

Fuel cell power conditioning for electric power applications: a summary

X. Yu, M.R. Starke, L.M. Tolbert and B. Ozpineci

Abstract: Fuel cells are considered to be one of the most promising sources of distributed energy because of their high efficiency, low environmental impact and scalability. Unfortunately, multiple complications exist in fuel cell operation. Fuel cells cannot accept current in the reverse direction, do not perform well with ripple current, have a low output voltage that varies with age and current, respond sluggishly to step changes in load and are limited in overload capabilities. For these reasons, power converters are often necessary to boost and regulate the voltage as a means to provide a stiff applicable DC power source. Furthermore, the addition of an inverter allows for the conversion of DC power to AC for an utility interface or for the application of an AC motor. To help motivate the use of power conditioning for the fuel cell, a brief introduction of the different types, applications and typical electrical characteristics of fuel cells is presented. This is followed by an examination of the various topologies of DC–DC boost converters and inverters used for power conditioning of fuel cells. Several architectures to aggregate multiple fuel cells for high-voltage/high-power applications are also reviewed.

1 Introduction

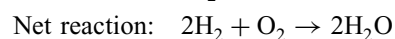
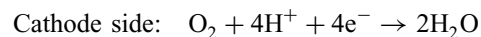
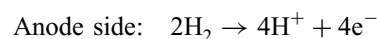
Fuel cells are environmentally sound renewable energy sources that are capable of operating at efficiencies greater than traditional energy production methods. Moreover, the scalability of fuel cells has allowed for applications in almost every field, including distributed generation. However, some inherent obstacles exist in the application of fuel cells. Low output voltage that varies with age and current, reduced efficiency with output ripple current, slow response to a load step response, no overload capability and no acceptance of reverse current provide many technical challenges that must be overcome by power-conditioning systems.

In this paper, a discussion of the construction, types, application and electrical characteristics of fuel cells is presented. This is followed by an examination of several different approaches to power-conditioning systems for single and multiple fuel cell combinations.

1.1 Fuel cell construction

In 1839, William Grove discovered that by combining oxygen and hydrogen in a particular configuration, electricity could be generated. Although this discovery was made more than 160 years ago, the basic operating principle discovered still applies. A basic schematic diagram of a fuel cell is shown in Fig. 1. Hydrogen is applied to the anode

where a catalyst separates the hydrogen into electrons and positive hydrogen ions. A membrane separating the anode and cathode allows the positive hydrogen ions to permeate through while rejecting the electrons. This forces the electrons to take the provided electrical path, or circuit, to the cathode. Once the electrons reach the cathode, they recombine with the oxygen and hydrogen ions to form water. The following basic reactions demonstrate the process:



When pure hydrogen is used as the fuel, only electricity and water are generated from the fuel cell. This attributes the fuel cell as an environmentally friendly source of energy. To obtain pure hydrogen, a fuel processor or reformer is often implemented. A reformer uses fuels such as natural gas, coal and biomass to generate hydrogen.

The construction of an actual fuel cell for power generation is composed of several components as seen in Fig. 2. The fundamental components are rectangular or cylindrical tubes that contain the anode, cathode and membrane and perform the generation and recombination of electrons. To create a fuel cell stack, these tubes are bundled together in series and parallel combinations to produce units between a few kilowatts to a hundred kilowatts. For utility applications where large-scale power is required, the fuel cell stacks can be amassed into tiers. These tiers can be assembled into sub-megawatt to megawatt generator assemblies.

1.2 Types of fuel cells and their applications [1–6]

Since William Grove's discovery, an assortment of fuel cells has been developed. The general classifications of

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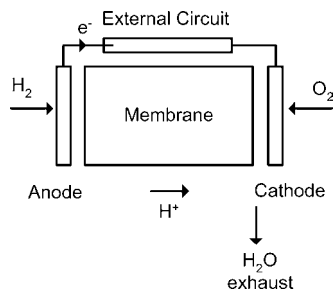


Fig. 1 Basic schematic of fuel cell operation

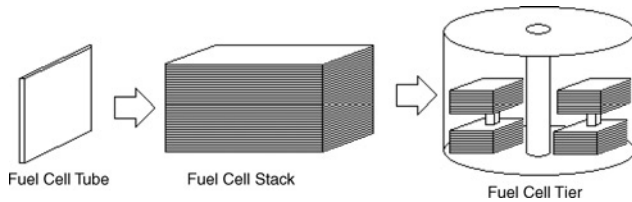


Fig. 2 Fuel cell assembly

fuel cells are based on the type of electrolyte used. The following is a list of the fuel cell types:

- alkaline fuel cells (AFCs),
- phosphoric acid fuel cells (PAFCs),
- proton exchange membrane fuel cells (PEMFCs),
- molten carbonate fuel cells (MCFCs) and
- solid oxide fuel cells (SOFCs).

Fuel cells can further be classified based on operating temperature. High-temperature fuel cells, which include MCFCs and SOFCs, operate at temperatures above 500 °C and react more readily and efficiently than their counterparts and do not necessitate the use of a reformer. In addition, high-temperature fuel cells can function without the employment of a costly noble metal catalyst such as platinum, reducing the overall cost. Higher-temperature operation furthermore accommodates the use of different fuels and cogeneration as shown in Table 1. Nevertheless, high-temperature material and high-temperature operational problems are severe and serve as deterrents for small-scale operations where quick start-up is required. Thus, present high-temperature fuel cell applications have focused on small to large stationary power plants, where the efficiencies of internal reforming and co-generative capabilities outweigh the disadvantages of material breakdown and slow start-up.

In terms of application, the Department of Energy (DOE) and Fuel Cell Energy, Inc. have researched MCFCs heavily

for stationary plant applications. Present efforts have yielded several sub-megawatt power plants in Europe that have provided 17 million kW h of power. SOFCs have likewise achieved success in stationary power applications. Siemens Westinghouse has developed and tested a 250-kW hybrid system that has achieved 52% efficiency. Yet, the anticipation for future SOFCs is for units with several MW output and efficiencies exceeding 75% due to co-generation.

Low-temperature fuel cells typically operate below 250°C and include AFC, PAFC and PEMFC types. As these low temperatures do not permit internal reforming, an external source of almost pure hydrogen is essential. Present low-temperature fuel cell applications have focused on vehicle applications on account of the higher power density, quick start-up and fewer high-temperature material issues. In particular, AFCs have been used in space vehicles, such as Apollo and Space Shuttle, whereas PEMFCs have been investigated for application in commercial vehicles. PEMFC and PAFC systems have also been investigated for employment in combined heating and power generation. In the early 1990s, 12 PAFC power plants were installed in Germany and have been under operation for over 40000 h.

1.3 Typical electrical characteristics of fuel cells [1–4]

The operation of a fuel cell is similar to that of a battery in that a fuel cell employs two electrodes (anode and cathode) and produces DC voltage. One key advantage that fuel cells have over battery technology is the seemingly unlimited amount of power that can be produced as long as fuel is supplied. Unfortunately, as the amount of current is increased, the voltage drop is increased. For this reason, fuel cells are often modelled as ideal DC voltage sources with a series resistor. The major factors that contribute to this voltage drop are: activation loss, ohmic loss and concentration loss (Fig. 3).

At low current densities, the dominant loss is a result of activation loss. Activation loss is the sluggish response of the electrochemical reaction of hydrogen and oxygen as a result of electrode kinetics. This creates a highly nonlinear voltage drop as seen in Fig. 3.

Ohmic losses originate from the flow of electrons through the electrolyte and electrodes. Ideally the electrolyte should only permit the transport of ions through the cell, but a small amount of the fuel is able to diffuse through the membrane. Unlike activation losses, which are nonlinear, ohmic losses are essentially linear and are directly proportional to the current density.

Table 1: Type of electrolyte, operating temperature and fuel for different fuel cells

Type	Electrolyte	Operating temperature, °C	Fuel	Applications
AFC	KOH	50–200	pure H ₂	transportation, portable power
PAFC	phosphoric acid	~220	pure H ₂	stationary power
PEMFC	solid polymer	50–100	pure H ₂	stationary power, transportation, portable power
MCFC	lithium and potassium carbonate	~650	H ₂ , CO, CH ₄ , other hydrocarbons	stationary power
SOFC	solid oxide electrolyte	500–1000	H ₂ , CO, CH ₄ , other hydrocarbons	stationary power, portable power

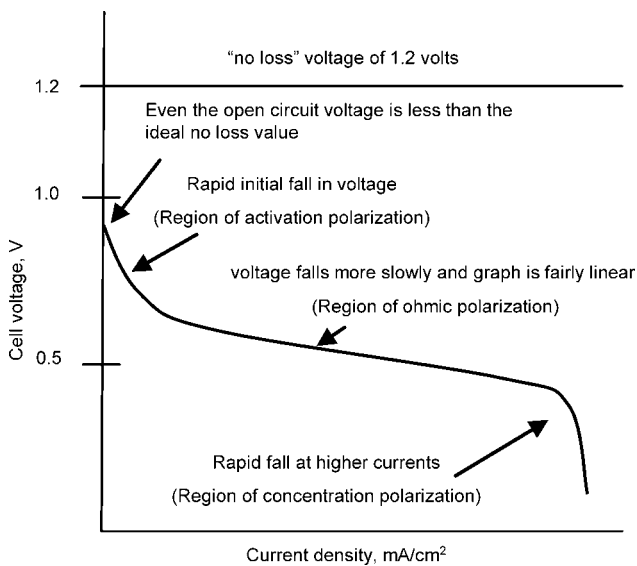


Fig. 3 Cell voltage for a low-temperature air pressure fuel cell [2]

Concentration losses are a result of the inability of the surrounding material to maintain the initial concentration of the fuel. As the reactant is consumed at the electrode, the concentration of the surrounding material reduces on account of the transportation rate of the reactants. This loss can be quite severe particularly at high current densities.

