Scientific Journal of Riga Technical University
Power and Electrical Engineering

2011

Volume 29

Analysis of State-of-the-Art Converter Topologies for Interfacing of Hydrogen Buffer with Renewable Energy Systems

Anna Andrijanovitsh[1], *Tallinn University of Technology*, Ingars Steiks, *Riga Technical University*,
Janis Zakis, *Tallinn University of Technology*,
Dmitri Vinnikov, *Tallinn University of Technology*

Abstract **– This paper compares state-of-the-art DC/DC converter topologies for electrolyzer and fuel cell applications in renewable energy systems (RES). The main components of the hydrogen-based energy storage system should be connected to the DC-bus of a RES via separate interface converters: the electrolyzer is interfaced by the step-down DC/DC converter, while the fuel cell is connected through the step-up DC/DC converter. Because of the high input and output voltage differences the topologies with a high-frequency voltage matching transformer are analyzed. The inverter and rectifier sides of the discussed DC/DC converters presented in schemes are analyzed in detail.**

Keywords **– Renewable energy, hydrogen, electrolyzer, fuel cell, DC/DC converter.**

I. INTRODUCTION

Use of alternative energy sources is an urgent issue today. Main advantages of renewable energy are zero fuel costs and lower impact on the environment. However, renewable energy sources, such as solar and wind power, are difficult to forecast. To compensate unstable operation of a renewable energy system (RES) the concept of hydrogen use was introduced in [1-4].

Fig. 1 shows a hydrogen-based energy storage system or a hydrogen buffer that stabilizes unregulated renewable energy generation. It consists of the following stages: hydrogen production, hydrogen storage and electricity production. In the excess energy periods the hydrogen generation system is connected to the DC-bus of the RES. In this stage electrical energy from the renewable energy source is converted into chemical energy by using water electrolysis and this energy is stored in a tank. In order to stabilize energy production during the absence of the renewable energy, stored hydrogen could be re-used. In this stage, hydrogen is converted into electrical energy by using a fuel cell (FC). The FC takes the hydrogen from the tanks to generate electricity, plus water and heat as by-products. Combination of an energy storage system and an RES allows controllable power production [5-6].

Typically, the electrolyzer (EL) and the FC are connected to the RES via separate interface converters. The EL is connected to the DC-bus of the RES through the step-down DC/DC converter, while the FC should be interfaced by the step-up DC/DC converter.

DC/DC converters can provide interfaces of different voltage levels in the hydrogen buffer system. In principle, many basic power converter topologies can be used for the EL and the FC interconnections with the DC-bus of the RES. Because of comparatively high input and output voltage differences the DC/DC converters with a high-frequency voltage matching transformer are used more frequently. For reasons of safety this transformer should also perform the function of galvanic isolation of the primary and the secondary side. In this paper, state-of-the-art DC/DC converter topologies for the EL and FC applications are analyzed in detail and compared.

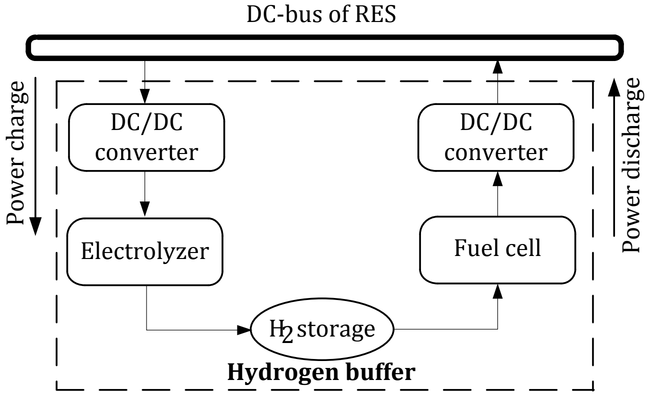


Fig. 1. Energy exchange processes in the hydrogen buffer.

II. DC/DC CONVERTER TOPOLOGIES FOR THE ELECTROLYZER APPLICATION

The EL and the FC perform opposite functions. Instead of generating electrical energy as the FC does, the EL consumes it. The EL is a low DC voltage sensitive load [7] and it cannot be directly connected to uncontrolled high DC voltages. To connect the EL to the DC-bus, it is required to buck the voltage of the DC-bus to the level of the EL [8]. The DC/DC converters with a high-frequency transformer fulfill these requirements. The DC/DC converter structure for the EL integration to the system of the RES is shown in Fig. 2. In FC applications, this DC/DC converter consists of the following main components: 1 – inverter, 2 – isolation transformer, 3 – rectifier, 4 – output filter.

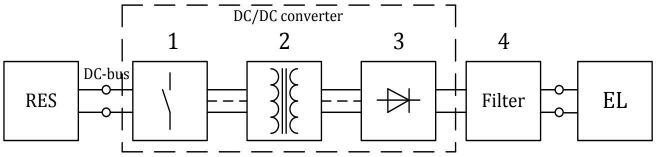


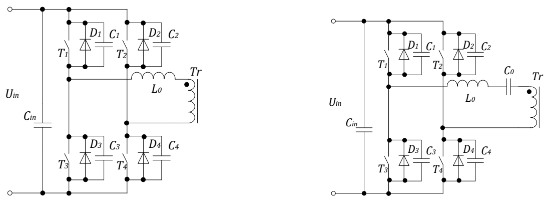
Fig. 2. Required structure of the DC/DC converter for an electrolyzer application.

