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

D. Vinnikov, T. Jalakas and I. Roasto

Department of Electrical Drives and Power Electronics
Tallinn University of Technology
Ehitajate tee 5, 19086 Tallinn, Estonia
phone: +372 6203705, fax: +372 6203701, e-mail: dm.vin@mail.ee

Abstract. This paper presents a new high-power step-up DC/DC converter topology with high-frequency isolation intended for residential fuel cell power systems. In contrast to traditional voltage source converters, the proposed topology utilizes the Z-source (impedance source) network represented by a combination of two inductors and two capacitors on the input side of the DC/DC converter. Due to the specific feature of boosting input voltage by introducing a shoot-through operation mode, the new converter provides a more reliable, simpler and cheaper solution than offered by those recently available for residential fuel cell power systems. The paper describes the design methodology, analyzes the results of simulation and optimization possibilities of the proposed topology.

Key words

Fuel cell, Z-source inverter, transformer, control method

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 to interconnect the fuel cell generating low DC voltage 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).

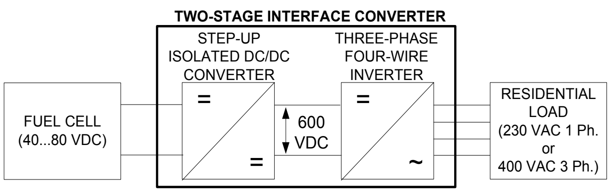


Fig. 1. Typical structure of the interface converter for the residential fuel cell power systems.

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 (Fig. 2).

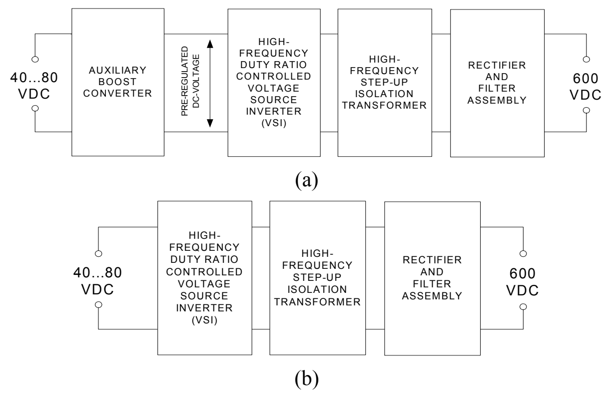


Fig. 2. Generalized structures of most widespread first-stage step-up isolated DC/DC converters for residential fuel cell power systems.

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 (Fig. 2*a*). 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. Moreover, due to pre-boosted input voltage the isolation transformer has the moderate turns ratio (1:10...1:12), which gives a positive impact in terms of leakage inductance and efficiency.

A direct step-up DC/DC converter without input voltage preregulation (Fig. 2*b*) is simpler in control and protection. Due to the reduced number of switching devices the converter tends to have better efficiency and reliability. 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 isolation transformer should have an increased turns ratio (approx. 1:17) to provide effective voltage step-up in the whole range of input voltage and load variations. 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%.

This paper proposes a new high power (≥ 10 kW) step-up DC/DC converter for residential fuel cell power systems. The topology proposed (Fig. 3) utilizes the Z-source (impedance source) inverter at the converter primary, three-phase high-frequency step-up isolation transformers stack, bridge rectifier and output filter assembly. As compared to the topologies presented earlier, the novel converter provides such advantages as increased reliability, isolation transformer with reduced turns ratio and reduced demands on output filter elements.

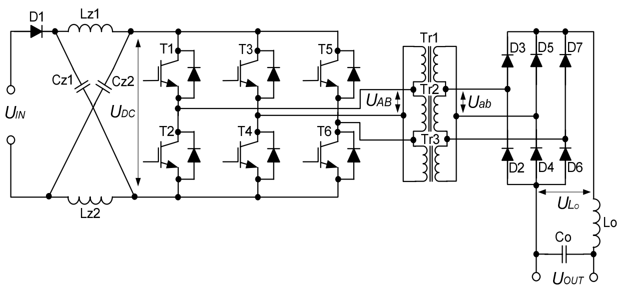


Fig. 3. Proposed step-up DC/DC converter with the Z-source inverter and three-phase isolation transformer.

