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New Integrated Converter for Hydrogen Buffer Interfacing in Distributed Energy Systems

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Abstract. This paper presents a new integrated (multiport) DC/DC converter for hydrogen buffer interfacing in renewable energy systems. In comparison with traditional solutions based on individual converters for interfacing of electrolyser and fuel cell the proposed topology features the reduced energy conversion stages. The paper analyzes and discusses the operating principle of a new converter. Several guidelines are presented for the new converter design. Finally, theoretical background was verified by the simulations.

Key words

Distributed energy systems, electrolyser, fuel cell, interface converter, multiport converter

1. Introduction

The energy conversion from renewable energy sources, such as wind turbines or photovoltaic arrays can play an important role in the development and operation of distributed energy systems (DES) [1, 2]. Due to the unpredicted nature of primary power sources (wind, solar) power fluctuations could appear in DES. Moreover, electrical production is not subject to the demand, which usually results in an unbalanced system [3]. The way to overcome these problems is to implement the long-term energy storage within the DES.

In recent years, implementation of hydrogen-based long-term energy storages in distributed energy systems has attracted much attention [2, 4-6]. Typically, the main components of such a system are an electrolyser (EL), hydrogen storage system and fuel cell (FC) (Fig. 1). Since the FC has a slow response time and also prefers to be operated under constant power, a battery is often used as additional energy storage in order to compensate the peak power demands.

As it seen from Fig. 1, for the proper voltage matching the main components of the hydrogen buffer should be connected to the DC-bus of DES via different power electronic converters: electrolyser is interfaced by help of step-down DC/DC converter, while the fuel cell is connected by help of step-up DC/DC converter. Typically, the battery is placed on the secondary side of the power conditioner of a fuel cell and its charging/discharging processes could also be more conveniently controlled by the power electronic interface.

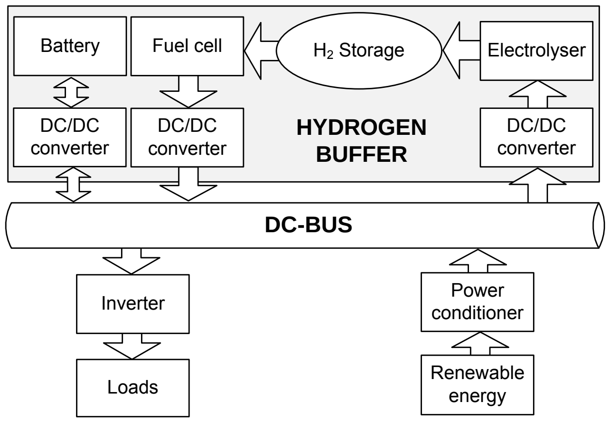

Fig. 1. Typical structure of the distributed energy system with hydrogen buffer interfaced via individual converters.

Traditionally, individual converters are used to provide interfaces for the power inputs and outputs of the hydrogen buffer. In principle, any basic power converter topology can be used to design a power interface for a fuel cell and electrolyser. All these converters should have a high-frequency voltage matching transformer, which could also perform a function of galvanic isolation demanded in several applications. It finally leads to complex multiconverter systems (Fig. 1) with a high number of energy conversion stages, complex control and reduced efficiency.

This paper proposes the new integrated DC/DC converter for hydrogen buffer interfacing in distributed energy systems (Fig. 2). Thanks to the implemented multiport converter concept (Fig. 3) the number of energy conversion stages was significantly reduced. The resulting advantages of that include reduced component count, lower cost, and control simplicity. Moreover, the multiport converter technology may best satisfy integrated power conversion, efficient thermal management, compact packaging, and centralized control requirements [7, 8]. These advantages can potentially improve the overall cost, efficiency and flexibility of the hydrogen buffers used in distributed energy systems.