Along with the losses, the V - I polarisation curve of the fuel cell is also dependent on operating temperature. Figs. 3 and 4 show two different fuel cell curves with the temperatures of 40 and 800°C, respectively. For low-temperature fuel cells, the open circuit voltage is lower than the ideal value, and a region of activation polarisation is present. Contrarily, the open circuit voltage for a high-temperature fuel cell is nearly identical to the ideal value and almost no region of activation polarisation is acquired.

2 Power electronics interface requirements

Currently, no standard output voltage rating for fuel cells has been established. Most of the present fuel cell stack modules produce an output voltage in the range 24–150 V_{DC}. However, the large number of applications in which fuel

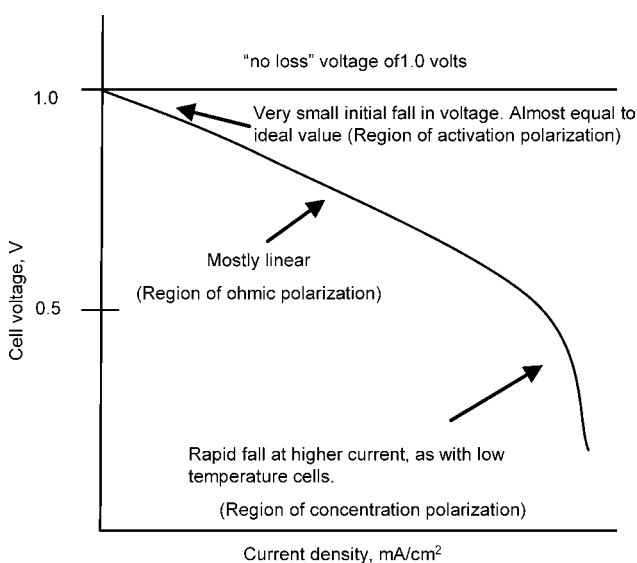


Fig. 4 Voltage of an SOFC operating at about 800 °C [2]

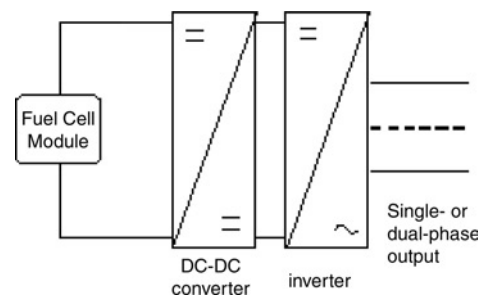


Fig. 5 Fuel cell power electronics interface block diagram for residential applications [4]

cells can be implemented necessitates that a power electronics interface be present. This interface should:

- control the fuel cell voltage
- convert the fuel cell output to the appropriate type and magnitude
- deliver a high power factor (grid applications)
- provide little to no harmonics
- operate efficiently under all conditions and
- add little to the cost of the overall system.

The power electronics interface for fuel cells often utilise DC–DC boost converters and inverters to boost the fuel cell voltage and convert the DC voltage to AC as seen in Fig. 5. The expectations from the boost converter, in addition to boosting the fuel cell voltage, are regulation of the inverter input voltage and electrical isolation of the low- and high-voltage circuits. The inverter need only convert the DC to AC with reasonable harmonic elimination and can either be single, dual, or three phase depending on the application. Single- and dual-phase inverters are used for residential applications, whereas three-phase inverters are implemented in industrial applications and in centralised power generation.

Another topology that is possible, but rarely capitalised, is that of Fig. 6. This topology neglects the use of DC–DC converters and instead relies on a transformer at the output of the inverter to boost the voltage. The advantage in exercising a DC–DC converter over this topology is 2-fold: size and cost. A transformer capable of boosting to a high voltage is significantly bulky and very costly.

The following sections discuss the specific fuel cell restrictions and possible methods for power converters to cope with these requirements.

2.1 No regeneration/reverse current

Fuel cells, in general, cannot accept current. Therefore to obstruct current flow to the fuel cell, a diode D_{FC} can be inserted in series with the fuel cell module as seen in

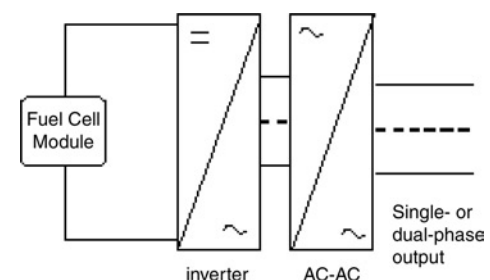


Fig. 6 Fuel cell power electronics interface block diagram for residential applications [7]

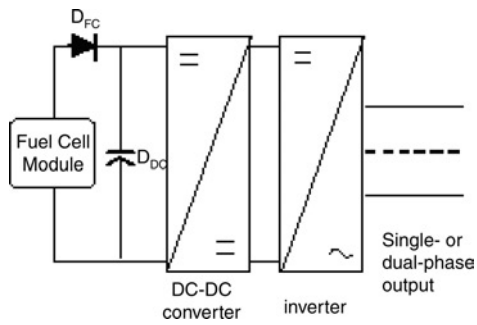


Fig. 7 Fuel cell interface with modifications

Fig. 7. In regeneration applications, where reverse current can be expected, a capacitor C_{DC} can be implemented to absorb the current. Nevertheless, the designer must be cautious in selecting this capacitor and in operating the system to ensure that the capacitor is not overly stressed.

2.2 Input ripple current

For optimum performance, fuel cells prefer a pure DC load. Any disturbance on the DC output of the fuel cell can have a significant impact on the conditions within the fuel cell diffusion layer. Unfortunately, the DC–DC boost converter connected to the fuel cell can inject ripple onto the fuel cell. Some of this ripple current can be absorbed through the addition of a capacitor. However, addition of a capacitor adds to the cost, size and reliability of the converter. Fortunately, a study performed in [8] suggests that ripple currents with frequencies above 400 Hz have minor impact on the fuel cell’s operation. A ripple factor of less than 4% for the fuel cell’s output current will have negligible impact on the conditions within the fuel cell diffusion layer and thus will not severely impact the fuel cell stack lifetime.

2.3 Secondary energy source

Considering the fuel cell’s slow response, a secondary energy source is often desired to help maintain bus voltage during transients and start-up. Lead acid batteries and ultracapacitors are suitable choices and can be interfaced at the output of the fuel cell or at the high-voltage DC link via a bidirectional DC–DC converter as shown in Fig. 8. For some applications, this secondary energy source can also be applied as an active filter, mitigating load current harmonics, thus decreasing the input current ripple [8–11].

The application of a second DC–DC bidirectional converter instead of a direct connection of the secondary energy source to the fuel cell has the benefit of a faster, more stable response. Fig. 9 shows test results for the