2. Converter Design Guidelines

The Z-source inverter (ZSI) [6] implemented at the converter input side has a unique feature: it can boost the input voltage by introducing a shoot-through operation mode, which is forbidden in traditional voltage source inverters (VSI). 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 a voltage of a certain magnitude from the inverter operating with the constant duty cycle. Although the control principle of the ZSI is more complicated than with traditional VSI, it provides a potentially cheaper, more powerful, reliable and efficient approach to be used for fuel cell powered systems.

A. Simplified Control Methodology of the Three-Phase ZSI

As was discussed earlier, compared with a traditional VSI, the Z-source inverter has an extra switching state: shoot-through, when the top and bottom switches of the inverter legs are turned on. Fig. 4 presents the simplified control principle of the single-phase ZSI in the shoot-through state (T_0 is the operating cycle, T is the cycle of triangular carrier, T_Z is the time of shoot-through state, *SA*, *SB*, *SC* are the signal generators). To control the shoot-through states, the two straight lines (U_p and U_n) were introduced. When the triangular waveform is greater than the upper envelope U_p or lower than the bottom envelope U_n, the inverter switches turn into the shoot-through state. Otherwise, when the input voltage is high enough, the inverter operates with a traditional carrier-based PWM utilizing two conventional zero-states to control the magnitude of the output voltage. The waveforms of the line voltages seen on the primary windings of the isolation transformers are presented in Figs. 4 as U_{AB}, U_{BC}, U_{CA}.

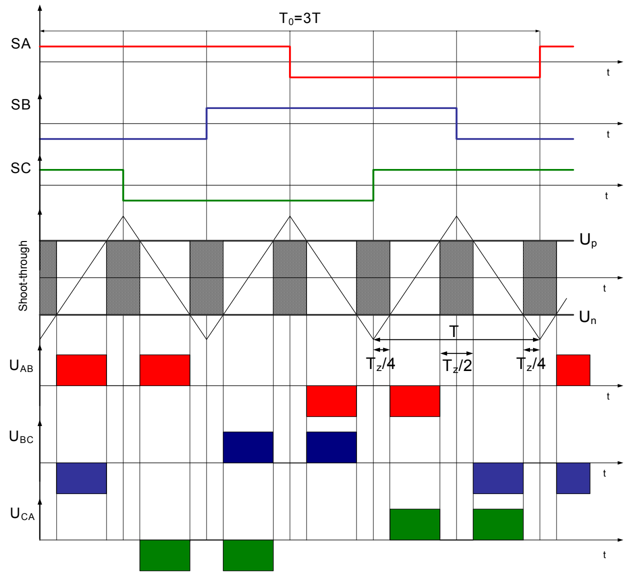


Fig. 4. Operating principle of the proposed DC/DC converter in the shoot-through states.

Each operating period of the proposed topology consists of a shoot-through state t_Z and an active state t_A:

$$T = t_Z + t_A \,. \tag{1}$$

In the active mode, one and only one switch in each phase leg conducts. The (1) could also be represented as

$$\frac{t_Z}{T} + \frac{t_A}{T} = D_Z + D_A = 1 \,, \tag{2}$$

where D_Z is the duty cycle of a shoot-through state and D_A is the duty cycle of an active state. The duty cycle of the shoot-through state could not exceed 0.5.

It should be noted here that in the presented control scheme the switching frequency of the transistors will be six times higher than the frequency of the fundamental harmonic of the isolation transformers' primary voltage. That fact should always be considered when selecting proper components and operating frequencies of the proposed converter. Otherwise, due to the twofold increased frequency of the rectified voltage the proposed topology provides a serious benefit in terms of reduced output filter demands that cannot be achieved with traditional three-phase isolated DC/DC converter with the full-bridge (B6U) rectifier.

B. Power Circuit Design Considerations

This section describes the design process of the 10 kW isolated DC/DC converter. The desired operating parameters are presented in Table I.