The DC-bus voltage is converted to AC voltage by means of an inverter. To step down the voltage an isolation transformer is employed. The secondary side of the voltage is rectified by help of a rectifier. The output filter is used to improve the quality of the output voltage. It should be taken into account that the frequency of the current ripple at the output of the DC converter should be kept low, as higher frequencies increase the power losses in the electrolyzer [9]. The inverter side and the rectifier side topologies of DC/DC converters are described below.

As a result of the analysis of the references according to the DC/DC converter applications of electrolyzers [10-19], topologies of inverters can be classified into full-bridge (FB) [10-17] and half-bridge (HB) [17-19].

A. Inverter Side Topologies

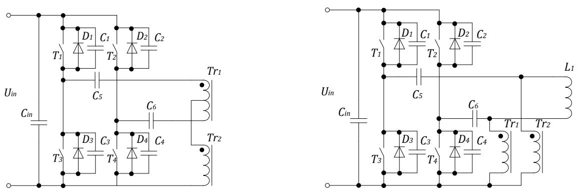
In [10-12] a classical single-phase FB topology with an inductance and a capacitor in series is analyzed (Fig. 3). The case where only an inductance is presented (Fig. 3(a)) is called a phase-shifted zero-voltage-switching (ZVS) PWM bridge inverter. It is called an LCL series resonant inverter (SRC) if a capacitor is added in series (Fig. 3(b)). It has been approved in [10] that an LCL SRC with capacitance output has desirable features over a phase-shifted ZVS PWM bridge inverter in applications where the low DC-bus voltage is applied. In [12] a boost zero-voltage-transition (ZVT) is added to improve the LCL SRC and make it more suitable for electrolyzer applications.



(a) (b)

Fig. 3. Single-phase FB topology with: (a) inductance; (b) inductance and capacitor.

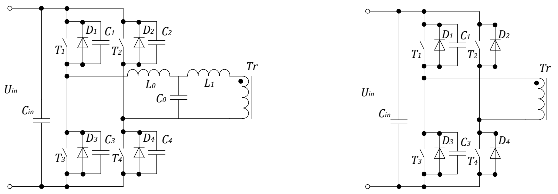
Different phase-shifted FB ZVS topologies (Fig. 4(a)) of an inverter are proposed in [13-14]. Presented circuits are based on the usage of two transformers, connecting them in various ways and combining with capacitors. It has been reported that this topology can achieve complete ZVS in a wide range of load current and input voltage [13-14]. One of the transformers is used to achieve ZVS, but other or power transfer. As in [13-14], in [15] an FB inverter with ZVS over the entire power conversion range is proposed. Inverter topology in [15] also consists of two transformers (Fig. 4(b)), only in this case both transformers are used for power transfer.



(a) (b)

Fig. 4. Implementation of phase-shifted FB ZVS PWM inverter with two transformers: (a) one auxiliary transformer for ZVS; (b) both transformers for power transfer.

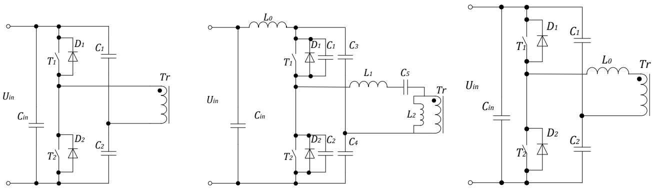
L, LC, and LCL filter and LCL series-parallel resonance inverters (SPRC) have been analyzed in [16] (Fig. 5(a)), but the scope of the converter was to convert DC voltage from 48V at the input to 5V at the output of the converter. Instead of low voltage conversions in [16], high voltage and high power converter application is analyzed in [17]. In [17], in the analysis of ZVS and zero current switching (ZCS), a zero voltage zero current switching (ZVZCS) PWM inverter is described. ZVZCS PWM inverter is derived from the phase-shifted FB ZVS PWM inverters.



(a) (b)

Fig. 5. FB topology: (a) ZVS PWM inverter with LCL filter; (b) ZVZCS PWM inverter.

No new trends relevant to HB topology inverters have been found if they are regarded as high-frequency inverters for EL applications. In fact, HB topology inverters were analyzed more than 20 years ago [18-19]. General comparisons are reported in [17] with an analysis of HB vs. FB whereas FB is chosen. In [18], an LCL resonance inverter for telecommunication power systems is analyzed, while in [19] pure series and parallel, series-parallel inverters are compared for low voltage applications. Topologies considered in [17-19] are depicted in Fig. 6.

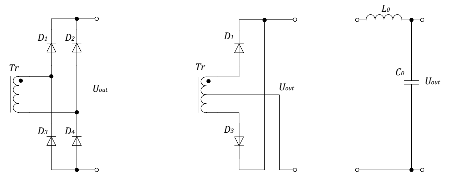


(a) (b) (c)

Fig. 6. Single-phase HB topology inverters: (a) fundamental; (b) LCL; (c) series-parallel.

B. Rectifier Side Topologies

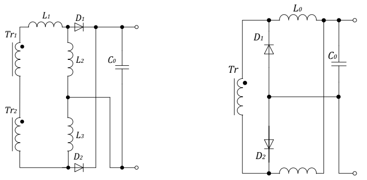
As a DC/DC converter requires DC voltage at the output, AC voltage must be rectified. Usually rectification of the voltage is realized by the single-phase FB topology [10, 12, 16, 18] or by the current doubler topology [11, 13-15, 17, 19]. Rectifier topologies: single-phase FB (a) and current doubler (b) are shown in Fig. 7. As rectified voltage contains voltage/current ripples, they must be filtered to operate the EL efficiently. A typical DC/DC converter output filter contains an inductor and a capacitor (Fig. 7(c)).



