

Family of multiport bidirectional DC–DC converters

H. Tao, A. Kotsopoulos, J.L. Duarte and M.A.M. Hendrix

Abstract: Multiport DC–DC converters are of potential interest in applications such as generation systems utilising multiple sustainable energy sources. A family of multiport bidirectional DC–DC converters derived from a general topology is presented. The topology shows a combination of DC-link and magnetic coupling. This structure makes use of both methods to interconnect multiple sources without the penalty of extra conversion or additional switches. The resulting converters have the advantage of being simple in topology and have a minimum number of power devices. The proposed general topology and basic cells show several possibilities to construct a multiport converter for particular applications and provide a solution to integrate diverse sources owing to their flexibility in structure. The system features a minimal number of conversion steps, low cost and compact packaging. In addition, the control and power management of the converter by a single digital processor is possible. The centralised control eliminates complicated communication structures that would be necessary in the conventional structure based on separate conversion stages. A control strategy based on classical control theory is proposed, showing a multiple PID-loop structure. The general topology and a set of three-port embodiments are detailed.

1 Introduction

Recent developments in sustainable energy sources such as fuel cells and photovoltaics (PV) have brought challenges to the design of power conversion systems. Future power systems will require interfacing of various energy sources. To enable multi-source technology, a multi-input power converter is of practical use. An ideal multi-input power supply could accommodate a variety of sources and combine their advantages. With multiple inputs, the energy source is diversified to increase reliability and utilisation of sustainable sources.

Basically, there are two structures suitable for such a system. In the conventional structure, shown in Fig. 1, to interconnect multiple sources, there usually exists a common high-voltage or low-voltage DC bus. Separate DC–DC conversion stages are employed for individual sources. These converters are linked together at the DC bus and controlled independently. In some systems, a communication bus may be included to exchange information and manage power flow between the sources. A number of so-called front-end DC–DC converters, such as the interleaved boost converter [1], the current-fed push–pull converter [2], the phase-shifted full-bridge converter [3], the three-phase converter [4] etc., have been developed to interface sources. Many papers also contribute to the design of bidirectional converters to connect storage [5–7]. However, a drawback of this structure lies in the fact that it is inherently complex and has a high cost due to the multiple conversion stages and communication devices between individual converters.

As shown in Fig. 2, this paper proposes a multiport structure. Compared to the conventional one, in this

structure the whole system is treated as a single power converter, which combines multiple sources. The regulation of outputs and management of source powers can be carried out by a powerful controller, such as a digital signal processor (DSP). The need for a multiport DC–DC converter is attracting research interest. The multi-input topologies for combining diverse sources found in the literature are either non-isolated direct link [8–11] or magnetic coupling [12–14]. The methods to combine multiple sources presented in these papers include putting sources in series [8], paralleling sources via a DC bus [9], using flux additivity by a multi-winding transformer [12], or the time-sharing concept [14]. However, these existing multi-input converters are either unidirectional or only for low-power applications. Based on a general topology using a combination of a DC-link and magnetic coupling, a new family of multiport bidirectional DC–DC converters is presented in this paper. The resulting converters present promising features such as simple topology and low cost. Besides power generation systems utilising multiple sustainable sources, the system is also of potential interest in applications that have a multiport structure or multiple voltage buses, such as uninterrupted power supplies (UPS), multi-voltage-bus electrical vehicles, systems with multiple regulated outputs etc.

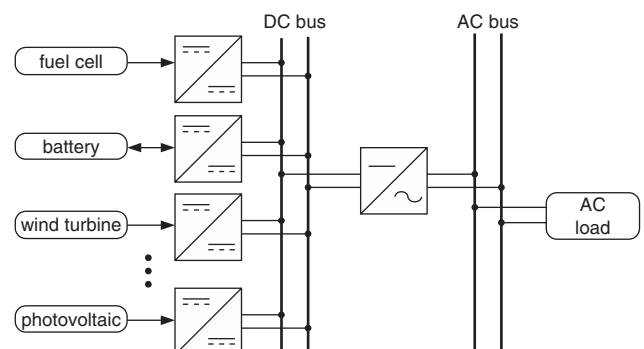


Fig. 1 Conventional structure

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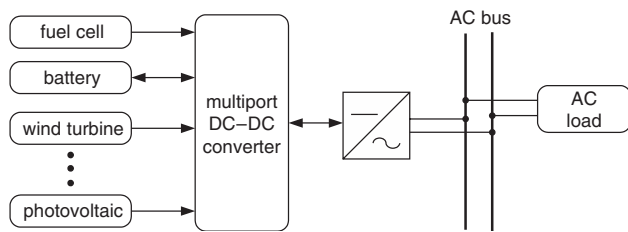


Fig. 2 Multiport structure

2 Novel multiport bidirectional converter

2.1 Multiport against conventional structure

To satisfy the applications where an energy storage element is indispensable, at least one port that connects the storages should be bidirectional. In general, all ports are considered to be bidirectional. Therefore, it is not essential to explicitly distinguish inputs (sources) or outputs (loads). Accordingly, the converter presented in this paper is called a multiport converter instead of a multi-input or multi-output converter. To this extent, loads and storages can be viewed as sources as well. This convention is adhered to in this paper.