TABLE I. - Desired Operating Parameters of the Converter

Parameter	Value
Minimal input voltage, $U_{IN,min}$	40 V
Maximal input voltage $U_{IN,max}$	80 V
Desired DC-link voltage amplitude U_{DC}	80 V
Nominal output voltage U_{OUT}	600 V
Output power P	10 kW
Switching frequency, f_{sw}	24 kHz
Fundamental harmonic frequency of the isolation transformers, f_{TR}	4 kHz
Desired peak-to-peak current ripple through the Z-inductors	10 %
Desired peak-to-peak current ripple through the output inductor L_o	60 %
Desired voltage ripple of the capacitors	1 %

In the given application the desired value the DC-link voltage U_{DC} was selected as 80 V. It is assumed that the converter is always operating with the rated load and between two boundary operating points, whose correspond to the minimal and maximal input voltages. If the input voltage is below the desired value the DC-link voltage, the shoot-through switching state should be used to boost the voltage to the predefined DC-link level. In the second case, when the input voltage is equal to the desired DC-link voltage, no shoot-through is applied and the Z-source inverter operates as a conventional VSI.

The selection of components should be performed for the operating point with the minimal possible input voltage and at rated power. In this operating point the converter utilizes the earlier discussed shoot-through switching state – produced by the simultaneous turning on the top and bottom swithes of one (or both) inverter leg. The duration of the shoot-through switching state in this operating point becomes maximal thus providing the maximal boost factor B_{max} of the input voltage

$$B_{max} = \frac{U_{DC}}{U_{IN,min}} = \frac{80}{40} = 2. \qquad (3)$$

It should be noted that in the real designs to achieve the proper efficiency of the converter as well as for the better transformer utilization, proper balance between the boost ratio and the transformer turns ratio should be found. In the current application, the maximal duty cycle of the shoot-through state is

$$D_{Z,max} = \frac{1-(B_{max})^{-1}}{2} = 0.25 . \qquad (4)$$

The duty cycle of the active state in this operating point is

$$D_A = 1 - D_{Z,max} = 0.75 . \qquad (5)$$

During the active states the amplitude value of line voltage of the primary winding of the three-phase isolation transformer stack equals to the amplitude voltage of the DC-link: $U_{AB}=U_{DC}$. The amplitude value of line voltage of the secondary winding for the given application is

$$U_{ab} = \frac{U_{OUT}}{D_A} . \qquad (6)$$

The turns ratio of the isolation transformer is

$$n = \frac{U_{AB}}{U_{ab}} = \frac{1}{10} . \qquad (7)$$

The output filter components should be calculated similarly to a traditional isolated DC/DC converter with bridge rectifier and output LC-filter. Neglecting second-order effects, the required inductance for the assumed 60% (10 A) peak-to-peak current ripple is

$$L_O = \frac{(U_{LO} - U_{OUT}) \cdot D_A \cdot U_{OUT}}{0.6 \cdot f_{sw} \cdot P} = 0.63 \text{ mH}. \qquad (8)$$

The required filtering capacitance for the 1% (6 V) voltage ripple is

$$C_O = \frac{0.6 \cdot P \cdot D_A}{0.01 \cdot f_{sw} \cdot (U_{OUT})^2} = 52.08 \text{ uF}. \qquad (9)$$

The elements of the impedance network should also be calculated in compliance with the desired current and voltage ripples on the elements during the shoot-through state. The impedance network implemented is symmetrical, thus the component voltage and current stresses are identical. The Z-capacitor voltage during the shoot-through is

$$U_{Cz1} = U_{Cz2} = \frac{U_{IN,\min} + U_{DC}}{2} = 60 \text{ V}. \qquad (10)$$

To keep the desired 10 % (25 A) current ripple, the inductance of the Z-inductor should be

$$L_{Z1} = L_{Z2} = \frac{D_{Z,max} \cdot U_{Cz} \cdot U_{IN,min}}{0.1 \cdot f_{sw} \cdot P} = 25 \text{ uH}. \qquad (11)$$

To limit the Z-capacitor voltage ripple by 1% (0.4 V) at peak power, the capacitance should be

$$C_{Z1} = C_{Z2} = \frac{P \cdot D_{Z,max}}{0.01 \cdot U_{IN,min} \cdot f_{sw} \cdot U_{Cz}} = 4.34 \text{ mF}. \qquad (12)$$

For every operating point within the predefined boundaries [$U_{IN,min}$; $U_{IN,max}$], the output voltage of the converter during the shoot-through state could be estimated as

$$U_{OUT} = \frac{U_{IN} \cdot D_A \cdot B}{n} = \frac{U_{IN} \cdot D_A}{n} \cdot \left(\frac{1}{1 - 2 \cdot D_Z} \right). \qquad (13)$$

It is seen from (13) that the voltage boost factor B and the transformer turns ratio n are inversely proportional.