(a) (b) (c)

Fig. 7. Rectifier side topologies: (a) single-phase FB; (b) current doubler; (c) LC output filter.

Single-phase FB rectifiers are used with FB LCL inverters [10, 12, 16, 18], as they require one transformer secondary winding to add an inductor or a capacitor as required. A two transformer current doubler rectifier with two inductors is presented in [15], but in [11] a current doubler rectifier with one transformer secondary winding is shown (Fig. 8).



(a) (b)

Fig. 8. Current doubler topologies: (a) with two transformers; (b) with one transformer secondary winding.

More common DC/DC converter topologies for electrolyzer applications are classified in Fig. 9.

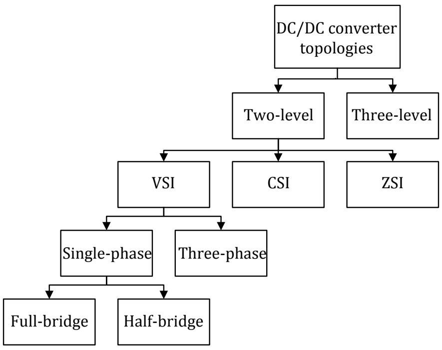


Fig. 9. The general classification of DC/DC converters for electrolyzer applications.

III. DC/DC Converter Topologies for the Fuel Cell Application

FC is a power source with low unregulated DC output voltage. To connect a FC to the load, it is necessary to boost and stabilize the relatively low output voltage of the FC to a certain operating voltage level. The DC/DC converter accomplishes both functions. Fig. 10 shows the DC/DC converter structure for the FC integration to the RES. This converter includes the following main components: 1 – inverter, 2 – isolation transformer, 3 – rectifier, 4 – output filter.

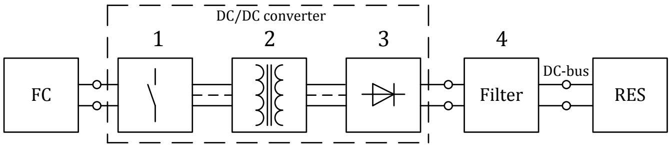


Fig. 10. Required structure of the DC/DC converter for fuel cell applications.

Low output DC voltage of a FC is converted to AC voltage by means of an inverter. For voltage step-up an isolation transformer is employed. The secondary side voltage is rectified by help of a rectifier. The output filter is an optional component. It is used to improve voltage quality. The inverter side and the rectifier side topologies of a DC/DC converter are described below.

A. Inverter Side Topologies

The inverters used in the DC/DC converters could be subdivided as two-level [20-43] and three-level [44-46]. In turn, both types of inverters can be classified into voltage source inverters (VSI) [20-25], current source inverters (CSI) [26-36] and Z-source (impedance source) inverters (ZSI) [37-43]. All these inverter types can be used for FC applications. More popular inverter topologies are as follows: single-phase (FB, HB, push-pull (PP)), and three-phase (FB, PP). Different types of switches can be used (MOSFET or IGBT technologies) for the inverter.

1. Two-Level Inverters

The single-phase FB VSI topology in Fig. 11(a) was presented in [20-23]. This inverter consists of two legs. Each leg consists of two switches and their anti-parallel diodes. The FB VSI eliminates the need for a separate filter inductor. Lack of separate inductance helps reduce the cost of the DC/DC converter. In the FB VSI the voltage and current stress of the switch is lower than in the HB topology.

In [24] the FB VSI is used with a start-up additional circuit to avoid an FC peak current demand at the system start-up. The additional diode in series with the FC stack prevents from any reverse current inside the stack.

The circuit of the three-phase PP VSI, as shown in Fig. 11(b), is proposed in [25]. The advantage of this inverter is the lower rms current through the switches. In the three-phase PP VSI topology the number of components is reduced in comparison with the three-phase FB topology.

In [26] it is shown that the single-phase FB VSI topology is less efficient for the FC application than the FB CSI topology. The FB CSI has stronger reliability for the inherent short current protection. The input current is continuous, and it prolongs the lifetime of the FC. As a result, in paper [27] the FB CSI has been chosen as an appropriate solution. Because of the high transient overvoltage across the semiconductors the CSI needs an additional clamping circuit to absorb this overvoltage. The FB CSI topologies with two different regenerative clamping circuits are presented in [27]. The circuit with external clamping energy feedback (Fig. 12(a)) consists of the diode and the capacitance. The circuit with internal clamping energy feedback (Fig. 12(a)) has an additional transistor in parallel to the diode. This transistor is responsible for feeding the stored energy in the capacitor back into the circuit [27].

In the circuit of a single-phase FB CSI instead of MOSFET a reverse block IGBT can be used [28]. Elimination of the diodes in the reverse block IGBT should lead to such benefits as lower cost, smaller packages and lower conduction loss [28].

The single-phase HB CSI topology in Fig. 12(b) was presented in [29] as a suitable topology. This inverter topology shows higher efficiency and has higher input current ripple frequency than the FB CSI topology. The HB CSI reduces the need of two switches and the transformer turns ratio to half. The additional snubber capacitors are in parallel to the diode. The HB topology is popular for the power range around 1 kW. [29-30].

In [31] the single-phase PP CSI topology presented in Fig. 12(c) is analyzed. In this paper the CSI of the DC/DC converter was selected because of less input filtering in order to minimize the high frequency current ripple. The PP CSI provides high efficiency and has a good utilization of the transformer.