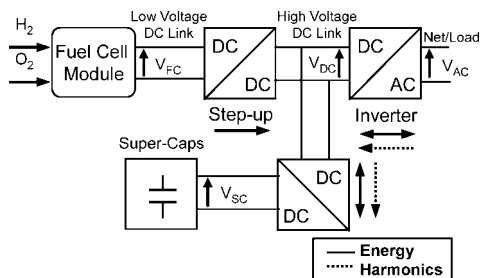


Fig. 8 Scheme of the series connection of the ultracapacitor bank

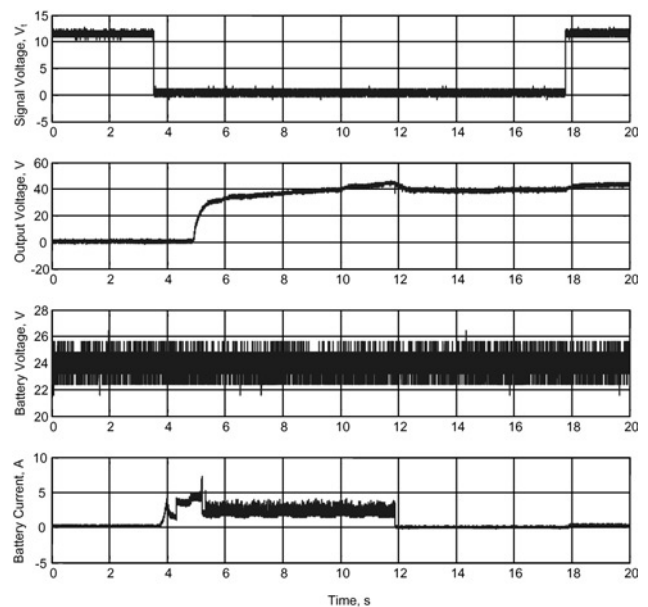


Fig. 9 Test results for the start-up of a fuel cell system

start-up of a commercial fuel cell module with no power conditioning. The first waveform is the signalling switch, which commands the fuel cell to turn on or off. The second waveform is the fuel cell’s output voltage. As evident, the output voltage does not respond instantly but requires time to reach a steady-state output. This is a response of the fuel cell powering up the mandatory components of operation, the pumps, heat exchangers, fuel processing unit and so on, otherwise known as the balance-of-plant (BOP). Another observation is the slight dip in the output voltage at 12 s. This slight dip arises from the powering of the fuel cell BOP. At approximately 18 s, a turn-off command is furnished, and the fuel cell BOP no longer receives power allowing the voltage to return to no-load voltage and the fuel cell to begin the turning off process. If there is no external load connected, the output voltage of the fuel cell decreases slowly because of no fuel flow and internal losses. The third and fourth waveforms are the 24 V battery (secondary energy storage) voltage and current during start-up.

A start-up process for a fuel cell system with the additional DC–DC bidirectional converter is described in [9]. Here the high-voltage DC bus is stepped-up by the secondary energy source. In this manner, the high-voltage DC bus supplies power to both the load and the fuel cell BOP, permitting a speedy increase in voltage. When the fuel cell voltage has finally reached a steady-state output voltage, the fuel cell takes over supplying power to the BOP.

2.4 Electrical isolation

To protect the fuel cell, electrical isolation between the low-voltage output of the fuel cell and high-voltage DC link is deemed necessary, particularly when the difference in voltage is substantial. Transformers are often incorporated in DC–DC converters for this reason. A transformer located at the output of the inverter might also bestow protection against the possibility of a DC offset at the output of the inverter.

3 Fuel cell restrictions on power electronics

The power electronics interface also imposes restrictions on the fuel cell. Power electronics are prone to high losses and

failure under high temperature. Although PEMFC and PAFC fuel cells have operational temperatures as low as 50°C, most of the fuel cells operate at temperatures exceeding 200°C. Thus, power electronics devices need to be thermally isolated from the fuel cell modules so that efficient and reliable operation can be guaranteed.

In addition, for any type of selected power electronics interface, the voltage gain is often limited and cannot function beyond a certain point. Hence the designer must ensure that the fuel cell's lowest output voltage exceeds some minimum value imposed by the power electronics interface.

4 DC-DC converters

With the ideologies of fuel cell requirements and operation examined, DC-DC converters for purposes of power conditioning are now reviewed. The first DC-DC converters under examination are of the conventional type. These converters are not only implemented in fuel cell applications, but have also been heavily employed in everyday applications. Following the discussion of conventional converters, a section representing DC-DC converter topologies specifically designed for fuel cell usage is introduced.

4.1 Conventional configurations

The conventional configuration of a DC-DC boost converter for fuel cell power conditioning is shown in Fig. 10. Although this configuration is a well-known boost topology, this design does meet the criteria of electrical isolation. Moreover, the large variance in magnitude between the input and output imposes severe stresses on the switch.

A full-bridge converter, as shown in Fig. 11, is the most frequently implemented circuit configuration for fuel cell power conditioning when electrical isolation is required. For electrical isolation and high boost ratio, forward, push-pull, half-bridge and full-bridge are other options. Nevertheless, the full-bridge converter is the best for fuel cell power conditioning, based on the following reasons:

- The full-bridge converter is suitable for high-power transmission because transistor voltage and current stresses are not high. Generally, push-pull and forward converters are not suitable for high-power applications.
- Compared to the half-bridge, both the device current rating and transformer turns ratio can be reduced by one-half.
- The full-bridge converter has small input and output current and voltage ripples.
- The full-bridge topology is a favourite topology for zero voltage switching (ZVS) pulse width modulation (PWM) techniques [10, 11].

4.2 DC-DC converters for fuel cells

Although conventional DC-DC converters are often implemented in fuel cell applications, not all of the problems encountered with fuel cell conditioning have been

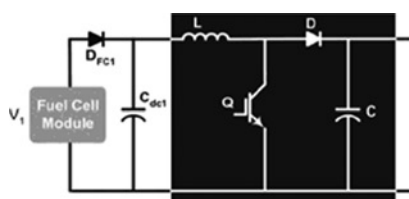


Fig. 10 Non-isolated DC-DC boost converter for fuel cell power conditioning [4]

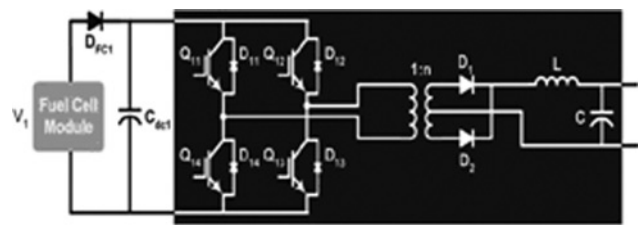


Fig. 11 Isolated DC-DC full-bridge converter for fuel cell power conditioning [4]

resolved. In the following sections, DC-DC converters designed specifically for application in fuel cell power conditioning are reviewed.

4.2.1 Modified typical DC-DC boost converter:

Several fuel cell power-conditioning systems that are based on the conventional DC-DC boost converter but have modified part of the basic topology are discussed below.

Full-bridge converter with multiple secondary coils. A full-bridge converter with multiple secondary coils is described in [12]. As shown in Fig. 12, the topology utilises a transformer with multiple secondary coils connected in series. This full-bridge converter topology has the capability to achieve ZVS allowing for high-efficiency operation. Furthermore, if the correct control algorithm is implemented, this converter topology can shift the phase as much as 180°, thus regulating the output voltage. This converter also has the capability to operate either under constant-voltage mode or constant-current affording the designer with flexibility.

To control the amount of voltage gain, the converter utilises electromechanical relays in the transformer secondary coils that manipulate the transformer turns ratio. Through this methodology, if the fuel cell's stack voltage decreases because of increasing load, a higher transformation ratio can be chosen to maintain the output voltage.

Soft switching direct converter. A power-conditioning system with the soft switching direct converter proposed in [13] is shown in Fig. 13. This power-conditioning system uses a boost converter, battery, DC/DC converter, clamp circuit and a three-phase inverter to condition the power for the fuel cell. The boost converter is employed to buffer the varying DC voltage from the fuel cell and regulate the voltage for the DC/DC converter and battery and can be of the simple design mentioned in Section 4.1.

The soft switching full-bridge DC/DC converter is composed of two H-bridge converters with an intermediate high-frequency transformer to boost the voltage to the appropriate level as seen in Fig. 14. Capacitors placed in

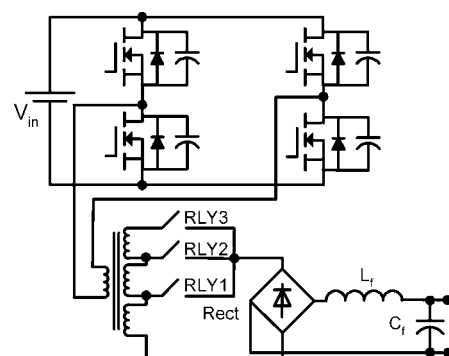


Fig. 12 Full-bridge converter with multiple secondary coils [14]

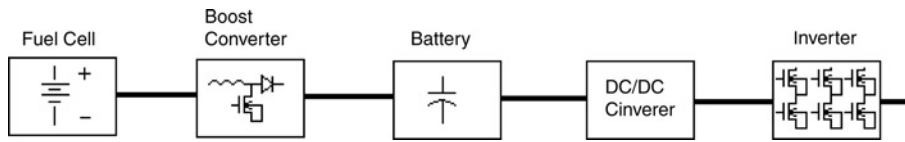


Fig. 13 Soft switching direct converter topology

parallel with the MOSFET switches enable the converter to have ZVS turn-on and zero current switching (ZCS) turn-off. The application of these soft switching techniques accredits the converter with a higher efficiency operation. Moreover, the absence of a DC-link capacitor provides this topology with a higher power density, but induces more design consideration for the clamp circuit and less dynamic response reliability against the traditional capacitor based DC-link. The full-bridge inverter on the output converts the output DC of the DC/DC converter and battery to the appropriate AC type.

