Power Electronic Converters for Fuel Cell Applications

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Abstract—**Power electronics plays an important role in providing an interface between fuel cells and loads. Furthermore, power electronic converters ensure that the power is reliably and efficiently delivered to the load in the required DC or AC form. In this paper, major types of fuel cells are presented. Basic structures, operating principles, and different applications of fuel cells are described. In addition, current status and future trends in the areas of power electronics for fuel cell applications are explained. A review of fuel cell power electronic system topologies and basic requirements are given as well.**

Keywords—**Battery chargers, DC-AC power conversion, DC-DC power conversion, fuel cells.**

I. INTRODUCTION

A fuel cell is typically similar in operation to a conventional battery, although they have some distinct physical differences. Primarily, a fuel cell is an electro-chemical device wherein the chemical energy of a fuel is directly converted into electric energy without combustion [1]-[6]. Unlike the conventional batteries, a fuel cell is supplied with reactants externally. Therefore, while a battery is discharged, a fuel cell, as long as the supply of fuel is provided, never faces the discharging problem. As is depicted in Fig. 1, electrodes and electrolyte are the main parts of a fuel cell. The most popular type of fuel cells uses hydrogen and oxygen to provide electric power.

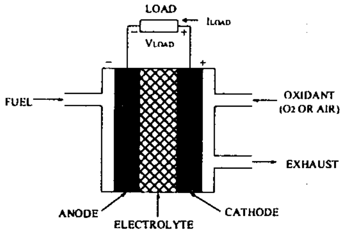

Fig. 1. Typical schematic diagram of a fuel cell.

As is shown in Fig. 1, hydrogen is used as the fuel to be fed to the anode. The cathode, on the other hand, is fed with oxygen, which may be acquired from the air. The hydrogen atom is split up into protons and electrons, which follow different paths, but ultimately meet at the cathode. The protons take up the path through the electrolyte, whereas the electrons follow a different external path of their own. This, in turn, facilitates a flow of current, which can be used to supply an external electric load. The electrode reactions are given as follows:

Anode: $2H_2 \rightarrow 4H^+ + 4e^-$
Cathode: $O_2 + 4e^- \rightarrow 2O^{--}$
Overall Reaction: $2H_2 + O_2 \rightarrow 2H_2O$ + Power

From these simple and basic expressions describing the operation of a typical fuel cell, we can see that there is absolutely no combustion and, hence, no production of emissions. This makes the fuel cell environmentally suitable. A typical *i-v* curve of fuel cells is shown in Fig. 2. The output voltage decreases as the current density increases.

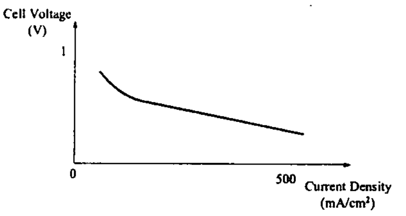

Fig. 2. Typical *i-v* curve of a fuel cell.

Fuel cells have many favorable characteristics for energy conversion. Typical values of efficiency range 40% to 85%. They are inherently modular, which means that they can be configured to operate with a wide range of outputs, from a few watts in small fuel cells, to 50 MW for natural gas fuel cells, and to 100 MW or more for coal gas fuel cells. Another unique advantage of fuel cells is that hydrogen, which is the basic fuel used, is easily acquirable from natural gas, coal gas, methanol, and other similar fuels containing hydrocarbons. The waste heat/exhaust can also be utilized for cogeneration and for heating and cooling purposes [7]-[9].

In order to provide power for an electrical load from a fuel cell, in most of the applications, a power electronic converter is required. Therefore, power electronics plays an important role in providing an interface between the fuel cell and the load. Furthermore, power electronics presents much more flexibility and improvements in operation when used in conjunction with fuel cells. In this paper, we explore the role of power electronics for the fuel cell applications.

II. STRUCTURES AND OPERATIONS OF FUEL CELLS

Fuel cells are generally characterized by the type of electrolyte that they use. Main fuel cell systems under development for practical applications are explained in this section.

A. Phosphoric Acid Fuel Cell (PAFC)

These fuel cells are known as the first generation fuel cells. They are also the closest to commercialization. The power generating efficiency of this type of fuel cells is typically in the range of 35-45%. They operate at a temperature of about 200°C. Schematic diagram of a typical PAFC is depicted in Fig. 3. An ion is transported through the electrolyte from the anode to the cathode. The electrodes are connected through an external load to complete the electrical circuit. Since these fuel cells operate at high temperatures, their exhaust can be considered for the purpose of co-generation [1], [2]. The waste heat generated may also be used for space heating or heating of water.