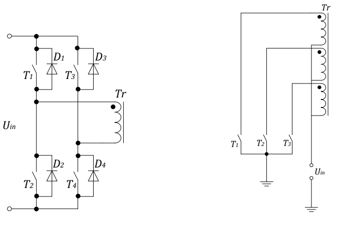
The single-phase PP CSI proposed in [32] is shown in Fig. 12(d). This topology includes an auxiliary circuit for protection of the switches against overvoltage. The auxiliary circuit is basically a flyback converter, which converts the stored energy of the clamp capacitor to the DC-bus [32].

The single-phase PP CSI topology described in [33] was modified by adding two coupled inductors to expand the duty cycle operation of the DC/DC converter. The proposed double-coupled PP CSI is shown in Fig. 12(e). The DC/DC converter with an inverter of such type can operate from 0 to 100% of the duty cycle.

The three-phase FB CSI topology with an active clamp in Fig. 12(f) was presented in [34]. The proposed converter includes the following features: increased power converter rating by employing three phases instead of a single phase; lower transformer turn-ratio by using a boost stage inherited by the current-fed type; achieve zero voltage switching in three-phase FB switches by a single common active clamp branch [34].

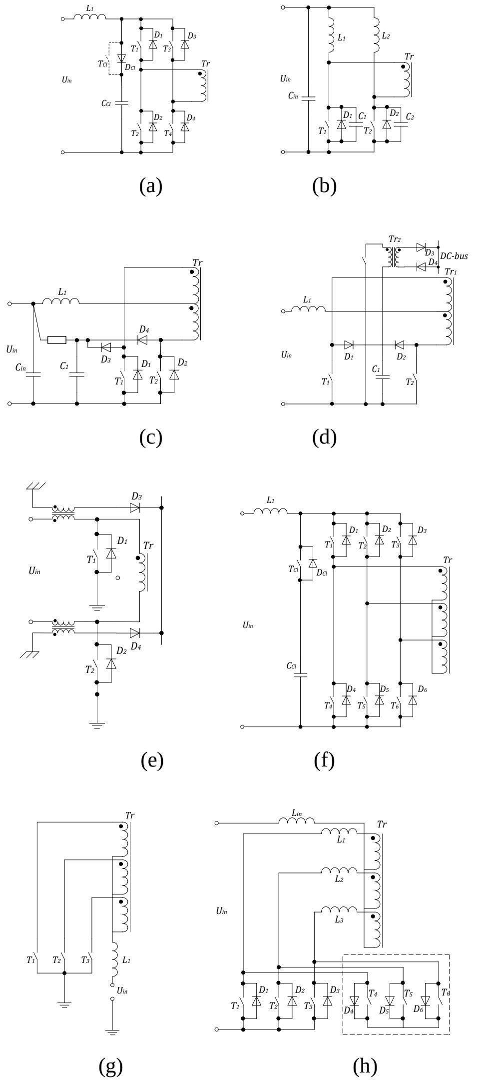
The circuit of the three-phase PP CSI illustrated in Fig. 12(g) is proposed in [35]. In this converter, the input boost inductor is placed in series with the power source. Three-phase transformers are generally smaller and lighter than single-phase ones for the same processed power due to reduced voltage and magnetic stresses. Thus, the losses in the three-phase PP CSI are better distributed than in the single-phase PP CSI.

In [36] the three-phase PP CSI topology with an active clamping (Fig. 12(h)) was analyzed. This clamp circuit consists of three clamp switches and a clamp capacitor at the low voltage primary side of the DC/DC converter. The active clamp limits the transient overvoltage caused by transformer leakage inductances and helps improve the efficiency by enabling soft switching of the main switches [36]. Thus, the active clamping method achieves higher efficiency and higher power density.



(a) (b)

Fig. 11. VSI topologies: (a) single-phase FB; (b) three-phase PP.

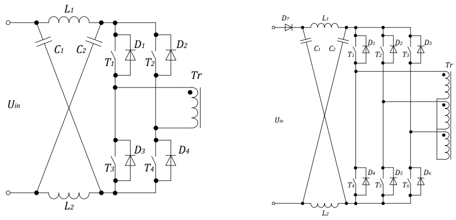


(a) (b)
(c) (d)
(e) (f)
(g) (h)

Fig. 12. CSI topologies: (a) single-phase FB with external and internal clamping energy feedback, (b) single-phase HB; (c) single-phase PP; (d) single-phase PP with an auxiliary circuit; (e) single-phase double-coupled PP; (f) three-phase FB with active clamp; (g) three-phase PP; (h) three-phase PP with active clamp.

In [37] the single-phase FB ZSI topology is presented, shown in Fig. 13(a). The single-phase FB topology is most useful in terms of cost and efficiency, especially when implemented for power levels higher than 3 kW [37]. The ZSI can boost or buck voltage, minimize component count, increase efficiency, and reduce the cost. This impedance source consists of a split-inductor and capacitors connected in X shape.

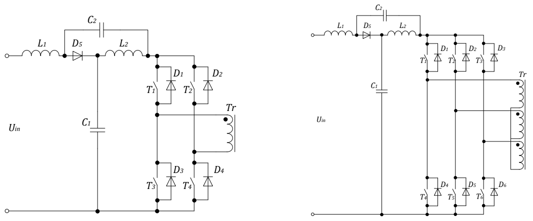
The application of the three-phase FB ZSI [38] (Fig. 13(b)) has one extra zero state when the load terminals are shorted through both the upper and lower devices of any one phase leg, any two phase legs, or all three phase legs. This shoot-through zero state provides the unique buck-boost feature to the inverter [38-39].