Obviously, the multiport structure has an advantage over the conventional structure in terms of the number of power devices and conversion steps used because the system resources (i.e. conversion devices) are shared. As a result, the system efficiency can be improved. Table 1 gives a comparison of the two structures. The multiport structure is

Table 1: Comparison of conventional and multi-port structure

	Conventional structure	Multi-port structure
Need a common dc bus?	yes	no
Conversion steps	more than one	minimised
Control scheme	separated control	centralised control
Power flow management	complicated, slow	simple, fast
Transformer	multiple	single, multiwinding
Implementation effort	high	low

promising from the viewpoints of low cost, centralised control and compact packaging. However, a multiport converter is complex and there are more design challenges, e.g. the control system.

2.2 Novel multiport bidirectional topology

Conceptually, both the DC-link and magnetic-coupling approaches allow bidirectional power flow and can incorporate diverse sources [15]. The DC-link is a method in which a number of different sources are linked together through switching cells to a DC bus where energy is buffered by means of capacitors. Current-mode or voltage-mode control may be applied to regulate input currents and the DC-link voltage. However, the DC-link cannot handle a wide variety of source voltages. Therefore, the operating voltages of different sources should be close to avoid large buck/boost conversion ratios. On the other hand, with the magnetic-coupling method, sources are interconnected through a multi-winding transformer. This makes it possible to connect multiple sources having quite different voltage levels. In addition, sources are galvanically isolated, which could be a compulsory requirement for safety reasons in some applications.

Taking into account the merits and demerits of these two approaches, this paper presents a general multiport bidirectional DC-DC converter which combines a DC-link with magnetic coupling. Figure 3 shows the general topology, where the system has N different DC buses (i.e. DC bus 1, DC bus 2, ..., DC bus N). The structure of the basic switching cells is shown in Fig. 4.

As seen in Fig. 3, a multi-winding transformer couples N DC buses with individual windings (i.e. N_1, N_2, \dots, N_N). Each DC bus can be viewed as a subsystem, within which a number of directly connected switching cells (i.e. cell_{1,1}, cell_{1,2}, ..., cell_{1,K1} for DC bus 1, ...) are tied together at the DC-link capacitors. Each switching cell comprises two active switches (i.e. $S_{1,1A}$ and $S_{1,1B}$ for cell_{1,1}, ...) and an inductor (i.e. $L_{1,1}$ for cell_{1,1} ...). The switching cell is usually referred to as a two-quadrant buck/boost cell or canonical switching cell [16]. In addition, an extra source (i.e. V_1, V_2, \dots, V_N , as shown in Fig. 3) can be directly coupled to the DC buses. The unique structure of the boost-half-bridge (i.e. cell_{1,1}, cell_{2,1}, ..., cell_{N,1}) makes it multifunctional: in addition to coupling one source, it is also used to generate a high-frequency voltage. The capacitors at each DC bus (i.e. C_{1A} and C_{1B} , C_{2A} and C_{2B} , ..., C_{NA} and

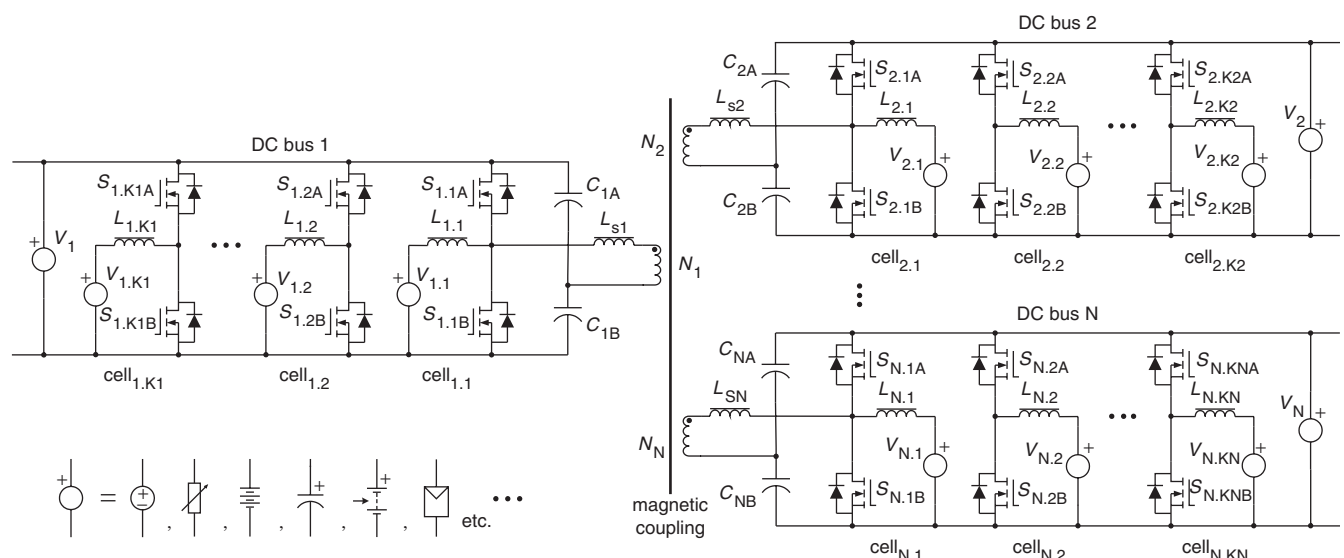


Fig. 3 Proposed general topology with combination of DC-link and magnetic-coupling for multiport bidirectional DC-DC converters