Voltage doubler converter. A full-bridge DC/DC converter with an attached H-bridge inverter is discussed in [15]. As shown in Fig. 15, the high-voltage side of the full-bridge converter assumes a controlled voltage doubler circuit instead of the traditional diode rectifier. The voltage doubler circuit allows for a reduction in the turns ratio of the transformer, therein supplying reduced leakage inductance, affording the system with a higher efficiency, and more simple control. One of the benefits of the voltage doubler is the control that is imposed on the current waveforms on the low-voltage side. This can help alleviate some of the current ripple problems often associated with DC/DC converters. In addition, a reduction in one phase leg is possible because the voltage doubler phase leg and the neutral phase leg in the PWM inverter are one and the same. Following the voltage doubler, a high-voltage battery pack can be inserted to provide transient power for load dynamics, thus minimising the need for the DC-link capacitor and in turn reducing the cost and size of the fuel cell power-conditioning system significantly.

This topology has multiple advantages including decreased voltage/current stress, decreased device count and low cost. Nevertheless, some complications do exist. Although the combined voltage doubler phase leg and the neutral phase leg in the PWM inverter decrease the device count, the controlled voltage doubler circuit, instead of the commonly used diode rectifier, increases the cost and control complexity. In addition, the high-voltage battery may be unstable after long-term use. A low-voltage battery connected with a bidirectional converter may be a more reliable choice.

4.2.2 Push-pull converter: In general, push-pull converters are not suitable for high-power fuel cell applications

because of the difficulty to avoid transformer saturation [15, 16]. Yet, in medium-power fuel cell applications, push-pull converters have been found to be in use, a 1.5 kW in [17] and 1 kW in [18]. This is primarily on account of the reduced conduction losses during operation via the use of a single switch at any given time. This increases the efficiency of the converter yielding a higher efficiency for the fuel cell power-conditioning system.

4.2.3 New topologies designed for fuel cell power conditioning: Multiple new topologies that do not follow the conventional configurations have been designed especially for fuel cells. These topologies are covered below.

High step-up DC–DC converter with coupled-inductor. A high step-up DC–DC converter with coupled-inductor is investigated in [19]. This converter, shown in Fig. 16, has been constructed for PEMFC power conditioning. The converter is composed of three elements: a primary circuit, devised of a transistor and diode combination Q along with a coupled inductor L_1 that stores energy during the switch on state; a regenerative snubber circuit, composed of two diodes, D_1 and D_2 , an inductor, L_2 , and two capacitors C_1 and C_2 that not only uses the stored energy to boost the voltage, but also provides protection; and a filter circuit, consisting of a diode D_0 and a capacitor C_0 .

The advantages of this system over conventional power conditioners are 2-fold. First, experimental results have shown that this converter is able to achieve a maximum efficiency of over 96.5%, a higher efficiency than the conventional step-up DC–DC converter. Second, this converter has a large gain. This is an extremely important aspect as fuel cells tend to have low output voltages. Another benefit to this design is that the coupled-inductor prevents voltage drift at the output. This grants the fuel cell the capability to operate independent of the output of the converter. However, this converter does have some disadvantages. Although a snubber circuit has been added to provide protection to the circuit components, no electrical isolation between the input and output is present. In addition, compared with the basic boost converter, the component count of this converter is over two times higher than that of the conventional DC–DC converter.

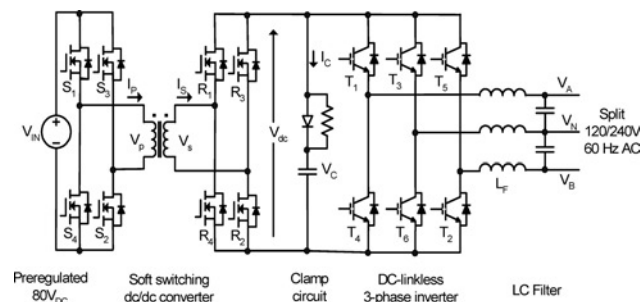


Fig. 14 Soft switching full-bridge DC/DC converter without DC link [13]

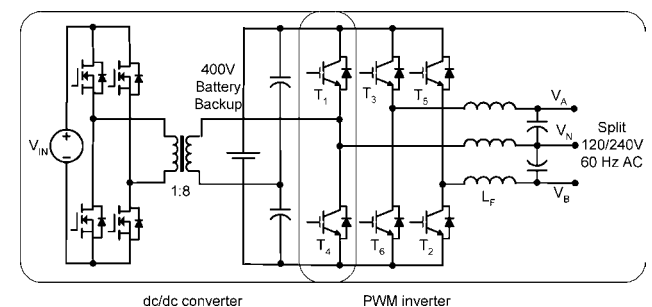


Fig. 15 Voltage doubler converter [11]

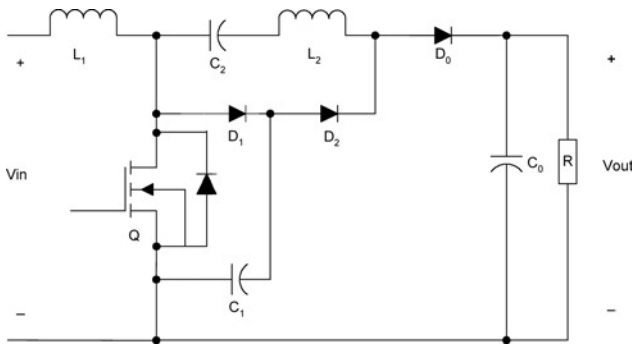


Fig. 16 High step-up DC–DC converter with coupled-inductor

Wide input range fuel cell power conditioner. A wide input range fuel cell power conditioner is shown in Fig. 17 and is discussed in [20]. This power conditioner is capable of maintaining a constant output with fluctuations of the fuel cell voltage from 36 to 60 V_{DC} . This converter maintains the steady output through the use of two boosting stages connected in series. A three-level parallel boost converter steps up the output to 80 V and is deemed as the primary booster. One of the advantages of using a three-level parallel boost converter is that compared with the conventional boost converter this converter necessitates a much smaller inductor to achieve low current ripple. The second stage is composed of an isolated two-inductor boost converter and boosts the voltage to the final level [20, 21]. This fuel cell power conditioner is capable of achieving overall efficiencies of 90% or higher.

The complexity of this power-conditioning system is relatively high with two transformers and eight switches. Yet, decreases in the current rating, conduction loss and increase in overall efficiency can be expected from the use of the two identical three-level boost converters in parallel. In addition, through pre-regulation of the voltage by the primary converter, improvements in the efficiency of the high-frequency transformer, simplification in control, decrease in the current rating of the secondary boost converter and transformer ratio, and lower overall cost can be anticipated.

Three-phase transformer isolated DC/DC converter. A three-phase transformer-isolated phase-shift DC/DC converter is discussed in [22]. This converter, as shown in Fig. 18, consists of three full-bridge converters connected to three single-phase transformers. The secondary sides of the single-phase transformers are connected in Y form to a three-phase full-bridge rectifier. This Y connection allows for the boost of the output voltage without an

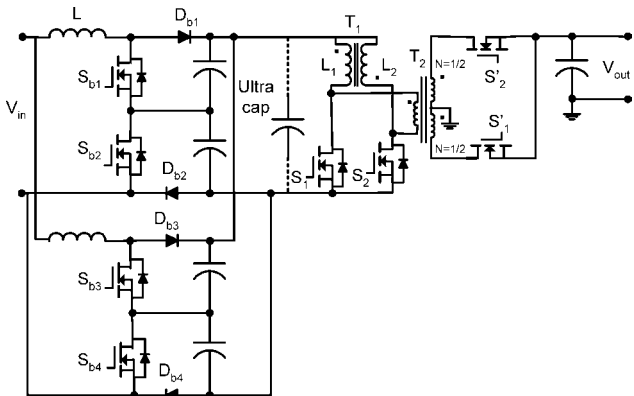


Fig. 17 Wide input range 5 kW fuel cell power conditioner [20]

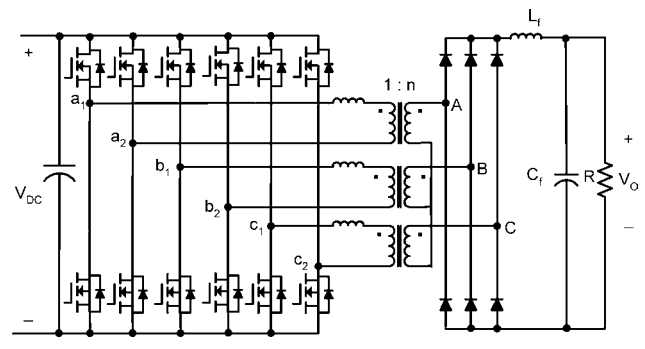


Fig. 18 Multiphase DC/DC converter [22]

increase in the transformer turns ratio. Furthermore, this interleaved connection permits the converter to be controlled in a manner such that the phase of their output waveforms will be 120° apart. Another benefit of this connection is the increase in frequency of the output ripple signal. The output ripple frequency is six times the switching frequency of the single-phase inverters granting a significant reduction in the output filter.