(a) (b)

Fig. 13. ZSI topologies: (a) single-phase FB; (b) three-phase FB.

The single-phase and three-phase FB quasi-Z-source inverter (qZSI) proposed in [40-41] is derived from a traditional ZSI (Fig. 14(a, b), respectively). As compared to the ZSI, the qZSI has two distinctive advantages, such as continuous constant DC current from the source and lower operating voltage of the capacitor C2. To further improve the boost properties of the qZSI topology the cascaded quasi-Z-source circuit was introduced [42-43].



(a) (b)

Fig. 14. qZSI topologies: (a) single-phase FB; (b) three-phase FB.

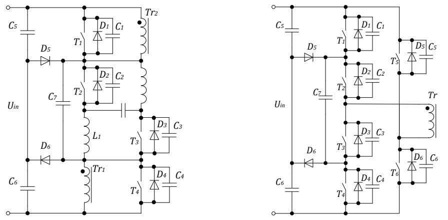
2. Three-Level Inverters

In contrast to the traditional two-level converters, the primary advantage of the multilevel converters is their smaller output voltage step, which results in high power quality, lower harmonic components, better electromagnetic compatibility, and lower switching losses. The disadvantage of the multilevel converters is the need for a large number of power semiconductor switches. Although low-voltage-rated switches can be utilized in a multilevel converter, each switch requires a related gate driver and protection circuits. This may result in higher costs and higher complexity of the overall system [44].

In [45] the three-level single-phase PP forward inverter topology (Fig. 15(a)) was analyzed. Half of the switches sustain half of the input voltage, and others sustain one and a half of the input voltage.

The three-level single-phase FB circuit illustrated in Fig. 15(b) was proposed in [46]. This converter can operate in three-level and two-level modes, so the output filter and input current ripple can be reduced. Lower output current ripple leads to higher efficiency and longer lifetime [46].

Since the three-level topologies are not so popular, in the next comparative analysis they are not used.

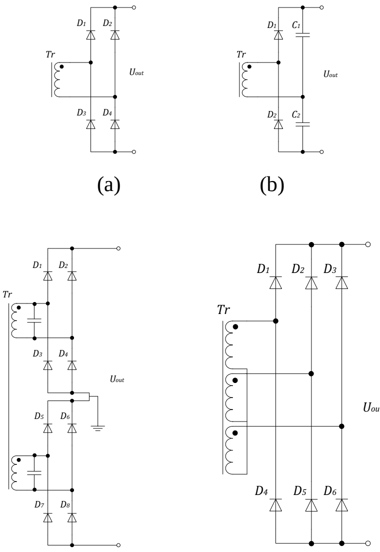


(a) (b)

Fig. 15. Three-level topologies: (a) single-phase PP forward; (b) single-phase FB.

B. Rectifier Side Topologies

Papers [22-24, 27, 31-32, 37, 42, 45, 46] report rectification on the secondary side of the DC/DC converter realized by an FB rectifier consisting of the diodes D1-D4, as shown in Fig. 16(a). In [29] to improve the efficiency as well as reduce the size and cost the output rectifier diodes are replaced with active switches.



(a) (b)

(c) (d)

Fig. 16. Rectifier topologies: (a) single-phase FB; (c) single-phase FB with two separated outputs; (d) three-phase FB.

The secondary side of the DC/DC converter is connected to the voltage doubler rectifier in [40]. This type of the rectifier (Fig. 16(b)) is derived from the FB rectifier by the replacement of diodes in one leg by the capacitors with an equal capacity. The main advantages of the voltage doubler rectifier are the doubling effect of the secondary winding voltage of the isolation transformer and reduced power dissipation due to a smaller number of rectifying diodes [40].

In the rectifier topology proposed in [20, 28], two DC output sources could be obtained with two separated output windings, as shown in Fig. 16(c). The output voltage can be fully controlled by changing the phase shift angle between the two legs. In [28] in this rectifier the additional resonant component Cr, which can help achieve zero current switching operation, is also used.

According to [34-36], the circuit of the secondary side of the DC/DC converter consists of a three-phase FB diode rectifier connected through a three-phase transformer, as shown in Fig. 16(d).

More common DC/DC converter topologies for fuel cell applications are classified in Fig. 17.

IV. COMPARATIVE ANALYSIS OF DC/DC CONVERTERS

The main converter ratings used to compare the efficiency of the above converter structures are presented in Table I.

TABLE I

MAIN RATINGS OF THE CONSIDERED DC/DC CONVERTERS FOR ELECTROLYZER AND FUEL CELL APPLICATIONS

Topologies / **Parameters**	Single-phase			Three-phase	
	Full-bridge	Half-bridge	Push-pull	Full-bridge	Push-pull
Input voltage, U_{in} (p.u.)	1	1	1	1	1
Rated power of the converter, P (p.u.)	1	1	1	1	1
Number of switches	4	2	2	6	3
Current rating of the switch, I_{sw} (p.u.)	1	2	1	0,7	0,7
Voltage across the switch, U_{sw} (p.u.)	1	1	2	1	2
Transformer primary windings	1	1	2	3	3
Transformer turns ratio, $n=Tr_2/Tr_1$ (p.u.)	2	1	2	2	2

A comparative analysis of the advantages and disadvantages of the DC/DC converters was made. In Table II the discussed DC/DC converters are compared side by side [47].