In the second boundary operating point, when the input voltage becomes maximal, the inverter utilizes the conventional zero state (when the primary winding of the isolation transformer is shorted through either the top or bottom inverter switches) to control the magnitude of the output voltage. In the current application, to obtain the desired 600 V on the converter output at the maximal input voltage ($U_{IN,max}$ = 80 V), the duty cycle of the zero state should be selected as D_0 = 0.25.

3. Simulation Results

Simulations were performed to confirm the above analysis. The assumptions presented above were verified in both operating points $U_{IN,min}$ and $U_{IN,max}$. To provide a better appearance, simulation waveforms are shown with the timescale corresponding to one full period of the operating voltage of the isolation transformer. The inverter is operated with no dead-time. The operating frequency seen on the isolation transformer windings is 4 kHz, while the inverter switching frequency as well as the frequency seen by the impedance network and output filter is 24 kHz.

The first simulations (Figs. 5-9) were performed with an input voltage $U_{IN,min}$ = 40 V and with the shoot-through mode (D_Z=0.25). The voltage and current ripple values are consistent with the results predicted by the theoretical analysis.

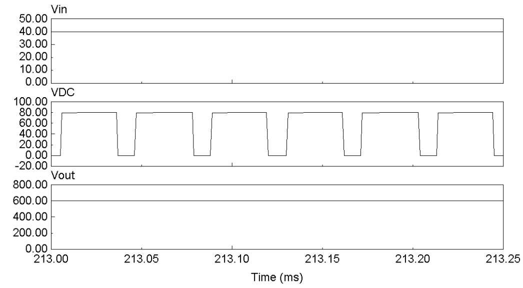
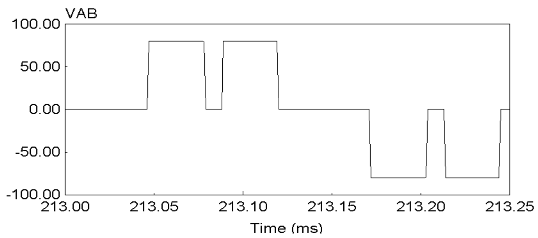
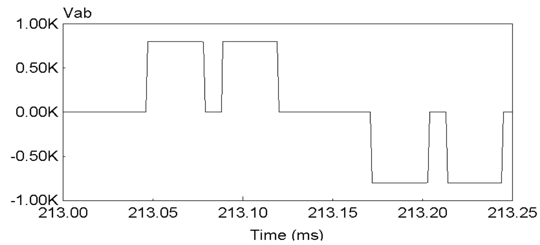


Fig. 5. Input, DC-link and output voltage waveforms of the proposed DC/DC converter operating at minimal input voltage (duration of the shoot-through state is t_Z=10.42 us).

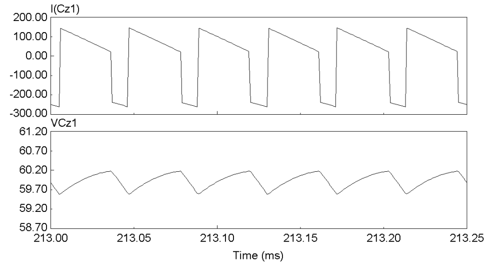


(a)

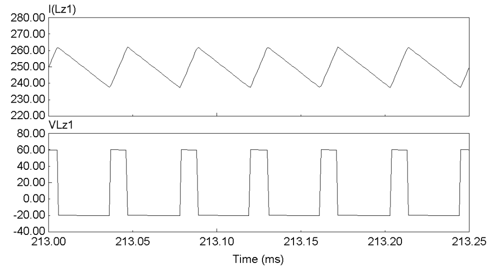


(b)

Fig. 6. Primary (a) and secondary (b) line-to-line voltage waveforms of the isolation transformer (duration of the active state t_A=31.25 us).



