared with the traditional voltage source inverter. It is a two port network that consists of split inductors L_1 and L_2 and capacitors C_1 and C_2 connected in X shape (Fig. 1). This impedance network is basically operating in two states: first is shoot-through when one or more inverter legs are short circuited. Second state is the non shoot-through state, when inverter is in active state as a traditional voltage source inverter. Between the inverter bridge terminals appears sum of the capacitor and inductor voltage, referred to DC link voltage in voltage source inverter [1], [2], [4], [5]. Switching between shoot-through states and non shoot-through states allows boost voltage of capacitors U_c and voltage of the inverter bridge over input voltage U_{in}.

During the design of ISI the most challenging is the estimation of values of the reactive components of the impedance network [6]. The component values should be evaluated for the minimum input voltage of the converter, where the boost factor and the current stresses of the components become maximal. Calculation of the average current of an inductor

$$I_L = \frac{P}{U_{in}} \cdot \tag{1}$$

The maximum current through the inductor occurs when the maximum shoot-through happens, which causes maximum ripple current. In our design, 60% peak-to-peak current ripple through the Z-source inductor during maximum power operation was chosen. Therefore, the allowed ripple current is ΔI_L, and the maximum current through the inductor is I_{Lmax}:

$$I_{L\max} = I_L + I_L \cdot 30\% . \tag{2}$$

$$I_{L\min} = I_L - I_L \cdot 30\% . \tag{3}$$

$$\Delta I_L = I_{L\max} - I_{L\min} . \tag{4}$$

The boost factor of the input voltage is:

$$B = \frac{1}{1-2D_Z} = \frac{U_{in1}}{U_{in}} , \tag{5}$$

where D_0 is the shoot-through duty cycle:

$$D_Z = \frac{B-1}{2B} . \tag{6}$$

The capacitor voltage during that condition is

$$U_C = \frac{U_{in} + U_{in1}}{2} . \tag{7}$$

Calculation of required inductance of Z-source inductors:

$$L = \frac{T_Z \cdot U_C}{\Delta I_L} . \tag{8}$$

where T_0 - is the shoot-through period per switching cycle:

$$T_Z = D_Z \cdot T . \tag{9}$$

Calculation of required capacitance of Z-source capacitors:

$$C = \frac{I_L \cdot T_Z}{U_C \cdot 3\%} . \tag{10}$$

Table II shows the initial and calculated values of all the parameters of the impedance system.

TABLE II.
INITIAL AND CALCULATED VALUES OF THE IMPEDANCE SYSTEM

Parameters	Fuel cell voltage	
	40 V	80 V
Boost factor B	10	5
Shoot-through duty cycle D_Z	0.45	0.4
Z-source inductance $L_1 = L_2$, μH	66	
Z-source capacitance $C_1 = C_2$, μF	1705	
Average current of Z-source inductor I_L, A	250	125
Maximum current of Z-source inductor I_{Lmax}, A	325	162.5
Minimum current of Z-source inductor I_{Lmin}, A	175	87.5
Ripple current of Z-source ΔI_L, A	150	75
Z-source capacitor voltage U_C, V	220	240

III. MODELING OF TRANSIENT PROCESSES OF THE Z-SOURCE INVERTER

To control the ISI all the traditional PWM schemes can be used. In discussed application to generate a desired output voltage a modified PWM with shoot-through states is used to boost the voltage. This control principle of the method is shown in Fig. 2 (T_0 – cycle, T – cycle of triangular carrier, T_Z – time of shoot-through state, $U_{AB,BC,CA}$ – line voltages, SA, SB, SC - signal generators).

The traditional PWM switching sequence based on the triangular carrier method is shown in Fig. 2. To control the shoot-through states, the two straight lines are introduced. When the triangular waveform is greater than the upper envelope or lower than the bottom envelope, the inverter switches turn into the shoot-through state. The duty cycle of the shoot-through state is varying between two predefined values and is inversely proportional to the fuel cell voltage.