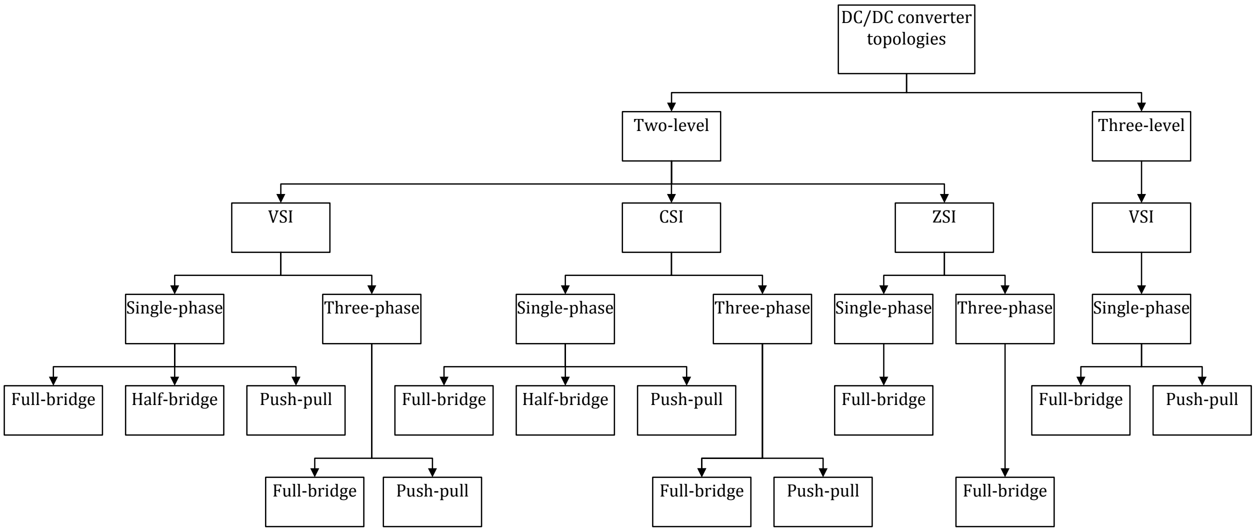


Fig. 17. The general classification of DC/DC converters for fuel cell applications.

TABLE II

COMPARATIVE ANALYSIS OF THE BASIC STRUCTURES OF THE DC/DC CONVERTER TOPOLOGIES FOR ELECTROLYZER AND FUEL CELL APPLICATIONS

Topologies / **Features**	Single-phase			Three-phase	
	FB	HB	PP	FB	PP
Advantages	The voltage and current stress of the switch is lower than in HB. Higher possible switching frequency. Lower isolation transformer primary current.	Reduces the need of two switches and the transformer turns ratio to half. Lower isolation transformer primary voltage.	Provides a high efficiency and has a good utilization of the transformer. No more than one switch in series conducts at any instant time. It can generate multiple output voltages.	Increases power converter rating by employing three phases. The losses in the three-phase FB are better distributed than in the single-phase. Inverter switch rating is better than in a single-phase topology.	Lower rms current through the switches. Number of components is lower than with the FB. The losses in the three-phase PP are better distributed than in the single-phase.

Topologies / **Features**	Single phase			Three-phase	
	FB	HB	PP	FB	PP
Disadvantages	Higher number of switches. Higher conduction number. Higher isolation transformer primary voltage.	Limited switching frequency. Higher isolation transformer current.	It requires very good matching of the switch transistors to prevent unequal on times, since this will result in saturation of the transformer core.	Active inverter switch utilization is lower than in the single-phase topology. More components than with the PP.	Control circuit is complexity.
Implementation possibilities	Most useful in terms of cost and efficiency, especially when implemented for power levels higher than 3 kW.	Feasible for the power range around 1 kW.	Feasible for the power range around 1 kW.	A three-phase transformer gives a potential feedom and flexibility to choose voltages and currents in the inverter, transformer and rectifier.	A three-phase transformer gives a potential feedom and flexibility to choose voltages and currents in the inverter, transformer and rectifier.

V. CONCLUSIONS

The DC/DC converter topologies that can be considered for EL and FC applications have been presented in this paper. All these converters have a high-frequency voltage matching transformer, which should also perform the function of galvanic isolation of the inverter and rectifier side. This paper gives an opportunity to compare the basic parameters of the DC/DC converters and select more feasible topology for particular applications.

In electrolyzer applications of the inverter side of the DC/DC converter, switching losses must be kept as low as possible. Thus, ZVS or ZCS is preferred. In the case of a rectifier side, a low component count is preferred, as the current is relatively high.

The FC is one of the promising technologies for RES. It can provide higher efficiency and enhanced reliability of the long-term energy storage systems. Because of the FC disadvantage due to high variations in its output voltage when the load changes, the DC/DC converter is used to supply a smooth output voltage to other electrical loads. According to power the discussed DC/DC converters can be classified like converters for small or medium power systems. In a power range about 1-3 kW, converters like half-bridge or push-pull are suitable topologies utilizing high-frequency transformer. For a power range higher then 3 kW, the full-bridge converter is an appropriate solution for fuel cell applications. The three-phase configurations of the DC/DC converter topology can be used to improve the losses distribution in the converter and to increase power converter ratings. However, the three-phase topology applications increase the number of components that may not be feasible. As an example, the discussed DC/DC converter circuits have been illustrated in this paper.

REFERENCES

[1] C. Cavallaro, F. Chimento, S. Musumeci, C. Sapuppo, C. Santonocito, "Electrolyser in H2 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.