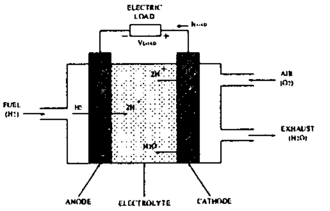

Fig. 3. Schematic diagram of a typical PAFC.

B. Proton Exchange Membrane Fuel Cell (PEMFC)

The electrolyte of a PEMFC consists of a layer of solid polymer, which allows protons to be transmitted from one side to the other. It basically requires hydrogen and oxygen as its input though the oxidant may also be ambient air. These gases must be humidified. A very simple depiction of this type of fuel cell is shown in Fig. 4. The anode conducts the electrons that are freed from the hydrogen molecules so that they can be used in an external circuit. The cathode, on the other hand, has channels etched into it, which distribute the oxygen to the surface of the catalyst. It also conducts the electrons back from the external circuit to the catalyst, where they can recombine with the hydrogen ions and oxygen to form water. The electrolyte is the proton exchange membrane. This specially treated material only conducts charged ions. The membrane blocks electrons. In fact, the catalyst is a special material that facilitates the reaction of oxygen and hydrogen. It is usually made of platinum powder coated very thinly onto carbon paper or cloth. The catalyst is rough and porous so that the maximum surface area of platinum can be exposed to the hydrogen or oxygen. The platinum-coated side of the catalyst is placed facing the membrane. Typically, these fuel cells can operate with efficiencies of about 55% at a temperature of about 90°C [1].

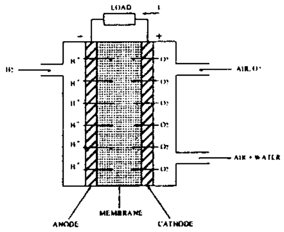

Fig. 4. Schematic diagram of a typical PEMFC.

C. Molten Carbonate Fuel Cell (MCFC)

This fuel cell, as its name suggests, uses a molten alkali carbonate mixture as the electrolyte. They operate at a temperature of about 650°C. The basic structure of a MCFC is shown in Fig. 5. Typical values of efficiencies for this type of fuel cell are about 45%.

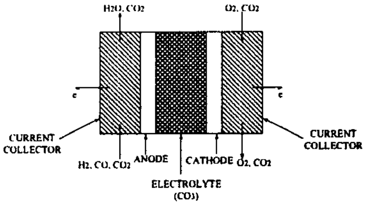

Fig. 5. Schematic diagram of a typical MCFC.

A single cell is a laminate of two porous electrodes made of Ni and NiO, an electrolyte, and separators. A fuel cell stack is made by alternating these single cells with cooling plates. The electrolyte is a porous plate of $LiAlO_2$ impregnated with carbonates. In this case the cathode must be supplied with carbon dioxide, which reacts with the oxygen and electrons to form carbonate ions, which carry the ionic current through the electrolyte [1]-[4]. At the anode, these ions are consumed in the oxidation of hydrogen, which also forms water vapor and carbon dioxide to be transferred back to the cathode.

D. Solid Oxide Fuel Cell (SOFC)

The SOFC has emerged as an alternative high temperature technology contender. The most striking quality is that the electrolyte is in solid state and is not a liquid electrolyte. The schematic diagram of a SOFC showing how oxidation of the fuel generates electric current to the load is shown in Fig. 6.

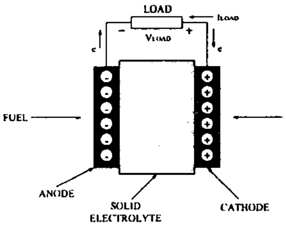

Fig. 6. Schematic diagram of a typical SOFC.

As is illustrated in the figure, the cell readily conducts oxygen ions from the air electrode (cathode), where they are formed through the zirconia-based electrolyte, to the fuel electrode (anode). Here, they react with fuel gas CO, H_2, or any other mixture and deliver electrons to an external circuit to produce electricity [5]. A number of different fuels can be used from pure hydrogen to methane to carbon monoxide. The nature of the emissions from the fuel cell varies correspondingly with the fuel mixture. The major advantage of this fuel cell lies in its operating temperature and efficiency. It has shown efficiencies ranging from 55-60% and temperatures of roughly 1000°C [4], [5].