Many advantages for this converter exist and include:

- a reduced per phase root mean square current,
- lower conduction losses,
- high system efficiency,
- low transformer turns ratio,
- reduced size of output filter,
- reduced size of input capacitor,
- zero-voltage zero-current switching over a wide load range without the need of an auxiliary circuit and
- excellent modularity.

The only unfavourable quality of this converter is the complexity of the design with a 12-switch soft-switching control that must be implemented.

4.2.4 Current-fed DC/DC converters: Several current-fed DC/DC converters are proposed in [16, 23–28]. Fig. 19a represents a conventional current-fed converter found in [23] with a diode rectifier attached to the secondary side of a transformer. Fig. 19b, also proposed in [23], is similar to that of Fig. 19a except for the voltage doubler circuit located on the secondary side of the transformer. This allows for a smaller turns ratio on the transformer and a higher voltage gain with the converter.

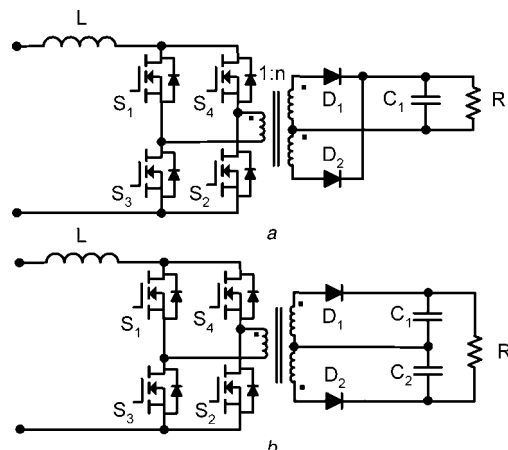


Fig. 19 Current-fed DC/DC converters [23]

Table 2: Comparison of different DC–DC converter topologies

DC–DC converter topology	Components	Advantages	Disadvantages
conventional boost	1 – capacitor 1 – diode 1 – inductor 1 – transistor total = 4	simple control and design	no electrical isolation
conventional full-bridge	1 – capacitor 6 – diode 1 – inductor 1 – transformer 4 – transistor total = 13	electrically isolated implements soft switching techniques (high-efficiency low switch stress) suitable for high-power transmission	
full-bridge with secondary coils	1 – capacitor 8 – diode 1 – inductor 3 – relays 1 – transformer 4 – transistor total = 18	electrically isolated implements soft switching techniques (high-efficiency low switch stress) suitable for high-power transmission adjustable transformer ratio (reduced leakage inductance)	
soft switching direct converter	1 – capacitor 9 – diode 1 – resistor 1 – transformer 8 – transistor total = 20	electrically isolated implements soft switching techniques (high-efficiency low switch stress) no DC-link capacitor (higher power density)	no DC-link capacitor (clamp required and less dynamic response)
voltage doubler	3 – capacitor 6 – diode 1 – transformer 6 – transistor total = 16	electrically isolated implements soft switching techniques (high-efficiency low switch stress) smaller transformers (reduced leakage inductance) reduced current ripple	complex control
high step-up	3 – capacitor 4 – diode 2 – coupled inductors 1 – transistor total = 10	implements snubber circuit for protection high boost capabilities	not electrically isolated
wide input fuel cell conditioner	5 – capacitor 8 – diode 2 – inductor 2 – transformer 8 – transistor total = 25	electrically isolated low current ripple constant output independent of input decrease in current rating (lower stress on switches)	highly complex

(continued)

Table 2: Continued

DC–DC converter topology	Components	Advantages	Disadvantages
three-phase transformer-isolated	1 – capacitor	electrically isolated	highly complex
	18 – diode	implements soft switching techniques (high-efficiency low switch stress)	
	4 – inductor	use of delta-Y transformer connection (additional boost, lower leakage inductance)	
	3 – transformer	high current ripple frequency	
current-fed	12 – transistor	modular	large inductors required (low power density)
	total = 38		
	1 – capacitor	electrically isolated	
	6 – diode	contains voltage doubler (lower requirements of transformer, lower leakage inductance)	
	1 – inductor		
	1 – transformer		
4 – transistor			
total = 12			

Most of the fuel cell power-conditioning systems implemented are voltage-source full-bridge converters. Yet, voltage-source inverters necessitate many large electrolyte capacitors to handle the ripple current. Moreover, the voltage from the fuel cell is actually further reduced in a voltage-source converter before being boosted by a transformer. Hence, the actual nature of a voltage-fed full-bridge converter is a buck converter.

For both these issues, a current-fed full-bridge converter appears to have better characteristics. In a current-fed full-bridge converter, the input current, or output current of the fuel cell, can be smoothed and precisely controlled, and the actual nature is that of a boost converter. This affords the current-fed converter with a lower transformer ratio than the voltage-fed converter for the same step-up level. Despite the initial appeal of the current-fed DC/DC converter, current-fed DC/DC converters are difficult to implement in fuel cell systems. This is predominantly due to the large inductor size required to meet the high output current of the fuel cell. This large inductor must also be charged to the rated current during start-up before the system can be activated.

4.3 DC–DC converter summary

As with typical designs, tradeoffs exist in choosing the optimum DC–DC converter. As seen in Table 2, a component increase is often necessitated to provide isolation, soft-switching and other benefits. In choosing a converter type, the designer must establish the exact requirements of the fuel cell system in question to determine the most advantageous design. As an example, if no electrical isolation is required but a low component count and high boost capabilities are necessitated (as often the case for PEMFCs), then the high step-up converter is the best choice.

5 Inverters

In almost every application, AC power is required demanding the utilisation of an inverter in the power-conditioning system. Hence, in the following sections several conventional configurations of inverters are reviewed along with

an investigation into designs specifically orientated towards application in power conditioning of fuel cells.

5.1 Conventional configurations

The conventional configurations of an inverter are used in many applications. In the following sections, the conventional inverter is examined, specifically single-phase, dual-phase, and three-phase inverters.

5.1.1 Single-phase inverter: For a single-phase inverter, the typical configurations of fuel cell power conditioning are full-bridge PWM inverter and half-bridge PWM inverter. Both designs are simple in nature and have low component count. However, compared with the half-bridge converter, the full-bridge inverter has two more switches adding to the cost while doubling the output voltage rating. Both these topologies are very well-known configurations and are not shown in this paper.

5.1.2 Dual-phase inverters: Four typical configurations of dual-phase inverters implemented for fuel cell power conditioning are shown in Figs. 20–23. The simplest configuration is that of Fig. 20 or topology A and consists of a single bus with two half-bridge inverters. Although this design is simple and has a low component count, the inverter might necessitate the use of some very large capacitors

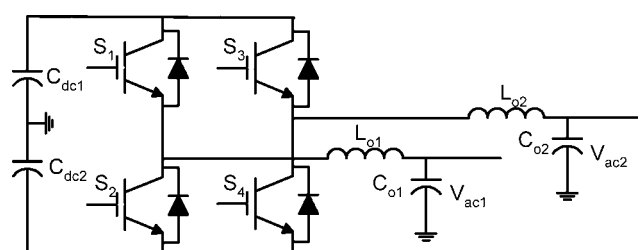


Fig. 20 Single DC bus inverter with split capacitor – topology A [29]

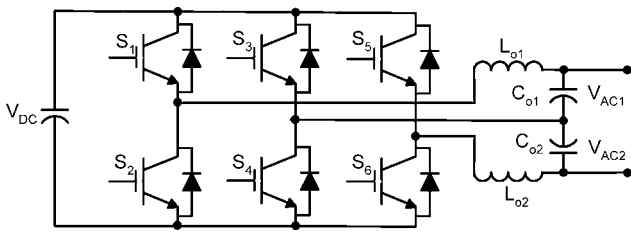


Fig. 21 Three-wire single phase inverter – topology B [29]

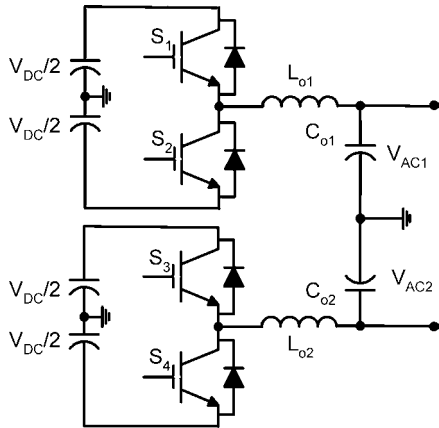


Fig. 22 Dual DC bus inverter – topology C [29]

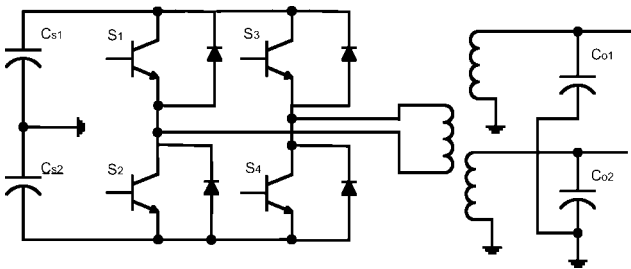


Fig. 23 Dual phase inverter with transformer – topology D [30]

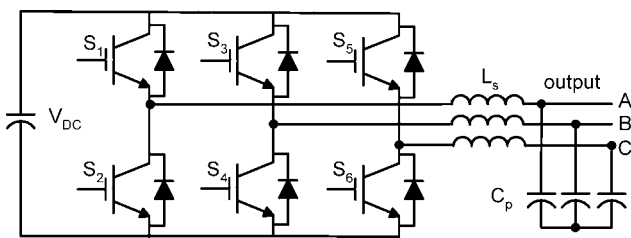


Fig. 24 Three-phase PWM inverter with LC filter [29]

because of the low-frequency neutral currents that may exist [29].