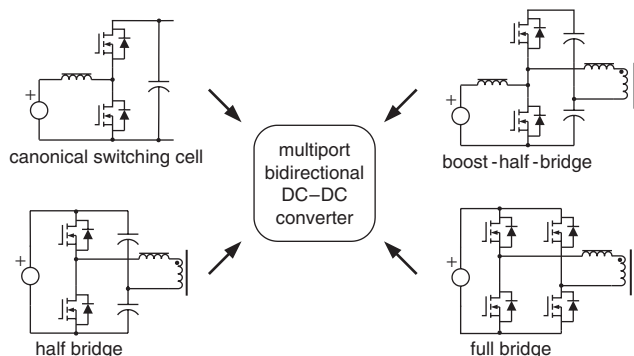


Fig. 4 Basic cells used for constructing multiport bidirectional converters

C_{NB}) are acting as both the DC-link and half-bridge capacitors.

In the topology presented in Fig. 3, the DC-link and the magnetic-coupling structures are successfully combined without the penalty of extra conversions or additional power switches, resulting from the presence of the boost-half-bridges on the DC buses. The topology has the natural property of being bidirectional in power for all the ports due to the active switching cells associated with them. In this bidirectional topology, the maximum number of switches is no more than twice the sources incorporated. For instance, to interconnect three sources (ports), a maximum of six switches is needed. For unidirectional ports, some switches could be replaced by power diodes.

Furthermore, the system in Fig. 3 is open to the addition of more sources via either DC buses or transformer windings. Further sources can be incorporated into the system by individual switching cells. Whether to integrate a source to the system by the DC-link or magnetic coupling depends on the isolation requirements and the operating voltage. Sources having nearly the same operating voltages can be interconnected at the same DC bus.

As already stated, each port of the converter is bidirectional in power. Consequently, what is connected to the ports can be a voltage-type DC generator, storage or load. The topology shows flexibility in incorporating diverse inputs, for example, fuel cells, batteries, supercapacitors, PVs, wind turbines, generic loads (e.g. inverters), resistive loads etc. However, only voltage-type DC sources are considered in this topology. Further current-type storage, such as superconducting magnetic energy storage (SMES), can also be incorporated into the system via the DC buses by individual bridge cells.

2.3 Basic cells

Figure 4 shows the basic cells that are used to construct a multiport converter. The cells used in the general topology comprise the canonical switching cell, boost-half-bridge cell and half-bridge cell. The half bridge, however, is not explicitly shown in the topology of Fig. 3. It emerges when there is only one source directly coupled to the DC bus, which is associated with a transformer winding. This is shown in the following Section. The full bridge is certainly a basic cell, although it is not shown in Fig. 3. For the case where there is only one source coupled to the winding and the operation mode is square wave, the full bridge and the half bridge are interchangeable. The use of the boost-half-bridge in the system brings many benefits because of its multiple functions. It plays a key role in combining the DC-link with magnetic coupling. As a result, the converter becomes more compact, resulting in fewer power devices.

3 Three-port converter — an example

To illustrate possible realisations of this multiport bidirectional converter topology, a set of three-port converters derived from the general topology are presented in this Section. As an example, a typical fuel cell generation system is considered, showing a three-port structure: a fuel cell, load and storage. To interconnect these three ports, a three-port converter can be employed. There are a number of possibilities to construct such a converter.

Figure 5 shows a converter with the fuel cell, storage and load linked by a DC bus. This is the simplest structure and a typical application can be found in fuel cell powered hybrid vehicles where high-voltage fuel cells and storage (a few hundred volts) are used [10]. Since all the switching cells are directly connected in parallel, a standard switch module is applicable (e.g. a full-bridge module, or a three-phase bridge module for four-port applications).

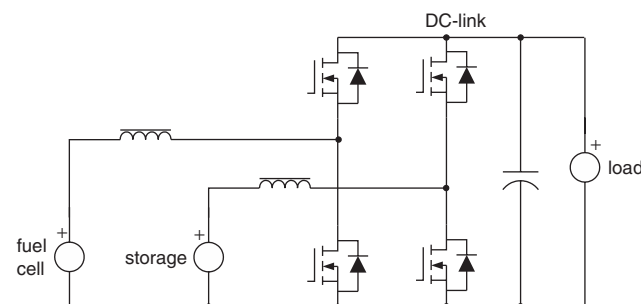


Fig. 5 DC-linked three-port converter – topology 1

Figure 6 shows the magnetically coupled three-port converter (the triple-active-bridge converter) [13, 17]. The half bridges can also be full bridges. In addition to galvanic isolation, a major advantage of this converter is the ease of matching the different voltage levels of the ports. This can be done just by choosing the appropriate number of turns for the windings. The resulting leakage inductances will be an integral part of the circuit as energy transfer elements. The converter is an extended version of the dual-active-bridge (DAB) converter. Each bridge generates a high-frequency voltage (square wave in the simplest case) with a controlled phase shift angle. The voltages applied to the windings have the same frequency. The power flow among the three ports is controlled by the phase shifts. This circuit can be operated with soft switching provided that the operating voltage at each port is kept constant. However, in the cases of widely varying operating voltages, such as supercapacitors, the soft-switching operating range will be reduced. A method has been proposed in [17] to extend the