(a)



(b)

Fig. 7. Simulated waveforms of the Z-source network at the maximal boost mode of the input voltage: operating current and voltage of Z-capacitors (a) and operating current and voltage of Z-inductors (b).

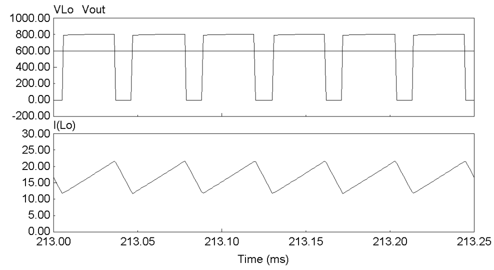


Fig. 8. Simulated waveforms of the secondary side of the proposed DC/DC converter: voltage before the output filter, output voltage and current ripple through the filtering inductor.

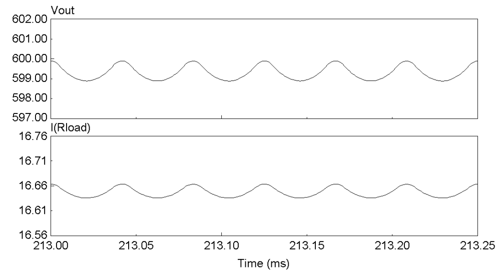


Fig. 9. Converter output voltage and current ripples.

The second group of simulations (Figs. 10 - 11) was performed with an input voltage $U_{IN,max}$ = 80 V. In that operating point 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 duty cycle of voltage delivered to the isolation transformer primary is D_A=0.75. It should be noted that the waveforms of the isolation transformer as well as those of the secondary side of the proposed DC/DC converter remain unchanged (see Fig. 6). The waveforms of the Z-source network components operating at the "no-boost" mode are presented in

Fig. 11. As can be seen from Fig. 11*a*, without the shoot-through state, the voltage of Z-capacitor is equal to the input voltage and the expected output voltage and current are obtained. This demonstrates that a three-phase Z-source inverter can be operated as a traditional voltage source PWM inverter without any modifications in hardware.

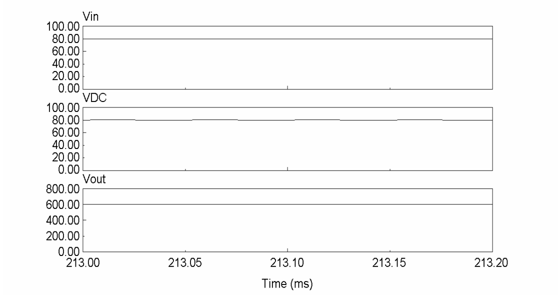
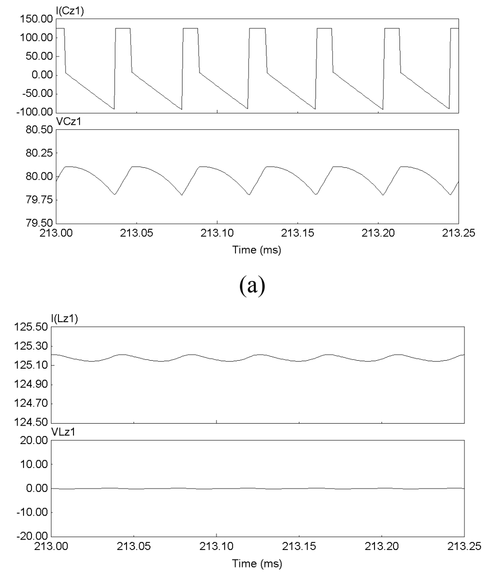


Fig. 10. Input, DC-link and output voltage waveforms of the proposed DC/DC converter operating at maximal input voltage (duration of the zero state is t_0 = 10.42 us).



(a)

(b)

Fig. 11. Simulated waveforms of the Z-source network at the "no-boost" mode: operating current and voltage of Z-capacitors (a) and operating current and voltage of Z-inductors (b).