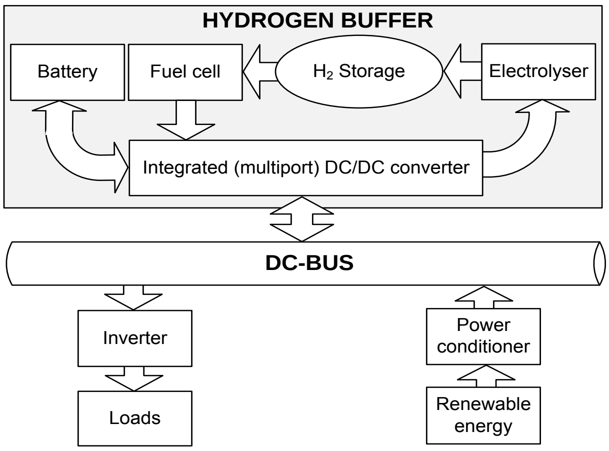

Fig. 2. Proposed structure of the distributed energy system with hydrogen buffer interfaced via multiport converter.

2. New Integrated Converter for Hydrogen Buffer Interfacing

The integrated (multiport) structure presented in Fig. 3 could be a technically feasible alternative for a small-scale DES, reducing a number of power processing stages and increasing an overall energy efficiency of the hydrogen buffer. The electrolyser and fuel cell are magnetically coupled with the DC-bus side converter by help of a multiwinding voltage matching transformer. Thus, all the ports of the interface converter are galvanically isolated, which could be a compulsory requirement for safety reasons in DES applications. The proposed converter consists of three ports: two unidirectional low-voltage ports for interconnection of electrolyser and fuel cell and one high-voltage bidirectional port for interconnection of hydrogen buffer with the main DC-bus of a DES.

3. Operation Modes of the Converter

In accordance with its operation principle the hydrogen buffer could have two main operating modes: hydrogen generation from surplus energy of a DES (i.e. EL mode) and a power back-up mode with the electricity generation by a fuel cell (i.e. FC mode).

A. EL operation mode

In the EL mode the converter acts as a traditional step-down isolated DC/DC converter with a voltage-source half-bridge inverter, step-down isolation transformer and current-doubler rectifier (Fig. 4). Implementation of half-bridge inverter together with current-doubler rectifier provides an opportunity of turns ratio reduction of the isolation transformer. The EL voltage could be simply controlled by the duty cycle variation of the transistors T1 and T2. Neglecting losses in components, the voltage U_{EL} during the EL mode (Fig. 4) is

$$U_{EL} = \frac{U_{DC-BUS}}{2 \cdot n_1} \cdot D, \quad (1)$$

where U_{DC-BUS} is the DC-bus voltage of the main system, D is the duty cycle of the VSI switches (T1 and T2). Input and output sides (ports) of the converter are magnetically coupled through the isolation transformer's windings 1 and 3, respectively (Fig. 4) and the desired turns ratio of the isolation transformer n_1 is:

$$n_1 = \frac{U_{Tr,1}}{U_{Tr,3}}, \quad (2)$$

where $U_{Tr,1}$ and $U_{Tr,3}$ is the amplitude voltages of the primary (high-voltage, DC-bus side) and tertiary (low-voltage, EL side) windings of the isolation transformer, respectively.

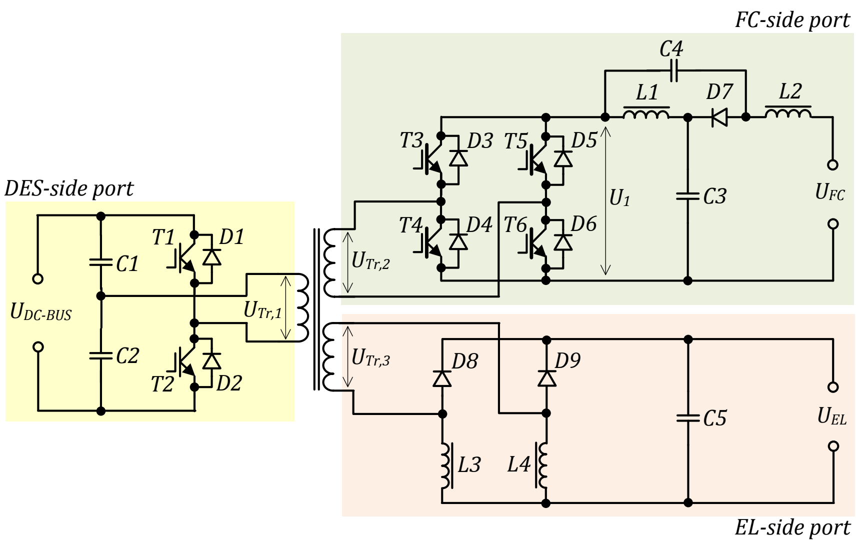

Fig. 3. Power scheme layout of the proposed integrated converter for hydrogen buffer interfacing in DES.

