Multiport Converters for Hybrid Power Sources

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Abstract—**Multiport converters, a promising concept for hybrid power sources, have attracted increasing research interest recently. The use of a single power processing stage to interface multiple power inputs integrates power conversion for a hybrid power source. This structure removes redundant power stages that would exist in the conventional approach that uses multiple converters. The multiport structure is promising from the viewpoints of centralized control and compact packaging. The proposed basic bidirectional switching cells show several possibilities to construct a multiport converter. Several three-port topologies are discussed. Furthermore, based on the interleaving technology, topologies for higher power applications are also provided.**

I. Introduction

Hybrid power sources are becoming more and more popular. For example, in renewable energy generation systems the production of electricity from solar sources depends on the amount of light energy. Like solar energy, the availability of wind energy is also uncertain, heavily relying on the weather. For stand-alone or grid-interactive systems, energy storage is often used to store the captured electrical energy. Power generators like fuel cells have slow dynamics. A storage element is needed for energy buffering and can therefore improve system dynamics. For electric vehicle applications, transient energy storage is required for acceleration and braking. A multiport interface is useful for those systems since they require energy storage to compensate for the mismatch between the sourcing and loading power patterns. A three-port power management system can accommodate a main source and energy storage and combine their advantages while using a single power conversion stage to interface the three power ports. Another advantage of incorporating energy storage is that oversizing of the main source can be avoided. A three-port system can therefore be economically beneficial.

There has been a growing interest in multiport power converters for small generation systems and electric vehicles. These applications have in common that the system needs to operate with multiple power inputs and/or outputs. Several converter topologies that can provide multiple interfacing ports have recently been reported in the literature [1], [2], [3], [4], [5], [6], [7], [8], [9], [10]. The reported multiport topologies for combining diverse sources are based on nonisolated direct link [2], [11], [12], [13] and magnetically coupled structure [14], [15], [16]. The methods used to provide a multiport interface include the time-sharing concept [2], dc-link

coupling via a dc bus [11], magnetic-coupling through a high-frequency transformer [7], using flux additivity by a multiwinding transformer [14], putting sources in series [13], based on a three-switch boost topology [17], or tri-modal operation [8].

Multiport converters are finding their applications in various systems like alternative generation [3], [6], [8], [18], electric vehicles [11], [17], UPS systems [19], [20], and hybrid energy storage systems [5]. Based on a general topology that uses a combination of a dc-link and magnetic-coupling, a family of multiport bidirectional dc-dc converters is presented in [4], [21]. This paper describes the multiport topology and gives several examples of three-port converters for applications at different power levels.

II. Two System Structures

Basically, there are two structures that can be used in hybrid power source systems, i.e., the conventional structure and the multiport structure [4], [21].

A. Conventional Structure

In the conventional structure, there usually exists a common high-voltage or low-voltage dc bus interconnecting multiple sources. Separate dc-dc conversion stages are often used for individual sources. Those converters are electrically linked together at the dc bus and are usually controlled separately.