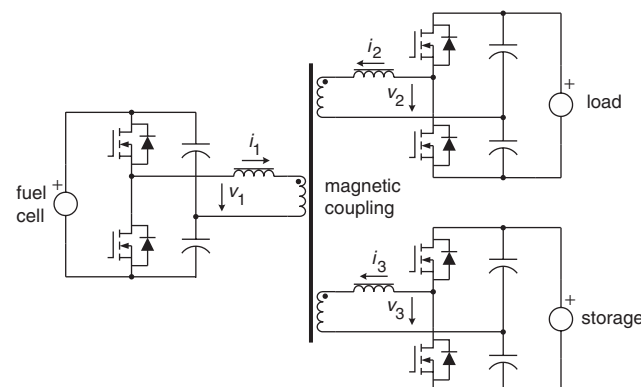


Fig. 6 Magnetically coupled three-port converter – topology 2

soft-switching range by controlling the duty cycle of the voltage applied to the winding (rectangular-pulse wave) according to the port DC voltage. This topology is detailed in the following Sections to illustrate the control scheme and experiments.

A converter combining a DC-link and magnetic coupling is illustrated in Fig. 7 [15]. This circuit is a miniature of the topology shown in Fig. 3. In this converter the fuel cell and the storage are interconnected through a DC bus because they have nearly equal operating voltages, and the load is incorporated through a transformer winding. Six switches are used and all the three ports are bidirectional. This system is suitable for applications in which the low operating voltage of the fuel cell and storage need to be boosted to match the load-side high voltage, e.g. 400 V, which further feeds an inverter to generate an AC output.

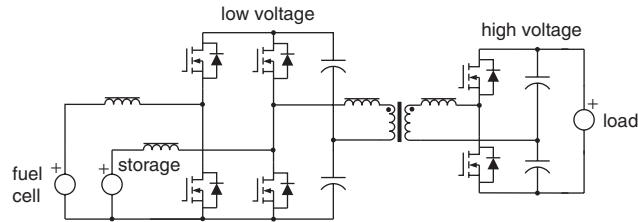


Fig. 7 Three-port converter combining DC-link and magnetic coupling – topology 3

In addition to the converter of Fig. 7, Fig. 8 shows the possibility of coupling the storage directly to the DC-bus, showing a simpler topology. In this case, only four switches are needed. However, the performance of this converter may not be as good as the converter of Fig. 7 since the DC-bus voltage (i.e. the terminal voltage of the storage) should not vary over a wide range. If a supercapacitor is chosen as the storage, the energy storage capacity of the supercapacitor cannot be fully utilised because the energy is proportional to the square of the terminal voltage. An example of this converter can be found in [18] for electrical vehicle applications.

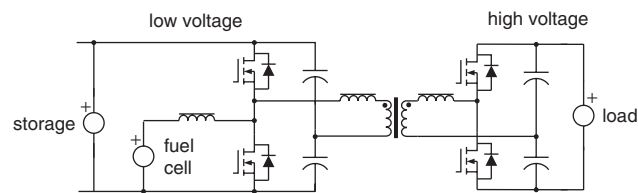


Fig. 8 Three-port converter with storage directly coupled to DC-bus – topology 4

Figure 9 illustrates a further possibility to use the boost-half-bridge in order to realise a current-fed port for a storage device or fuel cell. This configuration minimises the port's current ripple. In particular, with this structure the voltage variation on one port can be accommodated by adjusting the duty cycle of the boost-half-bridge to generate an asymmetrical square-wave voltage [19]. With this approach, the soft-switching operating range is extended, and both the current stress and the conduction losses of the power switches are reduced. This is possible because voltage variations are compensated for by operating at an appropriate duty cycle, resulting in smaller peak currents.

As a variant of the converter in Fig. 9, the other two ports could also use the boost-half-bridge instead of the half bridge, as shown in Fig. 10, especially for applications in

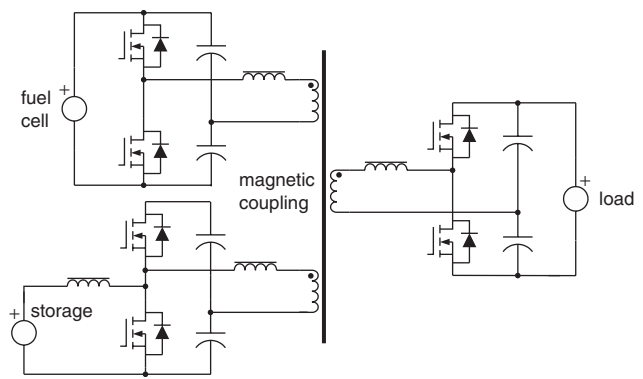


Fig. 9 Magnetically coupled three-port converter with one current-fed port – topology 5

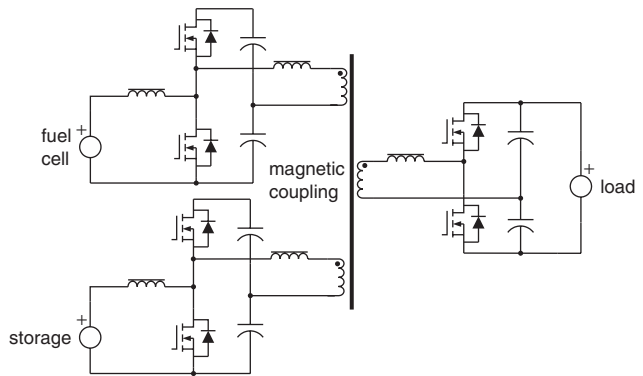


Fig. 10 Magnetically coupled three-port converter with two current-fed ports – topology 6

which the current ripple of the fuel cell and/or storage is strictly limited.