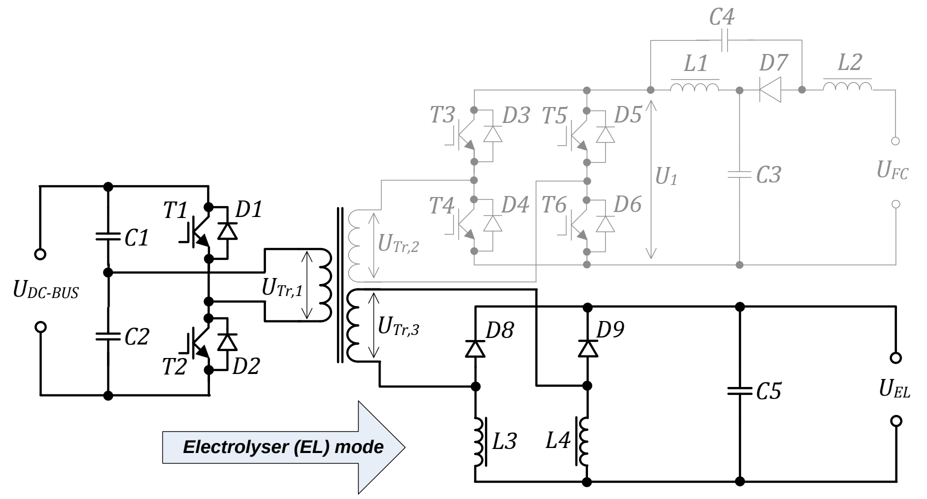

Fig. 4. Power circuit configuration in the electrolyser (EL) mode.

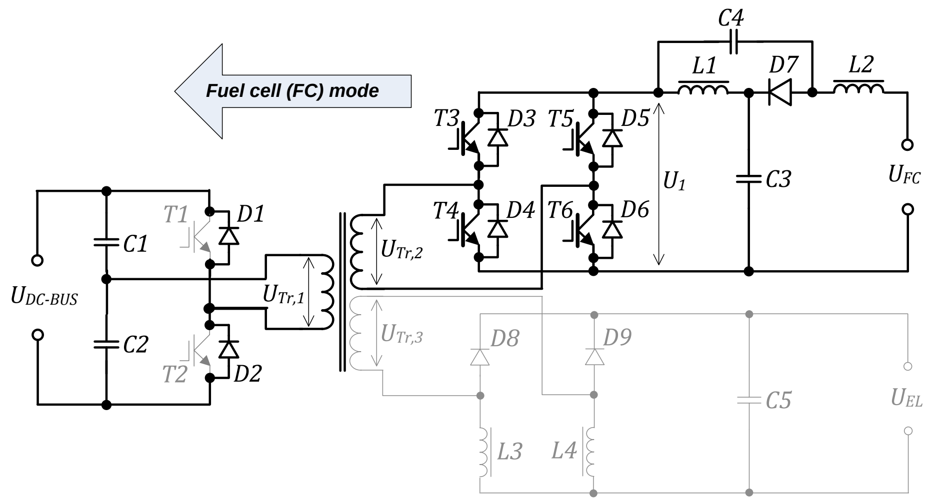

Fig. 5. Power circuit configuration in the fuel cell (FC) mode.