[2] F. Ibanez, A. Perez-Navarro, C. Sanchez, I. Segura, E. Bernal, J. Paya, "Wind generation stabilization using a hydrogen buffer", European Conference on Power Electronics and Applications, pp. 1-10, 2-5 Sept. 2007.

[3] C. Cavallaro, V. Cecconi, F. Chimento, S. Musumeci, C. Santonocito, C. Sapuppo, "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.

[4] J. J. Ugartemendia, X. Ostolaza, V. Moreno, J. J. Molina, I. Zubia; "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.

[5] A. Andrijanovitš, M. Egorov, M. Lehtla, D. Vinnikov, "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.

[6] J. A. Carr, J. C. Balda, "A grid interface for distributed energy resources with integrated energy storage using a high frequency AC link", IEEE Power Electronics Specialists Conference, pp. 3774-3779, June 2008.

[7] Supramaniam Srinivasan “Fuel Cells: from fundamentals to applications” Springer, USA, 2006.

[8] C. Wang, M. H. Nehrir, “Power management of a stand-alone wind/photovoltaic/fuel cell energy system”, IEEE Transactions on Energy Conversion, September 2008.

[9] F. da Costa Lopes, E. H. Watanabe, “Experimental and theoretical development of a PEM electrolyzer model applied to energy storage systems”, IEEE, September 2009.

[10] D. S. Gautam, A. K. S. Bhat, “A comparison of soft-switched DC to DC converters for electrolyser application”, Proceedings of India International Conference on Power Electronics 2006,pp.274-279, 2006.

[11] C. Cavallaro, V. Cecconi, F. Chimento, S. Musumeci, C. Santonocito, C. Sapuppo, “A phase-shift full-bridge converter for the energy management of electrolyzer systems”, IEEE, July 2007.

[12] D. S. Gautam, A. K. S. Bhat, “A two-stage soft-switched converter for electrolyser application”, Fifteenth National Power Systems Conference (NPSC), IIT Bombay, December 2008.

[13] Y. Jang and M. M. Jovanović, “A new family of full-bridge ZVS converters”, IEEE, pp. 622-628, March 2003.

[14] D. K. Nayak and S. R. Reddy, “Simulation of soft switched PWM ZVS full-bridge converter”, International Journal of Computer and Electrical Engineering, Vol. 2, No. 3, June 2010.

[15] M. Borage, S. Tiwari, S. Bhardwaj, and S. Kotaiah, “A full-bridge DC/DC converter with zero-voltage-switching over the entire conversion range”, IEEE Transactions on Power Electronics, Vol. 23, No. 4, July 2008.

[16] P. Chandrasekhar, S. Rama Reddy, “Design of LCL resonant converter for electrolyser”, International Journal of Electronic Engineering Research, Vol. 2, No. 3, 2010.

[17] J.Dudrik, J.Oetter, “High-frequency soft-switching DC/DC converters for voltage and current DC power sources”, Acta Polytechnica Hungarica, Vol. 4, No. 2, 2007.

[18] A. K. S. Bhat, “Analysis and design of LCL-type series resonant converter”, IEEE, pp.172-178, 1990.

[19] R. L. Steigerwald, “A comparison of half-bridge resonant converter topologies”, IEEE Transactions on Power Electronics, Vol. 3, No. 2, April 1988.