The main structural concern of a hybrid power source is the position of the storage (e.g., batteries). As illustrated in Fig. 1(a), storage can be connected in parallel with the main source. With this configuration, the main source is effectively a charger for the storage. The current of the main source, however, is not controlled directly. The mismatch between source and storage impedance also presents a problem [22]. As shown in Fig. 1(b), energy storage can also be on the main power flow path to define a bus voltage. A dc-dc converter (e.g., boost converter) can be placed between the main source and the storage. The converter controls the current taken from the main source. In the scheme shown in Fig. 1(c), energy storage is placed outside the main power flow path and connected to the dc bus through a bidirectional dc-dc converter. The converter acts as an active filter to improve the dynamic response and to level the power difference between the generator and the load [23]. An advantage of this configuration is that it is possible to choose an optimal voltage for the storage. Note that in some applications the
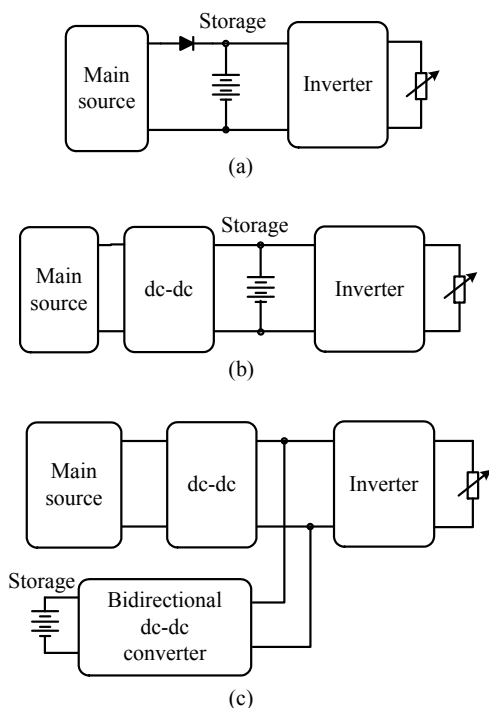
Fig. 1. Different storage positions in a hybrid power source, showing (a) in parallel with the main source, (b) on the main power flow path, and (c) connected to the dc bus through a bidirectional dc-dc converter.
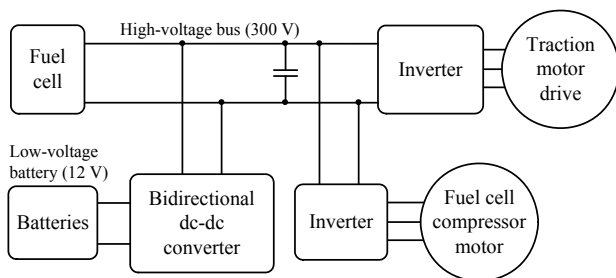

Fig. 2. System structure of a fuel cell vehicle [24].

dc-dc converter that connects the main source is not used (see e.g., Fig. 2).

Traditionally, multiple converters are used to provide interfaces for power inputs of the system. In principle, any basic power electronics topology can be used to design a power converter for a hybrid power system. For diverse applications, different system configurations were reported. Fig. 2 illustrates a structure for electric vehicles, where a high-voltage fuel cell is directly connected to the high-voltage bus (around 300 V) [24]. A bidirectional dc-dc converter is used, providing an interface between the low-voltage batteries (normally 12 V) and the high-voltage bus. The batteries are charged or discharged during the transients (e.g., acceleration and regenerative braking) through the bidirectional converter.

B. Multiport Structure

The multiport structure is emerging as an alternative for hybrid power sources. We propose the multiport system structure [4], [21]. It is different from the con-
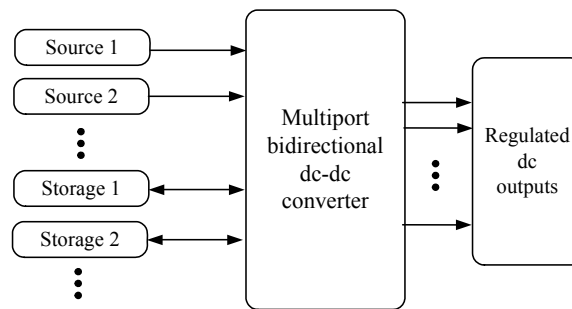

Fig. 3. Multiport system structure.

ventional one. The whole system is viewed as a single power processing stage that has multiple interfacing ports (Fig. 3). A multiport dc-dc converter can be used to interface multiple power sources and storage devices. It regulates the system voltages and manages the power flow between the sources and the storage elements. For small hybrid power systems, the multiport concept can provide a reduced parts-count solution compared with the conventional structure that uses multiple converters. A multiport converter may best satisfy integrated power conversion, efficient thermal management, compact packaging, and centralized control requirements.