The six-switch, single bus topology (topology B) in Fig. 21 is an improved version of topology A [29]. The control method of the first and third legs is the same as the first and second legs of topology A. Conversely, the second leg is controlled to provide an output of $V_{DC}/2$. Considering the different control strategies that are implemented, the carrier frequency may be different from the second and first and third legs adding more complexity to the control. The advantage of topology B is the minimisation of passive components, including the AC filter and the DC bus capacitors but comes at the cost of more control effort.

Topology C, as shown in Fig. 22, is composed of two independent half-bridge converters. Although this adds to the component count, the modularity of this design is

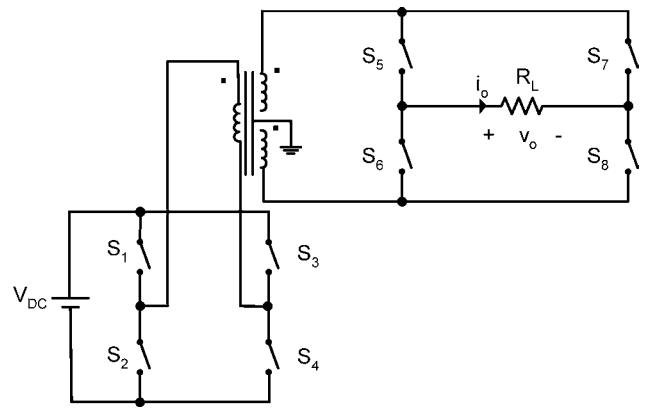


Fig. 25 Power-conditioning system with a high-frequency link inverter [31]

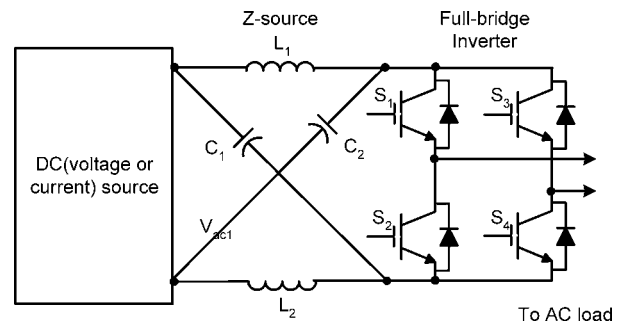


Fig. 26 Power-conditioning system with a Z-source inverter [3]

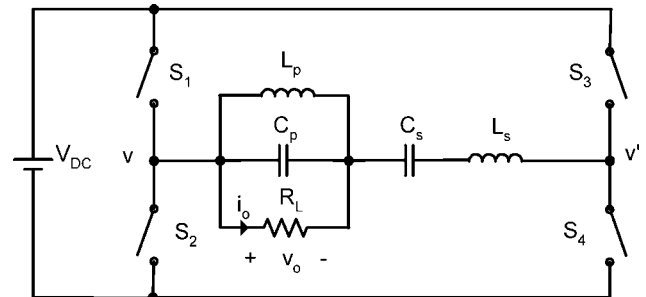


Fig. 27 LLC resonant inverter [32]

much increased. The provision of modularity increases the reliability and introduces redundancy through the addition of another circuit [29].

Topology D is composed of a full-bridge inverter with the output attached to a transformer [30]. The transformer, along with providing electrical isolation, supplies an additional boost reducing some of the gain requirements imposed on the DC–DC converter. Nevertheless, the addition of a transformer adds to the cost and size of the inverter.

5.1.3 Three-phase inverters: For a three-phase inverter, the conventional configuration of fuel cell power conditioning is a three-phase PWM inverter with an output LC filter, as shown in Fig. 24. This converter is simple in nature and with the filter can provide an adequate AC output.

5.2 Inverter configurations for fuel cells

In the following sections, multiple configurations for fuel cell power conditioning are reviewed.

Table 3: Comparison of different inverter topologies

Inverter	Components	Advantages	Disadvantages
conventional single-phase full-bridge	4 – diode 4 – transistor total = 8	simple design and control	
dual-phase single DC bus inverter with split capacitor	4 – capacitors 4 – diode 2 – inductors 4 – transistor total = 14	simple design and control two-phase output	
dual-phase three-wire single-phase inverter	2 – capacitors 6 – diode 2 – inductors 6 – transistor total = 16		complex control
dual-phase dual-DC bus inverter	6 – capacitors 4 – diode 2 – inductors 4 – transistor total = 16	highly modular redundant circuitry (more reliable)	
dual-phase inverter with transformer	4 – capacitors 4 – diode 1 – transformer 4 – transistor total = 13	provides electrical isolation boosting capability two phase output	higher cost and size
conventional three-phase	3 – capacitors 6 – diode 3 – inductors 6 – transistor total = 18	simple design and control	
high-frequency link inverter	8 – diode 1 – transformer 8 – transistor total = 17	provides electrical isolation boosting capability	highly complex higher cost and size
Z-source	2 – capacitors 4 – diode 2 – inductors 4 – transistor total = 12	boosting capability	high component stresses
LLCC resonant inverter	2 – capacitors 4 – diode 2 – inductors 4 – transistor total = 12	stable output with little current ripple implements soft switching techniques (high-efficiency low stresses)	low power density inverter highly dependent on capacitor and inductor parameters

5.2.1 High-frequency link inverter: A high-frequency link inverter for a fuel cell power-conditioning system is shown in Fig. 25. This inverter uses an AC–AC cycloconverter to first convert the DC to a high-frequency AC and then modifies this AC to the appropriate frequency and amplitude. The advantages of using high frequency and a

transformer are isolation and voltage boost. Furthermore, isolation allows for a simpler DC–DC converter at the input.

Complexity, size and component cost detract from this topology. The switching algorithm required to operate this inverter is complex and the transformer, although designed for high frequency, consumes space and increases the cost.

In addition, the viability of this inverter in fuel cell power conditioning is further reduced as the configuration does not support modularity [31, 33].

5.2.2 Z-source inverter: A Z-source inverter, as shown in Fig. 26, is a new topology that uses a half-bridge inverter with an impedance input. This unique impedance input consists of two small inductors and capacitors interconnected in the fashion of an X. These capacitors and inductors through careful control of the switches provide the capability to boost the voltage of the inverter through temporary energy storage techniques. In principle, the amplitude of the output voltage in the Z-source inverter could even reach infinity. This is an extremely attractive quality particularly for fuel cell power conditioning, considering that fuel cell modules have a low output voltage. Another benefit of this converter is that an additional DC/DC converter is no longer needed, saving in component cost and complexity. Notwithstanding the disadvantages of this converter include high current stress on DC link power devices, high voltage rating of the capacitors in Z-network and a pulsating DC current in the DC source [34–36].

5.2.3 LLC resonant inverter: A newly designed two-inductance two-capacitance (LLCC) resonant inverter is introduced in [32]. As seen in Fig. 27, the LLC inverter incorporates series and parallel combinations of inductors and capacitors otherwise known as a series-resonant tank (L_S, C_S) and parallel-resonant tank (L_P, C_P) to filter the voltage, remove some of the ripple current and provide a stable AC output. A half-bridge inverter converts the DC signal to AC using PWM with zero-voltage/zero-current switching. This reduces switching losses, thereby increasing the efficiency of the converter.

Unfortunately, the two capacitors and inductors increase the space and cost of the inverter. In addition, this resonant circuit highly depends on the parameters of the capacitors and inductances and may be influenced by their variation with operating conditions.

5.3 Inverter summary

In the previous sections, multiple types of inverter designs were examined. Table 3 displays some of the advantages and disadvantages of the inverter topologies discussed. As with DC–DC converters, added benefits come at the cost of extra components which increase the cost and size of the inverter. As an example, consider the Z-source inverter that adds a boosting capability to the conventional single-phase full-bridge at the cost of complexity and another four components, or the LLC resonant inverter that has a high efficiency through the implementation of soft switching techniques by sacrificing device count and power density.