B. FC operation mode

In the FC mode the converter starts operating in the boost mode and the power flows from the FC to the high-voltage DC-bus, thus performing the power back-up function. The configuration of the power circuit in FC mode is presented in Fig. 5. The power flow from the FC to the DC-bus is controlled by the quasi-impedance-source inverter (qZSI). The integrated freewheeling diodes D1 and D2 of transistor modules T1 and T2 together with capacitors C1 and C2 act as the voltage-doubler rectifier. In conditions of changing FC voltage the amplitude voltage $U_{Tr,2}$ of the secondary winding of the isolation transformer is kept constant by the variation of the duration of a shoot-through switching state of qZSI. The shoot-through switching state is the simultaneous conduction of both switches of the same phase leg of the qZSI. This switching state is forbidden for the traditional voltage source converters because it could destroy the inverter. In the qZSI, the shoot-through states are used to boost the magnetic energy stored in the DC-side inductors L1 and L2 without short-circuiting the DC-capacitors C3 and C4. This increase in inductive energy in turn provides the boost of voltage $U_{Tr,2}$ seen on the transformer secondary winding during active states of the qZSI [9].

Neglecting losses in components, the voltage $U_{DC\text{-}BUS}$ during the FC mode (Fig. 5) could be regulated by the variation of a shoot-through duty cycle D_S:

$$U_{DC-BUS} = \frac{2 \cdot U_{FC}}{n_2 \cdot (1 - 2 \cdot D_S)}, \qquad (3)$$

where U_{FC} is the fuel cell voltage, D_S is the shoot-through duty cycle of the qZSI switches (T3, T4, T5 and T6). FC-side and DES-side ports of the converter are magnetically coupled through the isolation transformer's secondary and primary windings, respectively (Fig. 5) and the desired turns ratio of the isolation transformer n_2 is:

$$n_2 = \frac{U_{Tr,2}}{U_{Tr,1}}, \qquad (4)$$

where $U_{Tr,1}$ and $U_{Tr,2}$ is the amplitude voltages of the primary (high-voltage, DC-bus side) and secondary (low-voltage, FC side) windings of the isolation transformer, respectively.

4. Some Design Guidelines of the Proposed Converter

This section provides the general design equations for the proposed integrated multiport DC/DC converter shown in Fig. 3. To simplify the discussion losses in components will be neglected. It is assumed that the hydrogen buffer is based on the 2.4 kW electrolyser, which capable to generate 1 nm^3 (1000 litres) of hydrogen in two hours. For electricity generation from the hydrogen two series connected 1.2 kW fuel cells were selected. The voltage selected for a DC-bus of a DES was 560 VDC (which is typical for 3×400 AC output). The desired operating parameters of the converter are listed in Table I.

Table I. - Desired Operating Parameters of the Investigated Converter

PARAMETER	VALUE
Electrolyser mode	
DC-link voltage of the main system, U_{DC-BUS}	560 V
Rated voltage of electrolyser, U_{EL}	80 V
Duty cycle of VSI switches, D	0.45
Fuel cell mode	
Light-load FC voltage, $U_{FC,max}$	70 V
Full-load FC voltage, $U_{FC,min}$	46 V
Desired voltage amplitude of the intermediate DC-link, U_I	70 V
Duty cycle of active state, D_A	0.4
Voltage and current ripples of passive components	
Operating frequency of isolation transformer, f	15 kHz
Desired voltage ripple of the capacitors, ΔU_C	≤ 5 %
Desired peak-to-peak current ripple through the inductors, ΔI_L	≤ 10 %

A. *Turns ratio selection for voltage matching transformer*

The transformer is a core component of an integrated multiport converter. It provides isolation and voltage matching between three ports. The amplitude voltage of the primary winding is always the half of the DC-bus voltage:

$$U_{Tr,1} = \frac{U_{DC-BUS}}{2} = 280\,(V). \qquad (5)$$

Thanks to the qZSI, the amplitude value of the intermediate DC-link voltage U_I as well as the amplitude voltage value of the secondary winding $U_{Tr,2}$ could be kept constant simply by the variation of a shoot-through duty cycle D_S. For example, for ensuring the demanded U_I=70 V the shoot-through duty cycle in conditions of minimal FC voltage should be:

$$D_{S,\max} = \frac{1}{2}\cdot\left(1-\frac{U_{FC,\min}}{U_1}\right) = \frac{1}{2}\cdot\left(1-\frac{46}{70}\right) = 0.17. \qquad (6)$$