In addition to the above mentioned converters, there are other possibilities to construct a three-port converter based on the topology concept proposed in this paper. For applications with four ports or more, there are certainly many more possibilities to design a converter in this way. A suitable converter topology can be developed in accordance with system specification and design parameters.

To summarise, the general topology and the basic cells show greater flexibility and the possibility to construct a multiport converter for particular applications where source voltages, isolation requirements, current ripple specifications and power throughput are considered. In the above three-port converters derived from the general topology, some of them are naturally soft-switched [13], whereas others need new control method or auxiliary circuits to achieve soft switching under certain operating conditions [15, 17]. Detailed analysis of operation principles and switching conditions of the converters is beyond the scope of this discussion. In general, the topology presented in this paper introduces a new family of multiport bidirectional converter with attractive features.

4 Control strategy

So far, the topology has been described in detail. A multiport converter integrates diverse sources and would be capable of managing the power flow and other functionality with a sophisticated control strategy.

4.1 Power flow control

In a practical system, power flow control at each port is implemented to regulate the port current, power or voltage

according to specifications. The power flow in the multiport system shown in Fig. 3 is manageable. First, each DC bus can be viewed as a local power exchange unit (i.e. a subsystem). Within the DC bus the power of each source can simply be controlled by regulating the source power/current with duty cycle as the control variable. For instance, suppose the DC bus has a regulated stiff voltage, choosing appropriate duty cycles for the switching cells determines the source powers (either sinking or sourcing). One source, e.g. the storage, should be devoted to regulating the DC bus voltage. Second, between the DC buses, the power flow can be controlled by proper phase shifts of the voltages applied to the transformer windings. Power is exchanged through the transformer with inductors acting as energy transfer elements. An arbitrary power flow profile among the DC buses can be realised by a unique set of the phase shifts.

According to the energy conservation law, the total power generated in the system must be equal to the total power consumed. In other words, the power sourced should be equal to all the power sunk by the ports regardless of system loss, i.e.

$$\sum_{i=1}^{M+N} P_i = 0 \quad (1)$$

where P_i is defined as positive when the port is sourcing power and negative when the port is sinking power. Therefore at least one of the storages should not be directly regulated in voltage, current, or power. It balances the power flow between the generators and loads automatically, i.e.

$$P_{\text{storage}} = -\left(\sum P_{\text{generator}} + \sum P_{\text{load}}\right) \quad (2)$$

This is an autonomous system. For instance, in a three-port fuel cell system, the storage matches the load variations while the power of the fuel cell is kept at the same level.

In brief, the powers of all the ports except one storage port can be controlled directly by phase shift or duty cycle. To distribute the powers to the generators and loads, the controller needs to set appropriate reference values. By means of magnetic coupling, power flow is controlled by phase shift, whereas by means of DC-link, power flow can be regulated by duty cycle. The master module on each DC bus, i.e. the boost-half-bridge cell, normally operates at 50% fixed duty cycle in order to generate a square wave. However, in some cases it could operate at a variable duty cycle, for example, generating an asymmetrical square-wave to extend the soft switching range [19]. As particular cases,

the power flow management in the three-port converters (topology 2 and 3) is presented in [17] and [15].

4.2 Control scheme

The control system of a multiport converter shows a typical multi-input multi-output (MIMO) situation, where the control objectives can be output voltages, source currents (e.g. fuel cell current), source powers (e.g. maximum power point tracking of a PV) etc. The system control variables are the phase shifts and duty cycles.

Figure 11 shows the conceptual control scheme. It is supposed that there are N sources that are incorporated into the system by magnetic coupling, whereas M sources are coupled by DC-link. Thus there are $N+M-1$ independent control variables in total ($N-1$ phase shifts and M duty cycles). Each control variable is generated by a PID/PI controller or by a computing unit. A sampling circuit samples all the necessary real-time circuit parameters such as voltages and currents, and calculates objective variables that are difficult to sample directly, for example, the power. The outputs of the sampling circuit are then compared with the references that are generated by a power flow management unit. The power flow manager is responsible for calculating the references in response to certain operating conditions and in charge of the state-of-charge (SOC) of the storages. For instance, when the storages are fully-charged/discharged, a proper reference set should be given by the manager in accordance with the operating specifications in the procedures of charging or discharging the storages. A phase shift and/or PWM generator is employed to generate phase-shifted square waves (PSSW) and pulse-width-modulation (PWM) control signals that control the transformer coupled switching cell and the DC-linked switching cells, respectively. In addition to this basic control strategy, further functionality can be added into the control system, for example using new control techniques to extend soft-switching ranges. It is possible to perform the control and power management of such a complex system with a single digital processor (such as a Texas Instruments TMS320F2812 DSP).