E. Direct Methanol Fuel Cell (DMFC)

As we have explained, the primary fuel used in fuel cells is hydrogen, which can be easily obtained from reformation of hydrocarbon fuels such as methane and methanol. But, such a method of electricity generation immediately suggests a low efficiency of fuel utilization as well as increased cost of operation. This limitation can be overcome by the use of the DMFC wherein methanol is directly used as the primary source of fuel. Therefore, the operation of the DMFC is based on the oxidation of an aqueous solution of methanol in a PEMFC without the use of a fuel processor. A typical DMFC structure is shown in Fig. 7. As is clear from the figure, the methanol fuel, which may be stored in a reservoir, is directly fed to the anode. As is the usual practice, O_2 from air is fed to the cathode. The catalyst used at the cathode is typically a Platinum-Ruthenium (Pt-Ru) combination, whilst only Platinum (Pt) is used at the anode [6].

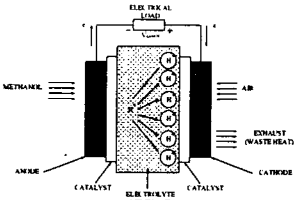

Fig. 7. Schematic diagram of a typical DMFC.

F. Alkaline Fuel Cell (AFC)

The AFC has recently attracted the attention of most fuel cell manufacturers. These fuel cells are also known as ambient temperature fuel cells wherein the electrolyte is circulated in order to transfer heat and water and, at the same time, aid in removal of the carbonate [3]. Schematic representation of a typical AFC showing all the essential parts is depicted in Fig. 8. Electrolyte used in an AFC, as the name suggests, is an alkaline solution, generally being Potassium Hydroxide solution (KOH). To prevent carbonation of the electrolyte, scrubbers are used to scrub both the air and the fuel gas inlets. Anode and cathode electrodes are also catalyzed with small quantities of Platinum (Pt) and Silver (Ag), respectively.

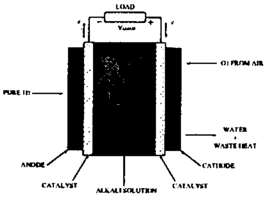

Fig. 8. Schematic diagram of a typical AFC.

III. FUEL CELL BASED POWER PROCESSING SYSTEMS

A typical fuel cell based power processing system showing the major plant processes is depicted in Fig. 9. There are three major steps involved in the generation of power from a fuel cell. The first and foremost step is to achieve purity of the available hydrogen gas. This is done with the help of a fuel processor. Carbonaceous fuel is fed to the fuel processor, which, in turn, produces a hydrogen rich gas. This hydrogen rich gas is then fed to the anode electrode of the fuel cell.

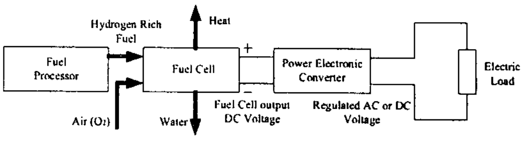

Fig. 9. Block diagram of a typical fuel cell based power processing system.

The second step involves the fuel cell operation itself. The fuel cell is fed with the hydrogen rich gas at its anode and a supply of air at its cathode. The hydrogen atoms at the anode split up into positive protons and negative electrons. These electrons follow an external path on their way to the cathode, thus supplying power to an external load in the process. For facilitating the splitting up of the hydrogen atoms, suitable catalysts are used.

The third and final step is the power-conditioning step, which includes power electronic converters. Power electronic converters add more flexibility to the operation of the system. There may be two stages of converters. Firstly, it consists of a DC/DC converter, which converts the low voltage DC output from the fuel cell to a level at which the next stage, i.e., a DC electric load or an inverter can safely operate. The inverter is basically used to invert the DC output from the DC/DC converter to a suitable AC voltage, if the electric load is of AC type. Ideally, the power conditioner must have minimal losses, thus, leading to a higher efficiency. Power conditioning efficiencies are typically higher than 90% up to 99%.

IV. UTILITY APPLICATIONS

In this section, utility applications of fuel cells are studied. Issues dealing with distributed generation and cogeneration systems are discussed. In addition, fuel cell based power generation systems for residential and commercial buildings are explained. The main challenge for these systems is to operate in accordance with the utility grids.

A. Distributed Generation and Cogeneration

With the increasing costs of transmission and distribution of electrical power, the utility companies are looking toward the options of onsite power generation and distributed generation. One of the most suitable options available involves the use of fuel cells for this purpose. Continued research has shown that the usage of fuel cells increases the overall efficiency of the system. Moreover, there are no emissions and, hence, no pollution involved.