The desired turns ratio of the isolation transformer n_2 is:

$$n_2 = \frac{U_{Tr,2}}{U_{Tr,1}} = \frac{70}{280} = \frac{1}{4}. \qquad (7)$$

In the EL mode the terminal voltage of the electrolyser could be regulated in accordance with (1). For the selected duty cycle value of D=0.45 and demanded EL voltage of 80 V (Table I) the amplitude voltage of tertiary winding could be calculated as:

$$U_{Tr,3} = \frac{U_{EL}}{D} = 177.8\,(V). \qquad (8)$$

The desired turns ratio of the isolation transformer n_1 is:

$$n_1 = \frac{U_{Tr,1}}{U_{Tr,3}} = \frac{280}{177.8} = \frac{1.6}{1}. \qquad (9)$$

B. *Selection of passive components*

The value of the required capacitance for capacitors C1 and C2 could be calculated from the rated power, desired voltage ripple and operating frequency of the converter operating in the EL mode:

$$C1 = C2 = \frac{P}{2\cdot U_{DC-BUS}^2 \cdot f_{sw}\cdot \Delta U_C}, \qquad (10)$$

where P is the rated power, U_{DC-BUS} is the input voltage, ΔU_C is the capacitor voltage ripple, and f_{sw} is the switching frequency. For selected operating parameters of the converter (Table I) the required capacitance value for C1 and C2 is 5.1 uF.

The current doubler rectifier topology implemented at the EL port offers a potential benefit of better distributed power dissipation, which might become a vital benefit for the integrated converters in terms of power density [10]. The filter inductances can be estimated by Eq. (11).

$$L3 = L4 = \frac{U_{EL}^2\cdot(1-D)}{P\cdot\Delta I_L\cdot f_{sw}}, \qquad (11)$$

where U_{EL} is the operating voltage of the electrolyser, D is the duty cycle, ΔI_L is the desired current ripple through the inductor and f_{sw} is the switching frequency. For selected operating parameters of the converter (Table I) the required inductance value for L3 and L4 is about 1 mH.

In the FC mode the maximum current through the inductors L1 and L2 occurs when the maximum shoot-through happens, i.e at the minimal operating voltage of the FC. With the desired peak-to-peak current ripple, the inductance for L1 and L2 could be calculated by

$$L1 = L2 = \frac{U_{FC,\min}^2}{2 \cdot P \cdot f \cdot \Delta I_L} \cdot \frac{D_{S,\max} \cdot (1 - D_{S,\max})}{(1 - 2 \cdot D_{S,\max})}, \qquad (12)$$

where f is the operating frequency of the isolation transformer, $U_{FC,min}$ is the full-load FC voltage, $D_{S,max}$ is the maximal shoot-through duty cycle, ΔI_L is the desired current ripple through the inductor and P is the power rating of the system. The required inductance value for L3 and L4 for current application is 63 uH.

In order to limit the voltage ripple on the qZSI during active states by demanded 5 % at the peak power (FC mode), the capacitance of capacitors C3 and C4 should be

$$C3 = C4 = \frac{P}{\Delta U_C \cdot U_{FC,\min} \cdot U_1} \cdot \frac{D_{S,\max}}{2 \cdot f}, \qquad (13)$$

where f is the operating frequency of the isolation transformer, $U_{FC,min}$ is the full-load FC voltage, $D_{S,max}$ is the maximal shoot-through duty cycle, ΔU_C is the desired voltage ripple of the capacitor, U_1 is the desired intermediate DC-link voltage and P is the power rating of the system. The required capacitance value for C3 and C4 is 169 uF.

5. Simulation Results

To verify the theoretical assumptions a number of simulations was performed by help of PSIM simulation software. The proposed multiport converter was studied in both operating modes. General operating parameters of the investigated system assumed for simulations are listed in Table I. Turns ratios for isolation transformer as well as passive component values were calculated by Eqs. (7), (9) and (10-13), respectively.

A. Operation in electrolyser mode

First, the system was studied in the electrolyser mode. During the simulation no control of the output voltage was performed and half-bridge VSI operated without dead time with the constant duty cycle D=0.45. Figs. 6 and 7 shows the simulation results of the proposed multiport DC/DC converter in the EL mode. It is seen that the converter operates normally, ensuring ripple-free voltage U_{EL}=80 V on the terminals of the electrolyser.