In this control strategy, all control of duty cycles is essentially decoupled from the system. However, the phase shift compensations are coupled and mutually influence each other. A decoupling network or bandwidth limitation should be applied to avoid undesirable oscillation in the system, as partly addressed in [20], where a three-port converter is analysed.

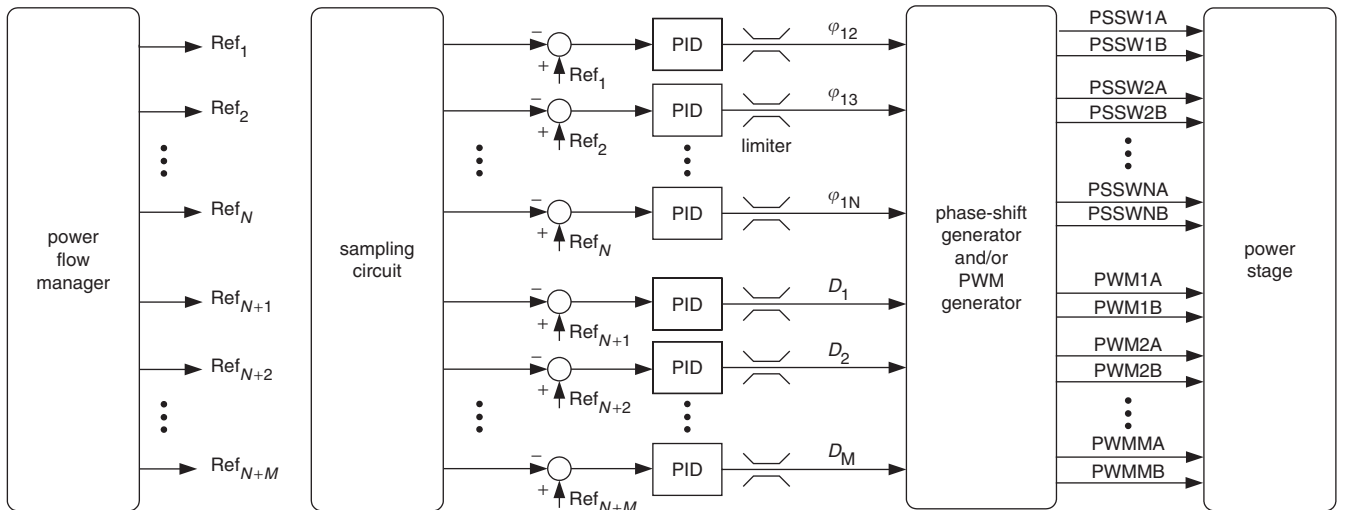


Fig. 11 Control strategy of multiport bidirectional converter

4.3 Control scheme for three-port converter — example

For a better understanding of the power flow control, the three-port converter (topology 2 as shown in Fig. 6) is taken as an example. In the fuel cell system, a supercapacitor is used to improve system dynamics. The converter can be viewed as a network of inductors driven by voltage sources with phase shifts between each other. The current waveforms are determined by the phase shifts and voltages. The ideal waveforms are shown in Fig. 12. All the voltages are referred to the primary and are equal in amplitude. They are shifted by φ_{12} and φ_{13} with respect to v_1 as the reference. The phase shift is positive when the voltage lags the reference and negative when it leads the reference.

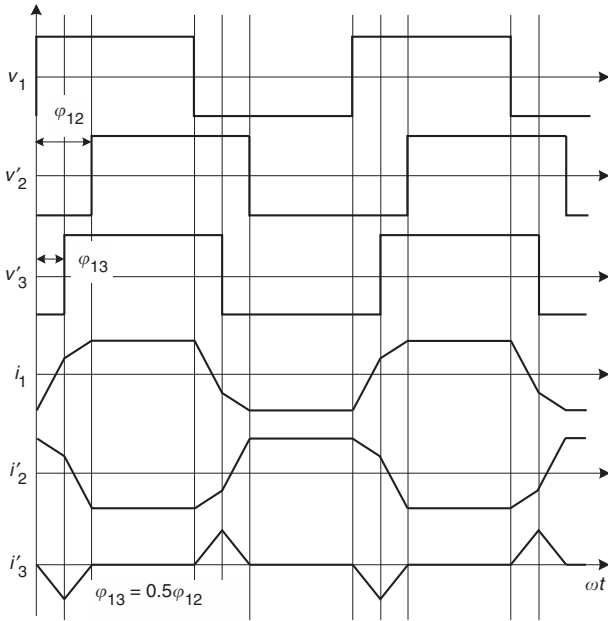


Fig. 12 Ideal key waveforms of topology 2

In this three-port system, the goal is to draw constant power from the fuel cell while the load power demand varies dynamically. Therefore the storage should sink/source the transient unbalanced power between the load and the fuel cell automatically. Since the transient load power is hard to predict, the control scheme aims to regulate the output voltage and the fuel cell power simultaneously. The proposed controller has two PI feedback loops. There are two independent control variables, namely φ_{12} and φ_{13} . With these two angles, any power flow profile in this system can be realised. Figure 13 shows the DSP-based control scheme. The output voltage V_{LOAD} is regulated by φ_{12} . The fuel cell power P_{FC} is calculated