The multiport topology has an advantage over the conventional approach. It is shown that the number of stages in the conventional structure can be reduced by recognizing redundancy in the power processing. In a multiport converter, it is possible to share the system resources (i.e., conversion devices) and to remove the redundancy. As a result, the overall system efficiency can possibly be improved by eliminating redundant power stages and their associated losses. A multiport converter is particularly interesting for on-site, small scale, residential power generation systems where energy is to be harvested from a variety of sources in combination and a means of energy storage is available.

For instance, Fig. 4 shows a possible fuel cell system for domestic application based on the multiport structure. A bidirectional converter manages the power flow between the fuel cell generator, storage, and load. The whole system is able to operate in both stand-alone and grid-connected modes. In case of stand-alone operation, the storage is used to match load transients. In case of grid-connected operation, the auxiliary energy source is needed for correct start-up and other functionalities. The power electronic system provides a complete interface between power sources and storage and supplies local ac loads and possibly dc loads with regulated outputs, as well as to connect to the utility grid.

III. BIDIRECTIONAL SWITCHING CELLS

In a hybrid power source, a source port delivers power, a load port consumes power, while a storage port is bidirectional. The port that connects to the storage should be bidirectional. For general purpose, all ports are considered to be bidirectional. Therefore, this type of converters are
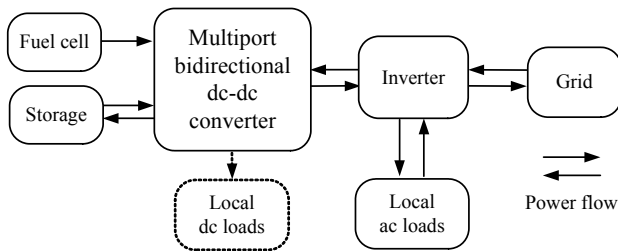
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Fig. 4. Small fuel cell generation system based on the multiport structure.

especially interesting for hybrid energy storage systems (e.g., battery and supercapacitor hybrid energy storage).

A. Dc-Link and Magnetic-Coupling

A basic classification of the energy flow link between power ports can be:

- dc-link, by means of coupling at a dc buffer capacitor;
- high-frequency (HF) ac-link, or magnetic-coupling;
- low-frequency (LF) ac-link, at a grid frequency, e.g., 50 Hz.

Electrical isolation between power ports is possible with either the HF or LF ac-link, whereas the dc-link provides no isolation. With the LF ac-link an isolation transformer is not always necessary when the voltages are matched. The LF ac-link relates to parallel operation of PWM inverters, i.e., active and reactive power control of paralleled ac systems.

Both the dc-link and magnetic-coupling approaches allow bidirectional power flow. The dc-link coupling is a method where several sources are linked together through switching cells to a dc bus. This method does have straightforward means of bidirectional power flow. The drawback, however, is that it cannot efficiently handle a wide variety of port voltages. Therefore, the operating voltage of the power ports should be close in order to avoid large buck/boost conversion ratios. On the other hand, with the magnetic-coupling method sources are interconnected through a multiwinding transformer. This makes it possible to connect power ports having quite different operating voltage levels. In addition to this, the power ports are galvanically isolated. It has been shown that these two methods can be combined for a multiport bidirectional dc-dc converter [3], [4], [21].

B. Basic Bidirectional Switching Cells

A multiport bidirectional converter can be constructed from the basic bidirectional switching cells shown in Fig. 5 [4]. The switching cells include the buck/boost, half-bridge, full-bridge, boost half-bridge, and boost full-bridge cell. The use of the boost half-bridge in the system brings many benefits because of its multiple functions. It plays an essential role in combining the dc-link with magnetic-coupling [3]. As a result, the converter becomes more compact and uses less power devices. Also shown in Fig. 5 is the boost full-bridge, which is the full-bridge counterpart of the boost half-bridge.

Other switching cells such as buck and buck-boost and their derivatives certainly can be used to interface a source. Since a smooth, continuous current is often preferred for most sources (like fuel cells, batteries, and PVs), they are not included in the basic bidirectional switching cells for the reason that their input currents are pulsating and discontinuous.