B. Operation in the fuel cell mode

It was assumed that during the fuel cell (power back-up) mode the FC is operating with the maximum power thus having terminal voltage of 46 V (Table I). To boost the FC voltage to the desired voltage level of the intermediate DC-link (70 V) the shoot-through duty cycle was set to 0.17. In active states the isolation transformer was supplied with voltage pulses with a duty cycle of 0.4. Simulation results of the proposed multiport converter in the FC mode are presented in Figs. 8-10.

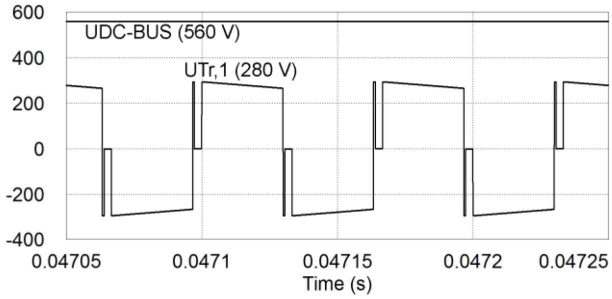

Fig. 6. General operating waveforms of the proposed multiport converter during the EL mode: DC-bus voltage (U_{DC-BUS}) and primary winding voltage of the isolation transformer ($U_{Tr,1}$).

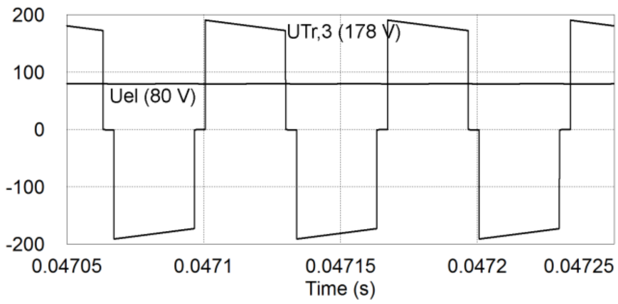

Fig. 7. General operating waveforms of the proposed multiport converter during the EL mode: electrolyser voltage (U_{EL}) and tertiary winding voltage of the isolation transformer ($U_{Tr,3}$).

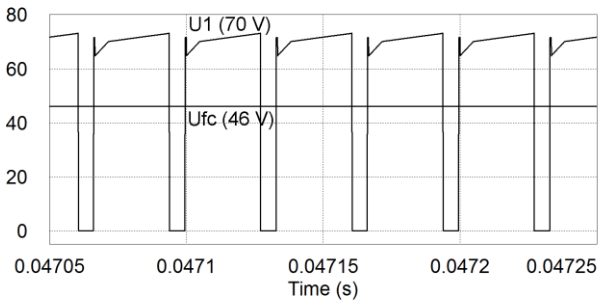

Fig. 8. General operating waveforms of the proposed multiport converter during the FC mode: fuel cell voltage (U_{FC}) and intermediate DC-link voltage (U_1).

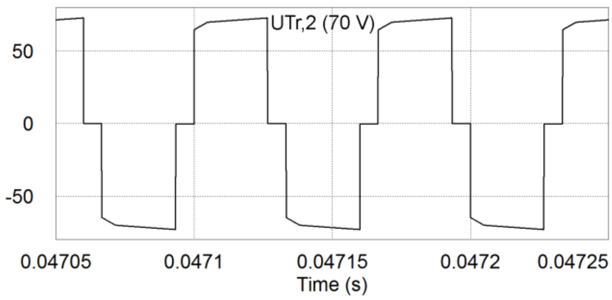

Fig. 9. General operating waveforms of the proposed multiport converter during the FC mode: secondary winding voltage of the isolation transformer ($U_{Tr,2}$).