In this circuit topology the parameters of reactive elements, like L and C are used as obtained from calculations. The inductors L_1 and L_2 and capacitors C_1 and C_2 have the same inductance and capacitance values, respectively, thus the impedance network becomes symmetrical [4], [7].

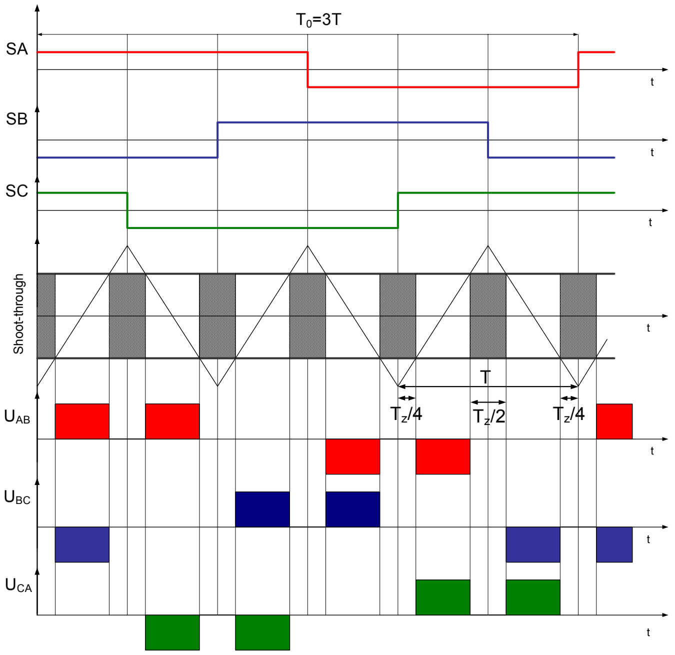

Figure 2. Control principle of the Z-source inverter.

Simulations were carried out by help of simulation package *PSIM*. The simulation circuit is presented in Fig. 3.

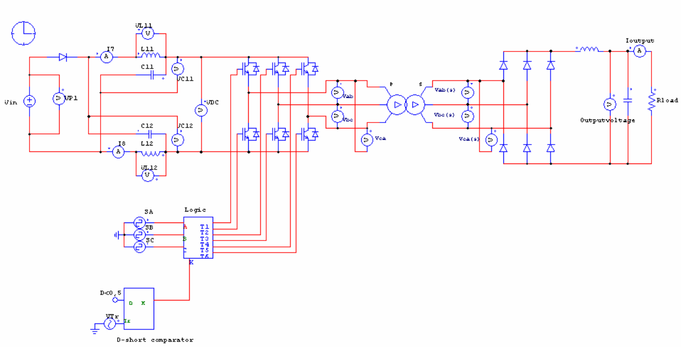

Figure 3. Simulation model (*PSIM*) of the proposed converter.

The simulations of the proposed converter were performed for two operating points – with the fuel cell voltages of 40 V and 80 V, and for the rated output power (10 kW). The isolation transformer assumed for the simulations was the "delta-delta" connected three-phase single core isolation transformer with the turns ratio of 1:2.5. The simulation results are presented in Figs. 4 - 13.

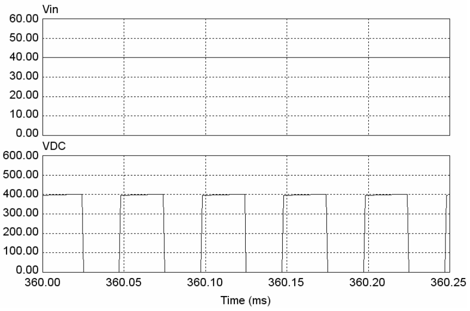

Figure 4. Voltage of fuel cell and DC-link voltage at the maximum boost factor.

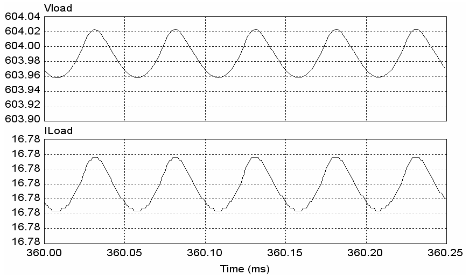

Figure 5. Output voltage and current ripples.