C. Polyphase Interleaved Structure

For high-power applications, a three-phase (or polyphase) interleaved structure of these switching cells is more promising because of much lower current ripple owing to the interleaving effect. The polyphase interleaving technique has been widely used in high-power dc-dc converters. A polyphase structure with interleaved control enables high-power boost/buck converters to reduce the ripple current and the size of the passive components. Through interleaving, the effective converter operating frequency is the device switching frequency times the number of interleaved phases. Moreover, interleaving allows magnetic components to be integrated by using coupled inductors. For high-power applications, the interleaved technique combined with coupled inductors can reduce the size and weight of the inductor [25].

Bidirectional switching cells shown in Fig. 5 can be implemented using interleaving. As such, the power rating of the port is increased and the current ripple is reduced. The topology depicted in Fig. 6(a) is an interleaved buck/boost switching cell. The full-bridge shown in Fig. 5(c) can be replaced with a three-phase bridge (Fig. 6(b)). Similarly, Fig. 6(c) shows an interleaved boost bridge. The shift between the phases of these three-phase bridges is 120°. The frequency of the ripple current is three times the device switching frequency. Because of the canceling effect of the three interleaved phases, the ripple current is significantly reduced.

IV. THREE-PORT CONVERTERS

To illustrate possible embodiments of the proposed topology concept, a set of three-port converters deduced from a general topology and the basic switching cells has been presented in [4]. Several promising examples are shown in the following.

A. Three-Port Topologies

Fig. 7 shows the three-port triple-active-bridge (TAB) converter [7]. In addition to galvanic isolation, this topology has the advantage of easily matching different port voltage levels in the overall system. This can be done just by choosing the appropriate numbers of turns for the windings. This circuit allows a fixed frequency operation and utilization of the leakage inductance of the transformer as the energy transfer element. Each bridge generates a high-frequency voltage (square-wave in the simplest case) with a controlled phase shift angle with respect to the primary side. The voltages presented to the windings have the same frequency. Power flow between the three ports can be controlled by the phase shifts.
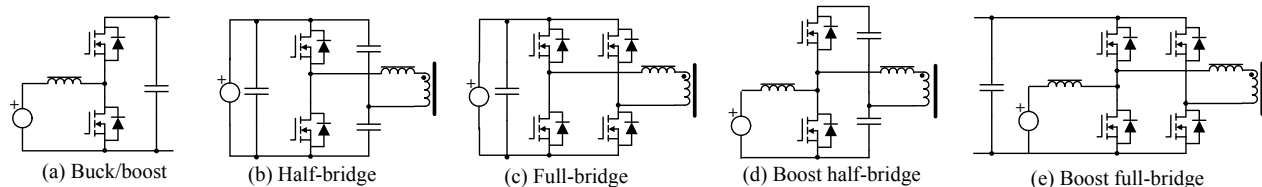
(a) Buck/boost   (b) Half-bridge   (c) Full-bridge   (d) Boost half-bridge   (e) Boost full-bridge

Fig. 5.   Basic bidirectional switching cells used for constructing multiport bidirectional converters.

(a) Three-phase buck/boost   (b) Three-phase bridge

(c) Three-phase boost bridge
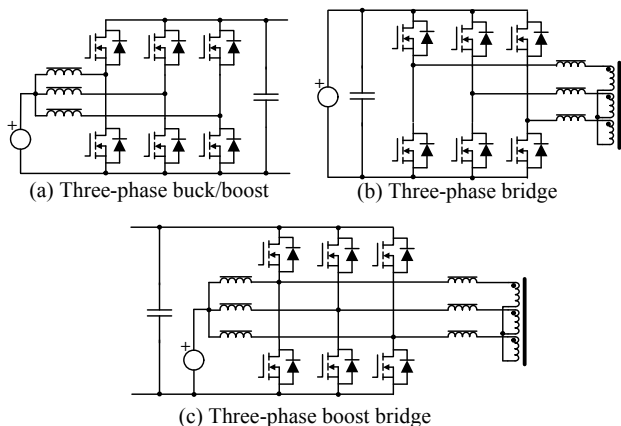
Fig. 6.   Interleaved bidirectional switching cells.