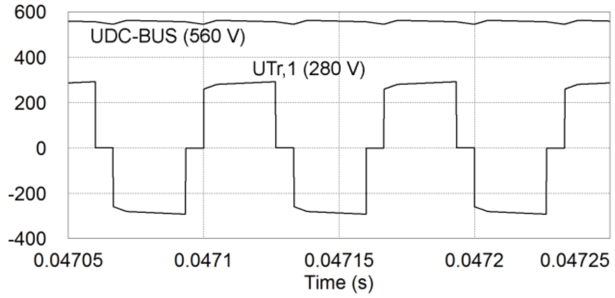

Fig. 10. General operating waveforms of the proposed multiport converter during the FC mode: DC-bus voltage ($U_{DC\text{-}BUS}$) and primary winding voltage of the isolation transformer ($U_{Tr,1}$).

6. Conclusions

This paper presents the brand-new integrated multiport DC/DC converter for hydrogen buffer interfacing in distributed energy system applications. The proposed converter has three ports: one bidirectional VSI port, one unidirectional VSI port and one unidirectional qZSI port. These three ports are magnetically coupled via the single multiwinding transformer. During the hydrogen production mode (electrolyser mode) the converter acts as a VSI-based step-down DC/DC converter thus ensuring ripple-free supply voltage for the electrolyser. In the power back-up (fuel cell) mode the converter operates as a qZSI-based step-up DC/DC converter providing the regulated voltage on the DC-bus despite the variation of the fuel cell voltage with the load. The paper analyzes and discusses the operation principle of the new converter and also provides some design guidelines. Finally, theoretical background is verified by the simulations.

Acknowledgement

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References

[1] Zobaa, A.F.; Cecati, C., "A comprehensive review on distributed power generation", International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM’2006, pp. 514-518, 23-26 May 2006.

[2] Cavallaro, C.; Chimento, F.; Musumeci, S.; Sapuppo, C.; Santonocito, C. "Electrolyser in H_2 Self-Producing Systems Connected to DC Link with Dedicated Phase Shift Converter", International Conference on Clean Electrical Power, ICCEP ‘2007, pp. 632-638, 21-23 May 2007.

[3] del Real, A.J.; Arce, A.; Bordons, C. "Hybrid model predictive control of a two-generator power plant integrating photovoltaic panels and a fuel cell", 46th IEEE Conference on Decision and Control, pp. 5447-5452, 12-14 Dec. 2007.

[4] Cavallaro, C.; Cecconi, V.; Chimento, F.; Musumeci, S.; Santonocito, C.; Sapuppo, C. "A Phase-Shift Full Bridge Converter for the Energy Management of Electrolyzer Systems", IEEE International Symposium on Industrial Electronics, ISIE’2007, pp. 2649-2654, 4-7 June 2007.

[5] Ugartemendia, J.J.; Ostolaza, X.; Moreno, V.; Molina, J.J.; Zubia; I. "Wind generation stabilization of fixed speed wind turbine farms with hydrogen buffer", 11th. Spanish-Portuguese Conference on Electrical Engineering (11CHLIE), pp. 1-5, 1-4 July 2009.

[6] Andrijanovitš, A.; Egorov, M.; Lehtla, M.; Vinnikov, D. "New Method for Stabilization of Wind Power Generation Using an Energy Storage Technology". Journal on Agronomy Research, vol. 8, (S1), pp. 12-24, May 2010.

[7] Tao, H.; Kotsopoulos, A.; Duarte, J.L.; Hendrix, M.A.M. "Family of multiport bidirectional DC-DC converters", IEE Proceedings on Electric Power Applications, vol. 153, no. 3, pp. 451- 458, 1 May 2006.

[8] Tao, H.; Duarte, J.L.; Hendrix, M.A.M. "Multiport converters for hybrid power sources", IEEE Power Electronics Specialists Conference, PESC’2008, pp. 3412-3418, 15-19 June 2008.

[9] Vinnikov, D.; Roasto, I., "Quasi-Z-Source-Based Isolated DC/DC Converters for Distributed Power Generation", IEEE Transactions on Industrial Electronics, vol.58, no.1, pp.192-201, Jan. 2011.

[10] Vinnikov, D. "Some Design Considerations for High-Power High-Voltage DC/DC Converter with Improved Power Density and Efficiency", The Brazilian Journal of Power Electronics / Revista Eletrônica de Potência, vol. 4, pp. 297 – 304, April 2009.