1. Modeling with the fuel cell voltage U_{in}= 40 V.

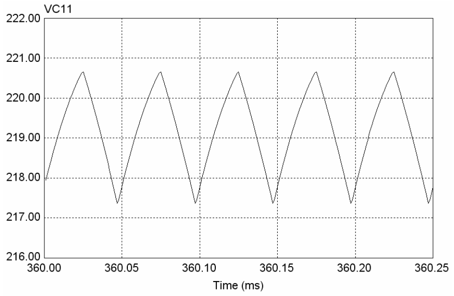

Figure 6. Voltage of the Z-source capacitor.

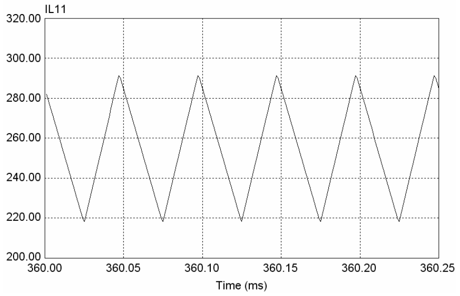

Figure 7. Current of the Z-source inductor.

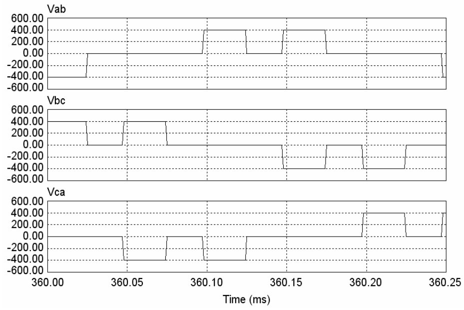

Figure 8. Voltage of the primary winding of the isolation transformer.

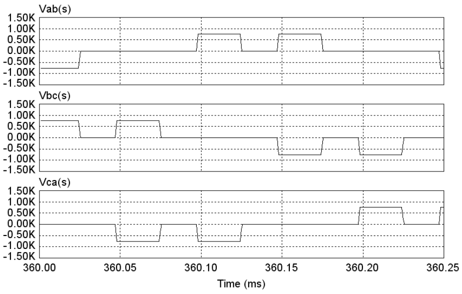

Figure 9. Voltage of the secondary winding of the isolation transformer.

2. Modeling with the fuel cell voltage U_{in}= 80 V.

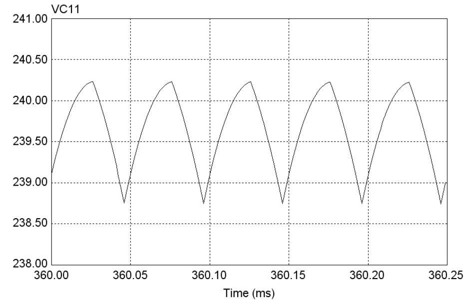

Figure 10. Voltage of the Z-source capacitor.

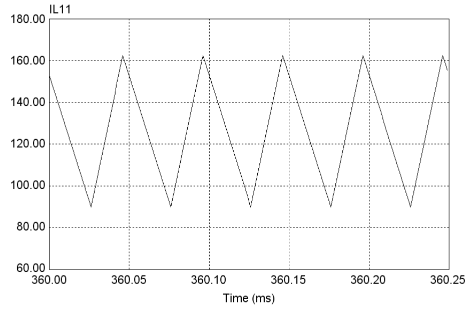

Figure 11. Current of the Z-source inductor.

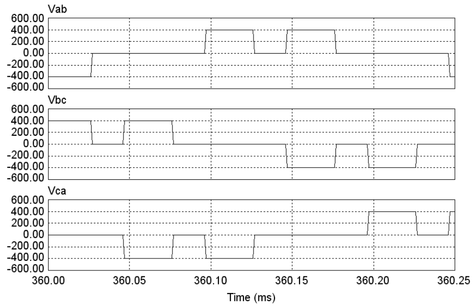

Figure 12. Voltage of the primary winding of the isolation transformer.