Fig. 7.   Three-port triple-active-bridge (TAB) converter.

Fig. 8.   Three-port converter combining dc-link and magnetic-coupling.
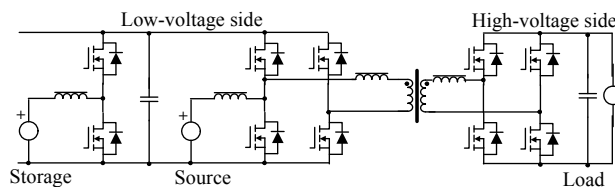
Fig. 9.   Full-bridge version of the converter topology in Fig. 8.

The maximum possible power flow is determined by the leakage (and externally added) inductances [7], [10], [21]. This circuit can be operated with soft-switching, provided that the operating voltage at each port is kept near-constant. However, when the port operating voltage varies widely, such as with supercapacitors, the soft-switched operating range will be reduced. In [10], a method has been proposed to extend the soft-switching range by adjusting the duty ratio of the voltage (a rectangular-pulse-wave) inversely proportional to the operating voltage of the port.

A converter topology combining a dc-link and magnetic-coupling is illustrated in Fig. 8 [3]. In this converter the main source (a fuel cell) and storage (a supercapacitor) are interconnected through a dc bus, since both of them are low-voltage devices and their operating voltages are close to each other. The load port is connected through a switching bridge and transformer winding. Six switches are used and all the three power ports are bidirectional.
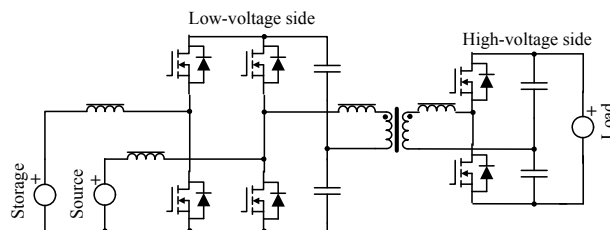
This system is suitable for applications where the low operating voltages of the main source and storage need to be boosted to match a high load-side voltage, e.g., 400 V, to supply an inverter that produces an ac output.

The half-bridge structure shown in the proposed topology could be an implementation issue, especially for high-power low-voltage high-current situations which would require a large number of low ESR film capacitors in parallel with the half-bridge electrolytic capacitors. In an effort to use more silicon and less passive components, the half-bridges in Fig. 8 can be replaced by full-bridges [21]. The resulting topology is illustrated in Fig. 9. As such, the current stress of the switching devices is reduced to a half. The operating principle remains similar to the half-bridge version. However, the switching condition of the converter becomes worse. The ZVS condition no longer holds under all situations.

Another possibility to use the boost half-bridge to realize a current-fed port for the storage device or main source is illustrated in Fig. 10. This topology has been discussed in [9], where it was named triple-half-bridge (THB) converter. The converter topology comprises a high-frequency three-winding transformer and three half-bridges, one of which is a boost half-bridge interfacing a power port with a wide operating voltage (e.g., a supercapacitor). The three half-bridges are coupled by the transformer, thereby providing galvanic isolation for all the power ports. The converter is controlled by phase shift, which achieves the primary power flow control, in combination with pulse-width modulation (PWM). The
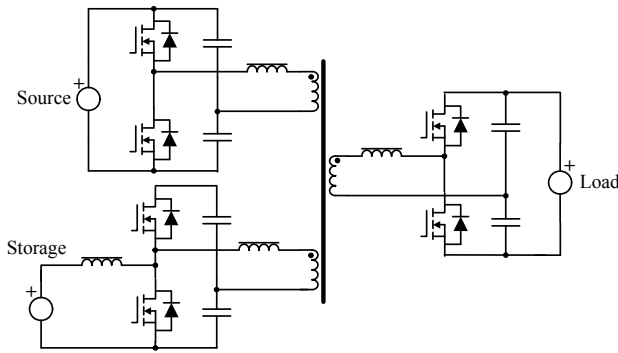
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Fig. 10. Magnetically-coupled three-port converter with one current-fed port (triple-half-bridge converter).