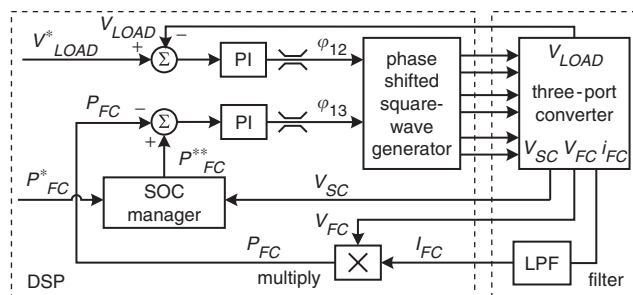


Fig. 13 Control scheme for three-port converter (topology 2) V_{LOAD}^* and P_{FC}^* are references of output voltage and fuel cell power, respectively

from the measurements of V_{FC} and the average current I_{FC} . The regulation of φ_{13} keeps the fuel cell power constant. However, the two PI control loops are coupled. The bandwidth voltage control loop is tuned higher than that of the power control loop in order to minimise the interaction and guarantee a fast response to load variations. In addition, thanks to the coupling between the SOC and the supercapacitor voltage, a SOC manager is integrated in the control scheme by monitoring V_{SC} . For instance, when the supercapacitor voltage reaches its limit, by slightly adjusting the fuel cell power reference signal P_{FC}^{**} , the control circuit is capable of charging/discharging the supercapacitor with an average current:

$$I_{SC} = (P_{FC}^{**} - P_{LOAD}) / V_{SC} \quad (3)$$

where P_{LOAD} is the power of the load, and I_{SC} and V_{SC} are the current and voltage of the supercapacitor, respectively.

5 Implementation and experiment

5.1 Transformer design

The transformer is a core component. It provides isolation and voltage matching. The selection of the transformer turns ratio is in accordance with the ratio of the DC bus voltages:

$$\frac{N_1}{V_1} = \frac{N_2}{V_2} = \dots = \frac{N_N}{V_N} \quad (4)$$

where N_1, N_2, \dots, N_N are the winding turns numbers and V_1, V_2, \dots, V_N are the DC bus voltages. The power throughput of the transformer should be the maximum of all the possible situations. When switching frequency is fixed, the power flow through the transformer is related to phase shifts and leakage inductances. For instance, in a two-winding situation, the power flow P is given by

$$P = \frac{N_1 V_1 V_2}{2\pi N_2 f_s L_s} \varphi \left(1 - \frac{|\varphi|}{\pi} \right) \quad (5)$$

where f_s is the switching frequency, L_s is the total inductance referred to the primary, and φ is the phase shift between two square waves applied to the primary and secondary windings. The maximum power flow occurs at $\varphi = \pi/2$. A smaller leakage inductance leads to a smaller phase shift while transferring the same amount power. Therefore the leakage (and possibly external) inductance can be designed according to the expected phase shift at the desired power throughput.

5.2 Experimental results

As special cases, the performances of the three-port converters derived from the general topology were reported in our previous papers. In [17] and [20], the converter shown in Fig. 6 (topology 2) and its derivatives were verified on an experimental prototype at a power level of maximum 2 kW at 20 kHz switching frequency. A new control method was introduced to extend the soft-switching region. A polymer electrolyte membrane (PEM) fuel cell (maximum power 1000 W at 54 V, 18.5 A) is used as generator and the supercapacitor of 145 F has 42 V rated voltage. The rated output is 400 V DC, which is intended to feed an inverter. The control scheme is implemented by the Texas Instruments TMS320F2812 DSP. To demonstrate the operation of the three-port converter, Fig. 14 shows key waveforms, giving the voltages (square-waves with phase shifts) across the transformer windings and the corresponding currents. Figure 15 shows the closed-loop power flow control in response to a pulsating load. A 25% step variation in the load is tested. As can be seen, the output voltage is regulated