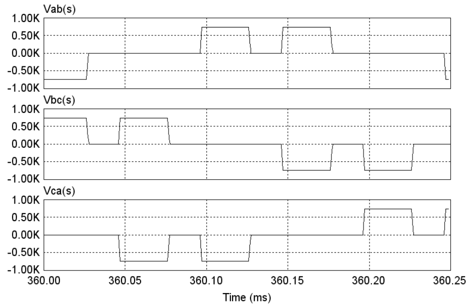

Figure 13. Voltage of the secondary winding of the isolation transformer.

IV. ANALYSIS OF SIMULATION RESULTS

The simulations performed show that the proposed ISI is capable of boosting the varying voltage of the fuel cell to the desired level (U_{in1} = 400 V). After the preregulation for achieving the required output voltage on the load terminals (U_{Load} = 600 V) the further increasing of voltage was realized by the three-phase step-up transformer.

The calculated voltage ripple on the Z-source capacitors is 3% at 40 V and 3% at 80 V (see Table II). The simulated values of voltage ripple on the Z-source capacitors at input voltages of 40 V and 80 V were 1.36% and 0.83%, respectively, which is much better result than the result obtained by the calculations. The calculated current ripple through the Z-source inductor is 60% at 40 V and 60% at 80 V. The values of ripple current received from the simulations were 28% and 57% at input voltages of 40 V and 80 V, respectively. The output voltage of the DC/DC converter remains constant (600 V DC) in all boundary operating points. The output voltage and current ripple were below 1%, which is very good result for such a powerful system.

V. CONCLUSIONS

The paper presented a new step-up isolated DC/DC converter for the fuel cell applications. By help of theoretical analysis and simulations it was stated and verified that the implementation of the Z-source inverter in the primary side of the isolated DC/DC converter could provide an effective boost of the input voltage only by the introduction of the shoot-through switching state. The desired DC-link voltage is preregulated by the variation of the shoot-through duty cycle, which is inversely proportional to the operating voltage of the fuel cell.

The simulations showed that the proposed converter is operating as predicted, without intolerable voltage and current ripples on its input and output sides. The future work is aimed to development, assembling and testing of the scaled prototype (3 kW) of the proposed converter.

ACKNOWLEDGMENT

Authors thank Estonian Science Foundation (Grant ETF8020 “Research of Advanced Control and Diagnostics Systems for the High-Power IGBT Converters” and Grant ETF7572 “High Power DC Voltage Converters with High Frequency Transformer Link”) for their financial support.

REFERENCES

[1] R. Strzelecki, and G. Benysek, *Power Electronics in Smart Electrical Energy Networks*, © 2008 Springer-Verlag London Limited.

[2] Fang Zheng Peng , “Z-source inverter,” *IEEE Transactions on Industry Applications*, Volume 39, Issue 2, Mar/Apr 2003 Page(s): 504 – 510.

[3] Vinnikov, D.; Isolated DC/DC Converter Topology with a Three-phase Intermediate AC-Link. 2006 International Baltic Electronics Conference, 2-4 Oct. 2006, pp.1 – 4.

[4] Fang Zheng Peng and Yi Huang “Z-source inverter for power conditioning and utility interface of renewable energy sources”.

[5] J. Rabkowski, “The bidirectional Z-source inverter as an energy storage/grid interface”. International conference “Eurocon 2007”, Warsaw, September 9-12, pp. 1629 - 1635.

[6] Mitch Olszewski “Z-Source Inverter for Fuel Cell Vehicles”, Michigan State University, Department of Electrical and computer Engineering, Oak Ridge National Laboratory, August 31, 2005.

[7] F. Peng, M. Shen, and Z. Qian, “Maximum boost control of the Z-source inverter,” Annual IEEE Power Electronics Specialists Conference, pp. 255-260, 2004, Aachen, Germany.