4. Possibilities of Topology Improvement

As it was verified by the simulations, the proposed step-up DC/DC converter with three-phase high frequency galvanic isolation provides a reliable and relatively simple solution for the first stage (front end) DC/DC converter for residential fuel cell power systems. This section provides a survey of further optimization possibilities of the proposed topology.

As it was reported earlier, in real design practice to provide better flexibility and efficiency of the converter, proper balance should be found between the duty cycles of the shoot-through and the active states. Utilizing the low boost factor region (B=1...3), the operating voltage and current ripple on the Z-network capacitors could be drastically decreased. Moreover, the inductance demands of the Z-inductors could be minimized, thus providing an opportunity of optimization of the space-weight constraints of the Z-source inverter stack. However, the low boost ratio leads to the step-up isolation transformer with a large turns ratio to be implemented. This could result in increased leakage inductance of transformer windings, which in turn gives a negative impact in terms of voltage overshoots and parasitic ringing on the semiconductors.

However, the most serious drawback of the proposed topology with the presented simplified control methodology (1) is lack of flexible control possibility of the output voltage. As (13) shows, during the shoot-through (voltage boost) modes the output voltage depends on both the shoot-through D_Z and active state D_A duty cycles. Taking into consideration (13), it should be pointed out that inside the desired boost range B = 0...2 the converter will produce higher output voltage than demanded. To resolve that problem, some modifications should be done in the control algorithm of the converter: to compensate the excess voltage on the converter output the zero state should be introduced during the voltage boost mode as well. Thus, if the input voltage of the converter lies within the range

$$U_{in,min} < U_{in} < U_{in,max}\,, \tag{14}$$

the three switching states should be utilized for the control of the inverter during one switching period:

$$D_Z + D_A + D_0 = 1\,, \tag{15}$$

where D_0 is the duty cycle of the zero state. In discussed application the desired DC-link voltage level is selected as U_{DC}=80 V and to obtain the desired 600 V on the converter output the duty cycle of the active state should be constantly set as D_A = 0.75. Taking that fact into the consideration the (14) could be rearranged as

$$D_Z + D_0 = 1 - 0.75 = 0.25\,. \tag{16}$$

For the operation range (14) the duration of zero state could be calculated by

$$D_0 = 0.25 - D_Z = 0.25 - \frac{1-\left(\dfrac{U_{in}}{U_{DC}}\right)}{2}\,, \tag{17}$$

where U_{in} is the input voltage and U_{DC} is the desired DC link voltage (80 V). With the utilization of three switching states the complexity of the control program will increase followed by the increased load on the control system. Moreover, the switching frequency of transistors will be further increased, which will result in higher power losses and reduced efficiency of the converter.

The simplest method to cope with the above-discussed problems will be to implement the voltage doubler rectifiers (VDR) on the output stage of the converter (Fig. 12). Due to the voltage doubling effect, the VDR provides a possibility of using the isolation transformers with a reduced secondary turns number. The amplitude voltage value of the secondary winding of each transformer in three-phase stack is only the half of the output voltage. Comparing that fact with (6) it should be stated that by the implementation of the VDR in the discussed application the turns number of the secondary winding of isolation transformer could be reduced by 62% (turns ratio 1:3.75 in case of VDR instead of 1:10 of FBR).

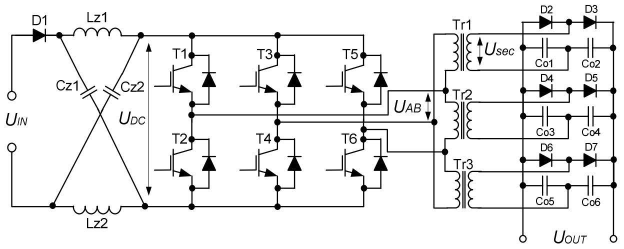


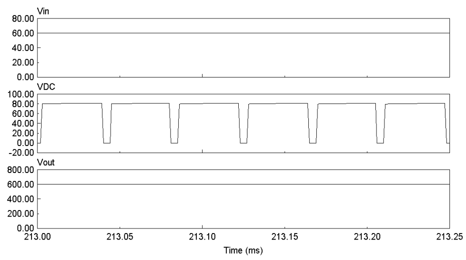
Fig. 12. Proposed power circuit layout of the three-phase isolated DC/DC converter with Z-source inverter and paralleled voltage doubler rectifiers.