Fig. 11. High-power three-phase TAB converter topology.

particular structure of the boost half-bridge plays an essential role in accommodating the wide operating voltage range of the port. Voltage variations can be compensated for by operating the boost half-bridge, together with the other two half-bridges, at an appropriate duty cycle to keep a constant voltage across the half-bridge. The resulting waveforms applied to the transformer windings are asymmetrical due to the automatic volt-seconds balancing of the half-bridges. With the PWM control, it is possible to extend the ZVS operating range to the entire phase shift region. Furthermore, both current stress and conduction losses of the power switches are reduced [9].

B. Interleaved Topologies

Using interleaved topologies, the proposed basic bidirectional switching cells can be used for higher power applications (greater than 10 kW, for example). We have presented in [26] a three-port three-phase TAB converter topology (Fig. 11) which is an extension of the single-phase TAB topology. As shown in Fig. 11, this circuit consists of three inverter stages operating in a six-step mode with controlled phase shifts. The three bridges are interconnected by a three-port three-phase symmetrical transformer, and the inductors in the circuit represent the leakage inductances of the transformer (and external inductors if necessary). The transformer can be either in Y-Y or in Δ-Δ connection. Note that coupling of the windings is between the ports and there is no interphase coupling. As indicated in the figure, windings marked with the same symbol are coupled. The major advantage of the three-phase version is the much lower VA rating of the dc side filter capacitors. Thanks to the nature of the symmetry, the current stress of the switching device is significantly reduced compared with the single-phase version. As the current through the transformer windings is much more sinusoidal than in the single-phase situation, there are less high-frequency losses in the transformer.

A second possible interleaved three-port converter topology is suggested in Fig. 12. It is an extension of the topology presented in [3] (see also Fig.8). The operating principle is similar. This topology is useful for higher power applications because of low current ripple. The three-phase concept has also been recognized in [27]
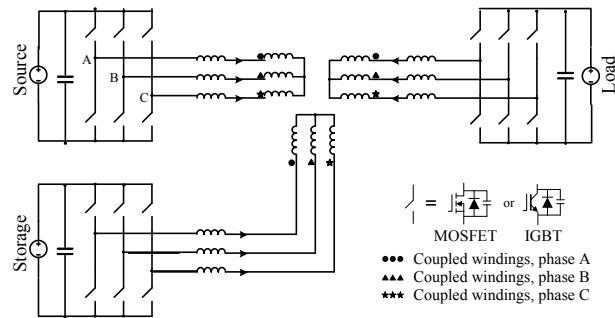
when a topology similar to the one in Fig. 12 has been studied. Similarly, other high-power topologies can be explored likewise.

In addition to the above mentioned converter topologies, there are other possibilities to construct a three-port bidirectional converter [4], [21]. For applications with four ports or more, there are certainly many more possibilities to design a converter in this way. Thanks to the flexibility resulting from the combination of the dc-link and magnetic-coupling, a suitable converter topology can be developed in accordance with system specification and design parameters at hand.

To summarize, the basic bidirectional switching cells show flexibility and several possibilities to construct a multiport bidirectional converter for applications with widely varying requirements for port voltage ranges, isolation, current ripple, and power throughput. Among the three-port converter topologies presented above, some are naturally soft-switched, whereas others need extra control or auxiliary circuits to achieve soft-switching under certain operating conditions. The topologies presented in this paper belong to a family of multiport bidirectional converter with attractive features. The proposed schemes combine traditional dc-link coupling and magnetic-coupling.