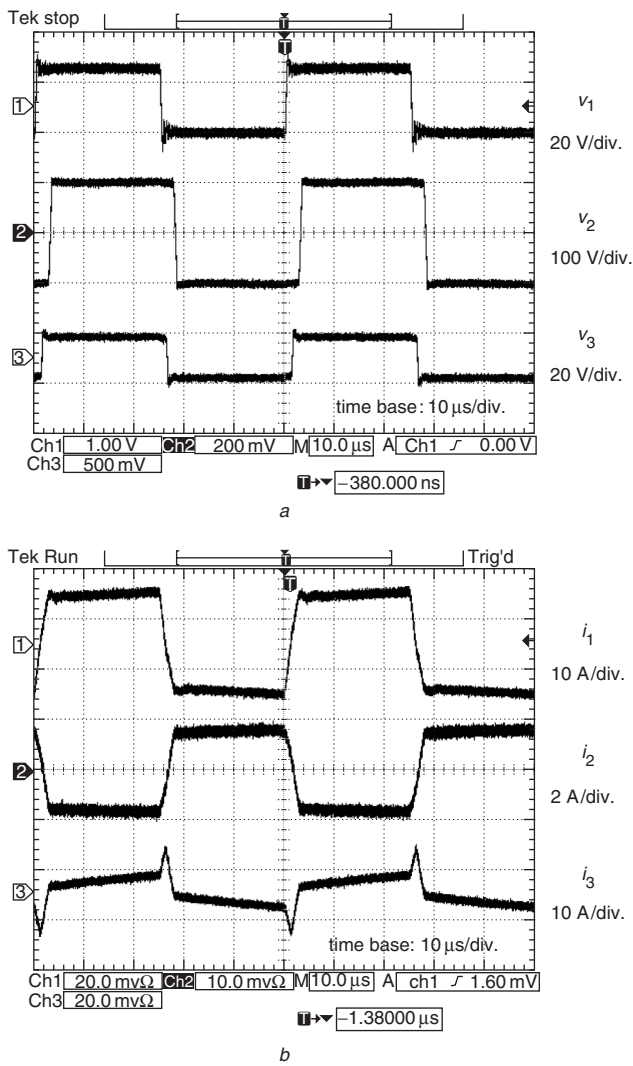


Fig. 14 Measurement results of topology 2
a Square-wave voltages across the transformer windings
b Corresponding current waveforms

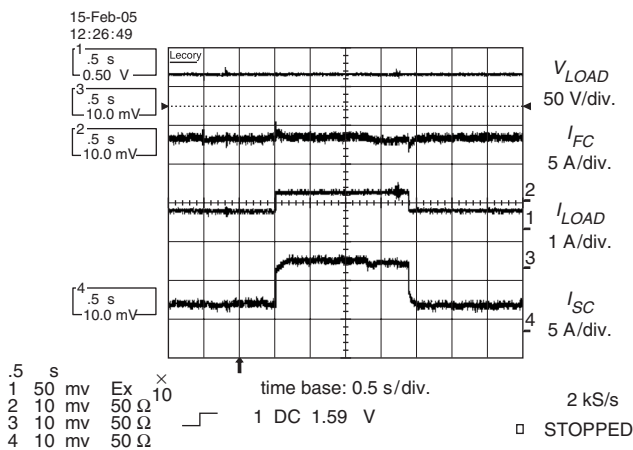


Fig. 15 Experimental result of power flow control (topology 2) in response to 25% step changes in load
 V_{LOAD} : output voltage, I_{FC} : fuel cell current, I_{LOAD} : load current, I_{SC} : supercapacitor current

to a constant value, while the current delivered by the fuel cells remains unchanged (as desired). It is clearly shown that the controller is capable of managing the power flow in the system. The efficiency of the whole system is around 90%. Since the converter under test is soft-switched, the system loss is mainly caused by the conducting loss. The measured

efficiency mainly depends on the selected power devices and could be improved.

In [15], the converter combining a DC-link with magnetic-coupling (topology 3, as shown in Fig. 7) was tested on a 1 kW experimental setup. A PEM fuel cell (500 W at 20 V, 25 A) and the same supercapacitor are used. The closed-loop power flow control in Fig. 16 shows the response to a 35% step increase in the load. It is clear that the fuel cell current remains constant and the supercapacitor supplies the deficiency in power. Good results of power flow management were obtained, as expected in the theoretical analysis. In addition, the converter of Fig. 9 (topology 5) was verified on a prototype as reported in [19], where not only low current ripple is achieved, but also the soft-switching region is extended by generating asymmetrical square-wave voltages.

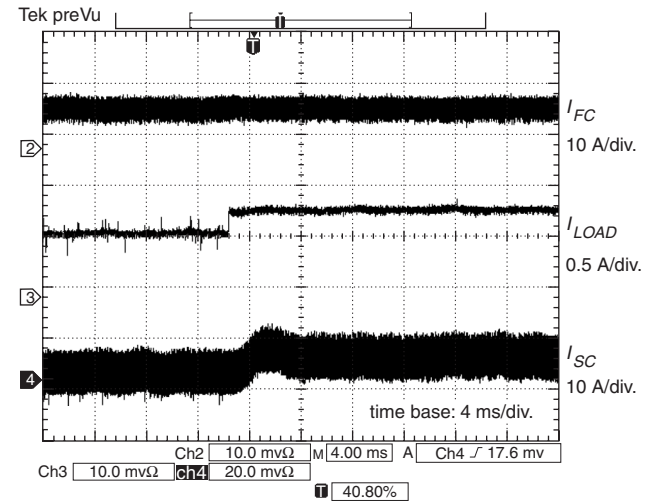


Fig. 16 Power flow control (topology 3) in response to 35% step increase in load

For applications of more than three ports, the performance of the system is expected to be comparably good. For example, if a further PV source, a second fuel cell, load or storage is incorporated into the system, the converter will be a four-port structure. With a single DSP controller, the control of the four-port converter is still manageable. The power density of the whole system may also be improved because it is a centralised conversion system. Power devices can be tightly packaged by using some modules as mentioned before.

6 Conclusions

Promising for power generation systems utilising multiple sustainable energy sources, a family of multiport bidirectional DC-DC converters has been presented in this paper, based on a general topology that uses a combination of a DC-link with magnetic coupling. In this way, multiple sources can be interconnected without the penalty of extra conversion stages or additional switches. The resulting converter features a simple topology, minimum conversion steps, low cost and compact packaging. For the multiport applications, this topology provides a general method to integrate multiple sources due to its flexibility and diversity in structure. Furthermore, a control strategy is proposed, showing a multiple PID-loop structure. With a sufficiently powerful digital controller, the control and power management of such a complex converter is possible. As an

example, a set of three-port converters derived from the general topology has been illustrated in this paper.

7 References

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