6 Aggregation of multiple fuel cells for high-voltage/high-power applications [14]

If more power is wanted than what is available from the standard size fuel cell, then modules need to be aggregated. There is more than one approach to aggregate numerous fuel cell modules for high-voltage/high-power applications. Four different approaches of these architectures are reviewed, including:

- series,
- DC distribution,
- high frequency AC (HFAC) distribution and
- multilevel architecture.

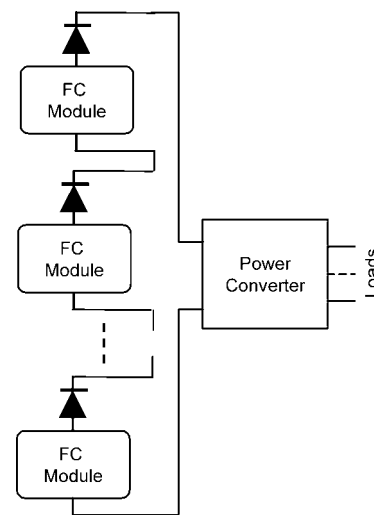


Fig. 28 Block diagram of the series architecture [18]

6.1 Series architecture

The series architecture, as shown in Fig. 28, simply connects all the fuel cell modules in series and interfaces the output with a power converter. A diode has been inserted in between each fuel cell to prevent reverse current. The power converter can use any of the DC/DC converters and inverters previously described in this report. As the cumulative fuel cell module output voltage is enough for the inverter to produce AC grid level voltages, the DC/DC converter is used to regulate the DC voltage instead of boosting voltage. The DC/DC converter can also be removed and the modulation index of the inverter can be regulated to get a fixed output AC voltage.

This architecture is the simplest of the topologies to be covered and is the most commonly used. The main quandary for this architecture is the failure mode. If one fuel cell module fails (open circuit), the whole system will stop working.

6.2 DC distribution

A DC bus distribution architecture is shown in Fig. 29. Each fuel cell module is connected by a separate DC–DC converter to the common voltage DC-link, which can be used to feed one or several inverters depending on the application.

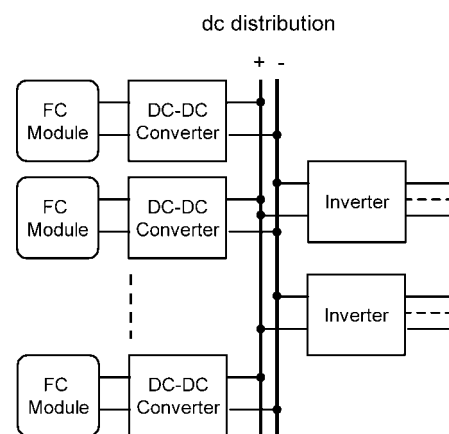


Fig. 29 Block diagram of the DC bus distribution architecture [18]

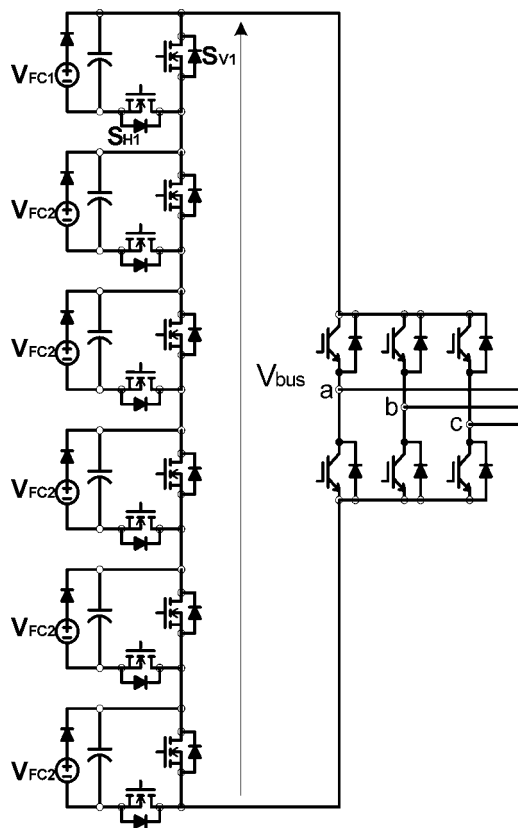


Fig. 30 Multilevel DC–DC converter connected to a three-phase inverter [37]

This architecture is inherently more reliable, as one individual fuel cell module’s failure will not affect the whole system operation. Each subsystem can be designed as an individual module and stocked as needed. The main dilemma of this converter is the higher device count. The addition of a DC–DC converter for every fuel cell multiplies the cost by a significant factor. In addition, each DC–DC converter’s output voltage must be balanced with the other DC–DC converters to ensure that no circulating currents are present.

Another possible architecture is shown in Fig. 30, where a cascaded multilevel DC–DC converter is shown [37]. Each fuel cell has a associated vertical (S_V) and a horizontal (S_H) switch. When S_H is on and S_V is off, the fuel cell supplies power to the load. On the other hand, if S_V is on and S_H is off, then the fuel cell does not supply any power; thus, it is inhibited. As seen in Fig. 25, if a three-phase AC output is needed, a three-phase inverter can be

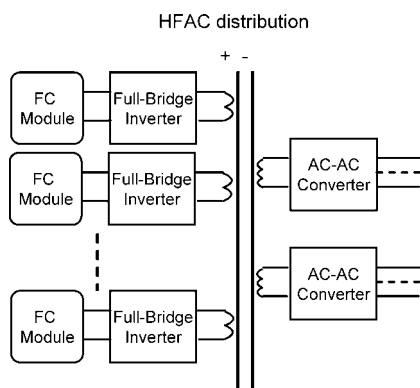


Fig. 31 Block diagram of the HFAC distribution architecture [18]

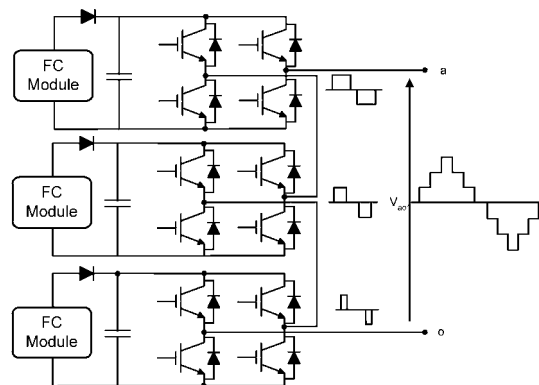


Fig. 32 Phase of a cascaded seven-level inverter [38]

connected to the high-voltage DC bus. This inverter will require a variable modulation index to compensate for the varying DC-link voltage.

6.3 HFAC distribution architecture

The basic configuration of this architecture can be implemented through the use of the high-frequency link inverter discussed in Section 5.2.1 as seen in Fig. 31. Each fuel cell is connected to a full-bridge inverter that converts the fuel cell DC voltage to a high-frequency AC. This AC is placed onto a small link and is shared among other fuel cells and their conditioning systems that are in parallel. Finally, a cycloconverter converts the high-frequency link voltage to the appropriate output voltage. Unfortunately to place the converters in parallel, a strict control of the high-frequency output of the full-bridge converter must be in place adding severe complexity to this design.

6.4 Multilevel architecture

There are many variations of multilevel architectures. Here, the cascaded multilevel inverter is reviewed with one phase shown in Fig. 32. Each half-bridge converter produces a pseudo-square wave with zero intervals at different duty ratios. Once summed, these voltages produce a stepped output voltage that can be made sinusoidal. Three of these single-phase voltages can be connected in wye or delta to form a three-phase supply. Just as with the HFAC distribution architecture, the modulation index of the overall converter needs to be regulated as each individual fuel cell module’s output voltage will change with load.

The advantages of multilevel converters include modularity, high reliability due to redundant levels, low device voltage rating and high efficiency because of fundamental frequency switching. However, several issues complicate this design including the high number of devices, the high lower-order harmonics brought on by fundamental frequency switching and the lack of any current ripple removal support.

7 Conclusions

As one of the most prominent sources of distributed energy in the future, fuel cells are under consideration for almost every application including both residential and industrial power generation. Yet, a power electronics interface must be incorporated between the fuel cell and output to provide flexibility due to the inherent restrictions fuel cells produce, such as low voltage, large voltage variation,

low efficiency when ripple current is high, slow load step responsibility and no acceptance of reverse current.

This paper first introduces different types, electrical characteristics and power electronic requirements of fuel cells. This is followed by a discussion of the various topologies of DC–DC boost converters and inverters used for fuel cells' power-conditioning system.

Several architectures to aggregate multiple fuel cells for high-voltage/high-power applications are also reviewed, including series, DC distribution, HFAC distribution and multilevel.