V. EXPERIMENTAL VERIFICATIONS AND DISCUSSIONS

Several prototypes have been developed to verify the three-port converter topologies and the results have been reported in our earlier publications [3], [9], [10], [21], [28].

The TAB converter (Fig. 7) was verified on an experimental prototype operated at 100 kHz. Fig. 13(a) and (b) show the measured voltages (v_1, v_2, and v_3) produced by the three full-bridges and the currents (i_1, i_2, and i_3) through the transformer windings. As shown, because of soft-switching the waveforms are free of ringing.

A polymer electrolyte membrane (PEM) fuel cell was used as the main source and the supercapacitor of 145 F has 42 V rated voltage as the storage. The rated output is 400 V dc which feeds a PWM inverter. The inverter is operated in grid-interactive mode, connecting the system to the utility grid. The control scheme was implemented by using a Texas Instruments TMS320F2808 digital signal processor (DSP).
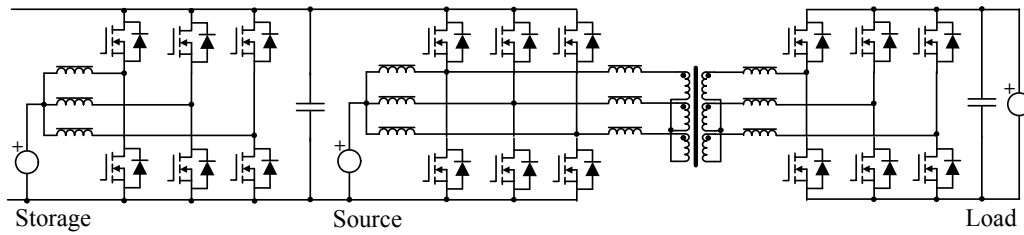
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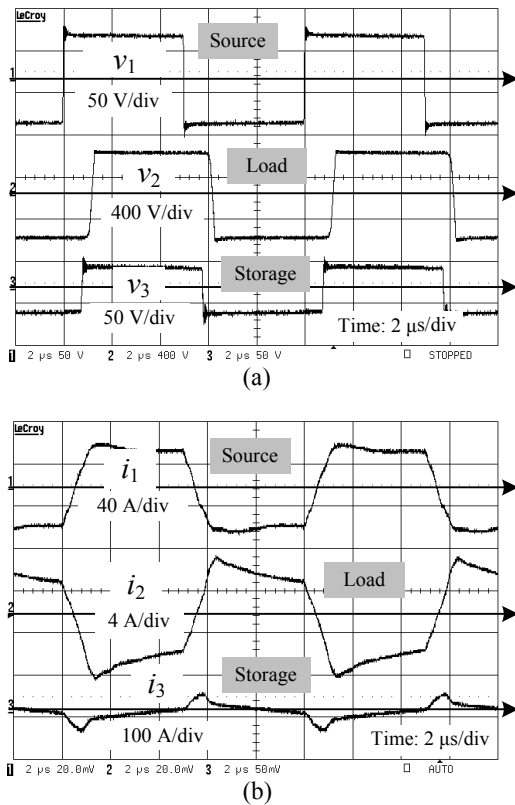Fig. 12. High-power three-port three-phase converter using interleaving.

(a)

(b)

Fig. 13. Experimental results of the TAB converter in Fig. 7, showing (a) voltages generated by the bridges, and (b) currents through the windings.
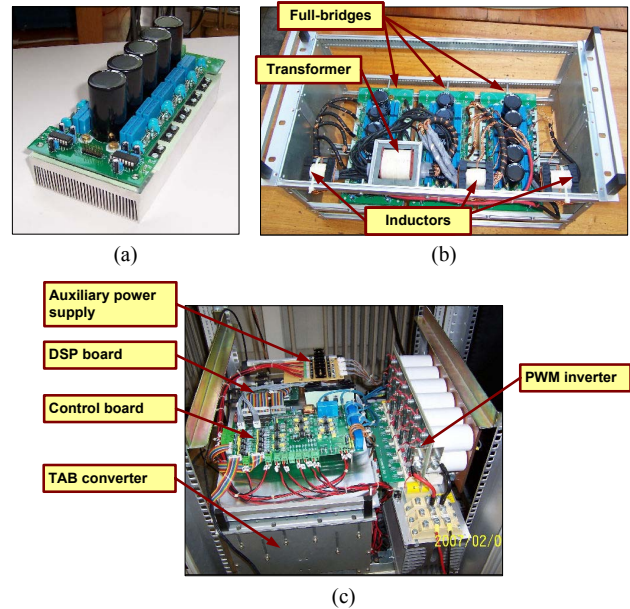