[20] Z. B. Shen, E. F. El-Saadany, "Novel interfacing for fuel cell based distributed generation", IEEE Power Engineering Society General Meeting, June 2007.
[21] R. Sharma, H. Gao, "A new DC/DC converter for fuel cell powered distributed residential power generation systems", IEEE, pp. 1014-1018, 2006.
[22] M. A. A. Younis, N. A. Rahim, S. Mekhilef, "Dynamic and control of fuel cell system", IEEE Industrial Electronics and Applications, pp. 2063-2067, June 2008.
[23] H. Xu, L. Kong, X. Wen, "Fuel cell power system and high power DC/DC converter", IEEE Transaction on Power Electronics, vol. 19, no. 5, pp. 1250-1255, September 2004.
[24] A. Narjiss, D. Depernet, F. Gustin, D. Hissel, A. Berthon, "Design and control of a fuel cell DC/DC converter for embedded applications", IEEE, 2008.
[25] H. R. E. Larico, I. Barbi, "Voltage-fed three-phase push-pull DC/DC converter", IECON´09, 35th Annual Conference of IEEE, pp. 956-961, November 2009.
[26] M. Mohr, F. Fuchs, "Voltage-fed and current-fed full-bridge converter for the use in three-phase grid connected fuel cell systems", IEEE Power Electronics and Motion Control Conference, August 2006.
[27] M. Mohr, F. Fuchs, "Current-fed full-bridge converters for fuel cell systems connected to the three phase grid", IEEE, pp. 4313-4318, 2006.
[28] X. Zhu, D. Xu, G. Shen, D. Xi, K. Mino, H. Umida, "Current-fed DC/DC converter with reverse block IGBT for fuel cell distributing power system", Industry Applications Conference, pp. 2043-2048, October 2005.
[29] A. K. Rathore, S. K. Mazumder, "Novel zero-current switching current-fed half-bridge isolated DC/DC converter for fuel cell based applications", Energy Conversion Congress and Exposition, pp. 3523-3529, September 2010.
[30] S. Meo, A. Perfetto, L. Piegari, F. Esposito, "A ZVS current-fed DC/DC converter oriented for applications fuel-cell-based", The 30th Annual Conference of the IEEE Industrial Electronics Society, pp. 932-937, November 2004.
[31] G. K. Andersen, C. Klumpner, S. B. Kjaer, F. Blaabjerg, "A new green power inverter for fuel cells", IEEE Power Electronics Specialists Conference, pp. 727-733, 2002.
[32] R. Bojoi, C. Pica, A. Tenconi, "New DC/DC converter with reduced low-frequency current ripple for fuel cell in single-phase distributed generation", IEEE Industrial Technology (ICIT), pp. 1213-1218, March 2010.
[33] H. R. E. Larico, I. Barbi, "Double-coupled current-fed push-pull DC/DC converter: analysis and experimentation", IEEE Power Electronics Conference, COBEP´09, pp. 305-312, October 2009.
[34] H. Cha, P. Enjeti, "A novel three-phase high power current-fed DC/DC converter with active clemp for fuel cells", IEEE Power Electronics Specialists Conference, pp. 2485-2489, June 2007.
[35] R. L. Andersen, I. Barbi, "A three-phase current-fed push-pull DC/DC converter", IEEE Transaction on Power Electronics, vol. 24, no. 2, pp. 358-368, February 2009.
[36] S. Lee, J. Park, S. Choi, "A three-phase current-fed push-pull DC/DC converter with active clemp for fuel cell applications", IEEE.
[37] D. Vinnikov, I. Roasto, T. Jalakas, "New step-up DC/DC converter with high-frequency isolation", IEEE, pp. 670-675, 2009.
[38] F. Z. Peng, "Z-source inverter", IEEE Transactions on Industry Applications, vol. 39, no. 2, pp. 504-510, April 2003.
[39] M. Shen, A. Joseph, J. Wang, F. Z. Peng, D. J. Adams, "Comparison of traditional inverters and Z-source inverter for fuel cell vehicles, IEEE Transactions on Power Electronics, vol. 22, no. 4, pp. 1453-1463, July 2007.
[40] D. Vinnikov, I. Roasto, J. Zakis, R. Strzelecki, "New step-up DC/DC converter for fuel cell powered distributed generation systems: some design guidelines", Journal of Electrical Review, vol. 86, no. 8, pp. 245-252, 2010.
[41] Y. Li, J. Anderson, F. Z. Peng, D. Liu, "Quasi-Z-source inverter for photovoltaic power generation systems", IEEE Applied Power Electronics Conference and Exposition, pp. 918-924, February 2009.
[42] D. Vinnikov, I. Roasto, J. Zakis, "New bi-directional DC/DC converter for supercapacitor interfacing in high-power applications", IEEE Power Electronics and Motion Control Conference, September 2010.
[43] D. Vinnikov, I. Roasto, J. Zakis, "Mathematical models of cascaded quasi-impedance source converter", Технічна електродинаміка, 59-64, 2010.
[44] M. Harfman Todorovic, L. Palma, P. N. Enjeti, "Design of a wide input range DC/DC converter with a robust power control scheme suitable for fuel cell power conversion", IEEE Transactions of Industrial Electronics, Vol. 55, No. 3, pp. 1247-1255, March 2008.
[45] Z. Yao, L. Xiao, Y. Huang, C. Gong, "Push-pull forward three-level converter with reduced rectifier voltage stress", IEEE, pp. 1654-1660, 2009.
[46] K. Jin, X. Ruan, M. Yang, M. Xu, "A hybrid fuel cell power system", IEEE Transactions of Industrial Electronics, Vol. 56, No. 4, pp. 1212-1222, April 2009.
[47] D. Vinnikov, "Research, design and implementation of auxiliary power supplies for the light rail vehicles", Ph.D. dissertation, Dept. El. Drives Pow. Elec., Tallinn Univ. Tech., Estonia, 2005.

Anna Andrijanovitsh received B.Sc. and M.Sc. degrees in electrical engineering from Tallinn University of Technology, Tallinn, Estonia, in 2006 and 2008, respectively.

She is presently PhD student in the Department of Electrical Drives and Power Electronics, Tallinn University of Technology.

Her research interests include switchmode power converters, modeling and simulation of power systems, applied design of power converters and development of energy storage systems.

Ingars Steiks received the B.sc.ing. and M.sc.ing. degrees from the Faculty of Power and Electrical Engineering, Riga Technical University, Riga, Latvia, in 2003 and 2005, respectively.

Since 2006, he has been a Researcher in the Institute of Industrial Electronics and Electrical Engineering, Riga Technical University.

His main research interests include modular multilevel power converter applications for fuel cells. Mr. Steiks is a Student Member of the IEEE Industrial Electronics Society since 2006.

Janis Zakis received B.Sc., M.Sc. and Dr.Sc.ing. degrees in electrical engineering from Riga Technical University, Riga, Latvia, in 2002, 2004 and 2008, respectively.

He is presently a Senior Researcher in the Department of Electrical Drives and Power Electronics, Tallinn University of Technology.

He has over 20 publications and is the holder of one Utility Model in power converter design. His research interests include flexible ac transmission systems (FACTS), simulation of power systems, switching mode power converters, applied design of power converters and energy storage systems.

Dmitri Vinnikov received the Dipl.Eng, M.Sc. and Dr.Sc.techn. degrees in electrical engineering from Tallinn University of Technology, Tallinn, Estonia, in 1999, 2001 and 2005, respectively.

He is presently a Senior Researcher in the Department of Electrical Drives and Power Electronics, Tallinn University of Technology.

He has authored more than 100 published papers on power converters design and development and is the holder of several Utility Models in this application field. His research interests include switchmode power converters, modeling and simulation of power systems, applied design of power converters and control systems and application and development of energy storage systems.