8 Acknowledgments

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9 References

- 1 'DOE fuel cell handbook' (EG&G Technical Services, Inc., DOE/NETL-2002/1179, 2002, 6th edn.), pp. 2-9–2-14
- 2 Larminie, J., and Dicks, A.: 'Fuel cell systems explained' (Wiley, UK, 2003), pp. 39–52
- 3 Hoogers, G.: 'Fuel cell technology handbook' (CRC Press, 2003), pp. 4-5–4-9
- 4 Williams, M.C., Strakey, J.P., and Singhal, S.C.: 'US distributed generation fuel cell program', *J. Power Sources*, 2004, **131**, pp. 79–85
- 5 Sammes, N., Bove, R., and Stahl, K.: 'Phosphoric acid fuel cells: fundamentals and applications' *J. Shanghai Univ. Elec. Power*, 2006, **22**, pp. 75–78
- 6 Sedghisigarchi, K., and Feliachi, A.: 'Dynamic and transient analysis of power distribution systems with fuel cells. Part I. Fuel cell – dynamic model', *IEEE Trans. Energy Conversion*, 2004, **19**, pp. 423–428
- 7 Andersen, G.K., Klumpner, C., Kjaer, S.B., and Blaabjerg, F.: 'A new green power inverter for fuel cells'. IEEE Power Electronics Specialists Conf., 2002, pp. 727–733
- 8 Gemmen, R.: 'Analysis for the effect of inverter ripple current on fuel cell operating condition' (Power Electronics for Fuel Cells Workshop, Irvine, CA, August 2002)
- 9 Michon, M., Duarte, J.L., Hendrix, M., and Simoes, M.G.: 'A three-port bi-directional converter for hybrid fuel cell systems'. IEEE Power Electronics Specialists Conf., June 2004, vol. 6, pp. 4736–4742
- 10 Jang, S.-J., Lee, T.-W., Lee, W.-C., and Won, C.-Y.: 'Bi-directional DC–DC converter for fuel cell generation system'. IEEE Power Electronics Specialists Conf., June 2004, vol. 6, pp. 4722–4728
- 11 Su, G.-J., and Peng, F.Z.: 'A low cost, triple-voltage bus DC–DC converter for automotive applications'. IEEE Applied Power Electronics Conf. and Exposition, March 2005, vol. 2, pp. 1015–1021
- 12 Cacciato, M., Caricchi, F., Giuhlii, F., and Santini, E.: 'A critical evaluation and design of bi-directional DC/DC converters for super-capacitors interfacing in fuel cell applications'. IEEE Industry Applications Society Annual Meeting, October 2004, vol. 2, pp. 1127–1133
- 13 Cha, H.J., and Enjeti, P.N.: 'A new soft switching direct converter for residential fuel cell power system'. IEEE Industry Applications Society Annual Meeting, October 2004, vol. 2, pp. 1172–1177
- 14 Zubietta, L., and Panza, G.: 'Wide input voltage and high efficiency DC–DC converter for fuel cell applications'. IEEE Applied Power Electronics Conf. and Exposition, March 2005, vol. 1, pp. 85–89
- 15 Wang, J., Peng, F.Z., Anderson, J., Joseph, A., and Buffenbarger, R.: 'Low cost fuel cell converter system for residential power generation', *IEEE Trans. Power Electron.*, 2004, **19**, (5), pp. 1315–1322
- 16 Meo, S., Perfetto, A., Piegari, L., and Esposito, F.: 'A ZVS current fed DC/DC converter oriented for applications fuel-cell-based', *IEEE Ind. Electron. Soc. Annu. Conf.*, 2004, **1**, pp. 932–937
- 17 Xu, H.P., Wen, X.H., and Kong, L.: 'High power DC–DC converter and fuel cell distributed generation system'. IEEE Industry Applications Society Annual Meeting, October 2004, vol. 2, pp. 1134–1139
- 18 Ozpineci, B., Tolbert, L.M., and Adams, D.J.: 'Trade study on aggregation of multiple 10-kW solid oxide fuel cell power modules'. ORNL/TM-2004/248. UT-Battelle, LLC, Oak Ridge National Laboratory, 2004
- 19 Wai, R.-J., and Duan, R.-Y.: 'High step-up converter with coupled-inductor', *IEE Proc., Electric Power Appl.*, 2005, **20**, pp. 1025–1035
- 20 Todorovic, M.H., Palma, L., and Enjeti, P.: 'Design of a wide input range DC–DC converter with a robust power control scheme suitable for fuel cell power conversion'. IEEE Industry Applications Society Annual Meeting, 2004, vol. 1, pp. 374–379
- 21 Zhang, M.T., Jiang, Y., Lee, F.C., and Jovanovic, M.M.: 'Single-phase three level boost power factor correction converter'. IEEE Applied Power Electronics Conf., March 1995, vol. 1, pp. 434–439
- 22 Liu, C.R., Johnson, A., and Lai, J.-S.: 'A novel three-phase high-power soft-switched DC/DC converter for low-voltage fuel cell applications', *IEEE Trans. Ind. Appl.*, 2005, **41**, (6), pp. 1691–1697
- 23 Kong, X., Choi, L.T., and Khambadkone, A.M.: 'Analysis and control of isolated current-fed full bridge converter in fuel cell system', *IEEE Ind. Electron. Soc. Annu. Conf.*, 2004, **3**, pp. 2825–2830
- 24 Zhu, X.C., Xu, D.H., Shen, G.Q., Xi, D.J., Mino, K., and Umida, H.: 'Current-fed DC/DC converter with reverse block IGBT for fuel cell distributing power system'. IEEE Industry Applications Society Annual Meeting, October 2005, vol. 3, pp. 2043–2048
- 25 Song, Y.J., Chung, S.-K., and Enjeti, P.N.: 'A current-fed HF link direct DC/AC converter with active harmonic filter for fuel cell power systems'. IEEE Industry Applications Society Annual Meeting, October 2004, vol. 1, pp. 123–128
- 26 Kim, J.-T., Lee, B.-K., Lee, T.-W., Jang, S.-J., Kim, S.-S., and Won, C.-Y.: 'An active clamping current-fed half-bridge converter for fuel-cell generation systems'. IEEE Power Electronics Specialists Conf., June 2004, vol. 6, pp. 4709–4714
- 27 Attanasio, R., Cacciato, M., Gennaro, F., and Consoli, A.: 'An innovative boost converter for fuel cells stationary generation systems'. IEEE Industrial Electronics Society Annual Conf., November 2004, vol. 3, pp. 2831–2836
- 28 Krein, P.T., and Balog, R.: 'Low cost inverter suitable for medium-power fuel cell sources'. IEEE Power Electronics Specialists Conf., June 2002, vol. 1, pp. 321–326
- 29 Nergaard, T.A., Ferrell, J.F., Leslie, L.G., and Lai, J.-S.: 'Design considerations for a 48 V fuel cell to split single phase inverter system with ultracapacitor energy storage'. IEEE Power Electronics Specialists Conf., June 2002, vol. 4, pp. 2007–2012
- 30 Tuckey, A.M., and Krase, J.N.: 'A low-cost inverter for domestic fuel cell applications'. 33rd Annual IEEE Power Electronics Specialists Conf., 2002, vol. 1, pp. 339–346
- 31 Krein, P.T., Balog, R.S., and Geng, X.: 'High-frequency link inverter for fuel cells based on multiple-carrier PWM', *IEEE Trans. Power Electron.*, 2004, **19**, (5), pp. 1279–1288
- 32 Wai, R.-J., Duan, R.-Y., Lee, J.-D., and Liu, L.-W.: 'High-efficiency fuel-cell power inverter with soft-switching resonant technique', *IEEE Trans. Energy Conversion*, 2005, **20**, (2), pp. 485–492
- 33 Song, Y.J., and Enjeti, P.N.: 'A high frequency link direct DC–AC converter for residential fuel cell power systems'. IEEE Power Electronics Specialists Conf., June 2004, vol. 6, pp. 4755–4761
- 34 Peng, F.Z.: 'Z-source inverter', *IEEE Trans. Ind. Appl.*, 2003, **39**, (2), pp. 504–510
- 35 Kim, Y.-H., Moon, H.-W., Kim, S.-H., Cheong, E.-J., and Won, C.-Y.: 'A fuel cell system with Z-source inverters and ultracapacitors'. Int. Power Electronics and Motion Control Conf., 2004, vol. 3, pp. 1587–1591
- 36 Xu, L., and Liu, J.: 'Comparison study of DC–DC–AC combined converters for integrated starter generator applications'. Int. Power Electronics and Motion Control Conf., August 2004, vol. 3, pp. 1130–1135
- 37 Ozpineci, B., Du, Z., Tolbert, L.M., and Su, G.-J.: 'Optimum fuel cell utilization with multilevel DC–DC converters'. IEEE Applied Power Electronics Conf., Anaheim, California, February 2004, pp. 1572–1576
- 38 Ozpineci, B., Tolbert, L.M., and Du, Z.: 'Multiple input converters for fuel cells'. IEEE Industry Applications Society Annual Meeting, Seattle, Washington, October 2004, pp. 791–797