Fig. 14. Photographs of the prototype, showing (a) the full-bridge module, (b) the power stage of the three-port TAB converter, and (c) the completely assembled power conversion system.

The efficiency of the TAB converter was reported in [21]. It has been shown that over 90% efficiency is possible. The efficiency was calculated by dividing the total output power by the total input power as

$$\eta = \frac{-P_{FC} - P_{SC} + P_{Load} + |P_{FC}| + |P_{SC}| + |P_{Load}|}{P_{FC} + P_{SC} - P_{Load} + |P_{FC}| + |P_{SC}| + |P_{Load}|}. \tag{1}$$

where P_{FC} is the power supplied by the fuel cell, P_{Load} is the power consumed by the load, and P_{SC} is the power supplied by the supercapacitor. This equation has been proved correct to evaluate the energy efficiency in all the operating conditions [17].

Photographs of the prototype are displayed in Fig. 14. Fig. 14(a) shows the full-bridge circuit with five paralleled modules. The printed circuit board (PCB) uses thick copper layers to reduce the conduction loss. The TAB converter is shown in Fig. 14(b), comprising a three-winding transformer, three inductors, and the three full-bridge circuits shown in Fig. 14(a). Because of their size and weight, the transformer and inductors are not mounted on the PCB, but are fixed on the metal box. High-frequency litz wires were used to wire the power stage. The completely assembled system is shown in Fig. 14(c), where the TAB converter is on the left side, the inverter is on the right side, and the control and the DSP board lie on the top of the metal casing of the TAB converter. The whole test setup is shown in Fig. 15. The fuel cell and the supercapacitor are mounted in the rack shown on the right. The power converters, connection panel, displaying meters, and auxiliary dc sources for testing are mounted in the second rack on the left.

VI. CONCLUSIONS

This paper discusses converter structures for hybrid power sources. A multiport system structure has been described. Compared with the conventional structure using multiple converters, a multiport converter promises integrated power conversion by utilizing only a single power processing stage. Based on the basic bidirectional switching cells and a combination of dc-link and magnetic-coupling methods, several multiport bidirectional dc-dc
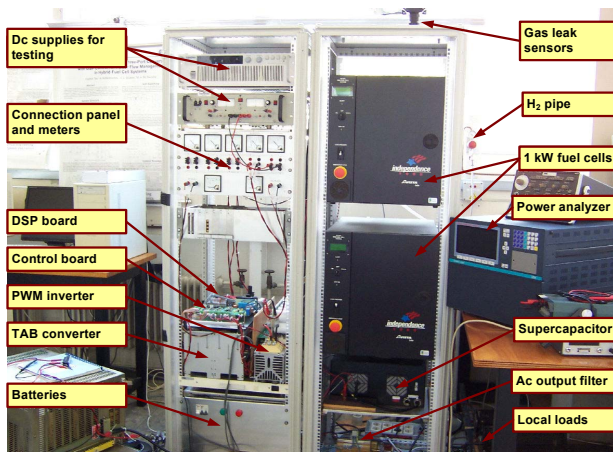
Fig. 15. Photograph of the test setup in the laboratory.

converter topologies have been presented. The presented three-port topologies provide a method to integrate a main source and energy storage. Furthermore, based on the interleaving technology the proposed basic bidirectional switching cells and three-port topologies have been extended to their polyphase interleaved versions.

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