For every operating point within the predefined boundaries [$U_{IN,min}$; $U_{IN,max}$], the output voltage of the converter at the shoot-through mode could be estimated as

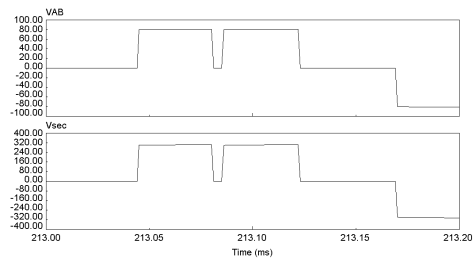
$$U_{OUT} = \frac{2 \cdot U_{IN} \cdot B}{n} = \frac{2 \cdot U_{IN}}{n} \cdot \left(\frac{1}{1 - 2 \cdot D_Z} \right). \qquad (18)$$

From (18) it is seen that the output voltage of the converter with the VDR does not depend on the duty cycle of the active state anymore. It improves the control flexibility of the proposed converter with no modifications in the control algorithm (simplified two-state control methodology could be used for all the operating points between the minimal and maximal input voltages). To limit the voltage ripple on the output half-bridge capacitors (C_{O1}…C_{O6}) by 1% (6 V) at peak power, the capacitance should be

$$C_{O1}...C_{O6} = \frac{P}{0.01 \cdot f_{sw} \cdot (U_{OUT})^2} = 115.7 \text{ uF}. \qquad (19)$$



(a)



(b)

Fig. 13. Input, DC-link and output voltage waveforms of three-phase isolated DC/DC converter with VDR (a) and voltage waveforms of the isolation transformer (b).

Fig. 13 presents the simulated waveforms of the updated converter with paralleled VDRs operating with the input voltage $U_{IN,min}$ = 60 V (shoot-through duty cycle D_Z=0.125) and at the rated load. It was verified that with the updated topology (Fig. 12) the simplified two-state control methodology (2) could be used without limitations for all the operating points of the converter.

5. 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.

It is concluded that the impedance-source inverters implemented in the isolated DC/DC converters could effectively solve the general problem of reliability of the voltage source inverter, because the ZSI can handle the shoot-through operation modes. Thus, momentary shoot-through caused by EMI will not affect the operation of the inverter [6].

Acknowledgment

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

References

[1] Sternberg, Kyle; Hongwei Gao, "A new DC/DC converter for solid oxide fuel cell powered residential systems", 34th Annual Conference of IEEE Industrial Electronics, 2008. IECON 2008., pp.2273-2277, 10-13 Nov. 2008.

[2] Yu Jin Song; Enjeti, P.N., "A high frequency link direct dc-ac converter for residential fuel cell power systems", IEEE 35th Annual Power Electronics Specialists Conference, 2004. PESC 04. 2004, vol.6, pp. 4755-4761, 20-25 June 2004.

[3] Mazumder, S.K.; Burra, R.K.; Huang, R.; Tahir, M.; Acharya, K.; Garcia, G.; Pro, S.; Rodrigues, O.; Stasinopoulos, M., "Single-stage low-cost and energy-efficient isolated phase-shifted high-frequency inverter followed by a forced cycloconverter for universal residential fuel cell power system," IEEE International Conference on Electro/Information Technology, 2008. EIT 2008., pp.408-413, 18-20 May 2008.

[4] Andersen, G.K.; Klumpner, C.; Kjaer, S.B.; Blaabjerg, F., "A new green power inverter for fuel cells", IEEE 33rd Annual Power Electronics Specialists Conference, 2002. PESC’02. 2002, vol.2, pp. 727-733, 2002.

[5] Oliveira, S.V.G.; Barbi, I., "A three-phase step-up DC-DC converter with a three-phase high frequency transformer," ISIE 2005. Proceedings of the IEEE International Symposium on Industrial Electronics, 2005, vol.2, pp. 571-576, 20-23 June 2005.

[6] Fang Zheng Peng, "Z-source inverter," IEEE Transactions on Industry Applications, vol.39, no.2, pp. 504-510, Mar/Apr 2003.