Fuel cells are connected to the utility grids via power electronic converters. These systems usually work on natural gas, which is readily available at most of the load sites. In these generation units, the waste heat may be used after recovery for the facility heating purposes. In addition, as is shown in Fig. 10, additional efficiency is gained from the usage of the thermal energy from the fuel cell exhaust to power a non-combusting gas turbine. In these hybrid systems, the fuel cell exhaust supplies a turbine-generator unit, the capacity of which, could be as high as 15MW [7], [8].

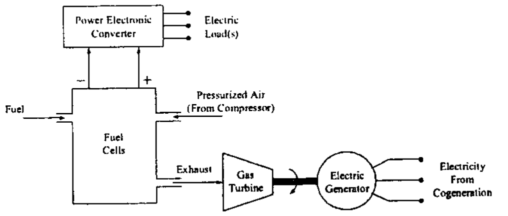

Fig. 10. Block diagram of a typical fuel cell hybrid system.

B. Applications for Buildings

Energy saving is the main advantage of utilizing fuel cell based generation systems in residential and commercial buildings. These applications are generally considered to meet the electrical and thermal load demands in buildings. By supplying electric and thermal energy using these systems, energy usage in buildings can be improved considerably. The conventional equipments used for heating and cooling purposes in buildings will form an efficient co-generation system, when used in conjunction with fuel cells [9].

Generally, the PEMFC is considered to be the best option for supplying the electric and thermal loads of buildings. At the moment, most of the building electricity program has its efforts concentrated on commercial buildings rather than on residential buildings. Even so, there are efforts being made and projects are being undertaken to power homes using this technology [9].

C. Typical Power Electronic Converter Configurations

Design of fuel cell based generation systems for utility applications is different from the design of these systems for portable devices or vehicular applications. This is mainly because, in utility applications, the output stage has an additional DC/AC inverter, which converts the DC voltage from DC link to a suitable AC voltage of magnitude and frequency matching those required by the utility or the AC load. Fig. 11 shows a typical power electronic interface for fuel cell utility applications. The output stage of this system is similar to that of an Uninterruptible Power Supply (UPS), with the only major difference being the built-in generating capability in the case of fuel cells [10].

When designing an inverter for fuel cells used in utility applications, the interconnection issues must be considered. The fuel cell system is designed so that it can be used in grid-paralleled operation or in stand-alone mode. Furthermore, protection issues must be considered and suitable static relays must be used for fault detection and clearing. Electric power quality issues such as Total Harmonic Distortion (THD) must be considered as well.

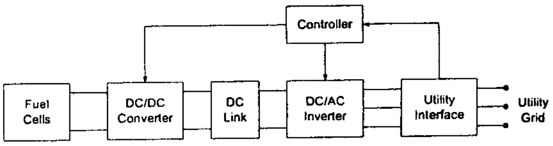

Fig. 11. Block diagram of a typical fuel cell based generation system for utility applications.

The main purpose of power electronic converters, in Fig. 11, is to convert the DC power output from the fuel cell to a suitable AC voltage, which can be connected to the utility grid or electric loads directly. In Fig. 11, the fuel cell output is connected to the DC/DC converter, which regulates the DC link voltage. DC/DC converter is usually a PWM Boost chopper. Additional filters may be used to further improve the quality. DC/AC inverter is connected to the DC link and converts the DC voltage to AC. The control of the inverter is generally achieved by PWM techniques. Battery storage system might also be connected to the DC link in order to provide the initial power at the start-up of the system.

Final stage of the system of Fig. 11 may utilize a transformer, which brings the voltage to a suitable level for interconnecting the fuel cell system to the utility grid. A feedback command from the utility grid is given to the controller section, which, in turn, controls the switching of the inverter switches. Thus, the power output from the inverter is controlled to a suitable level in accordance with the utility grid.

As is shown in Fig. 12, a multi-level inverter might be used to increase the voltage to the level of the utility grid. These inverters have a unique structure, which allows them to produce high levels of voltages with low production of harmonics [11]. By utilizing these inverters, there is no need for the output stage transformer. This is the main advantage of the system of Fig. 12 since transformers are relatively more expensive and require more space increasing the volume and weight of the system. However, in order to provide electric isolation, a high frequency transformer, with higher efficiency and lower weight and volume, could be used in the DC/DC converter or DC/AC inverter.

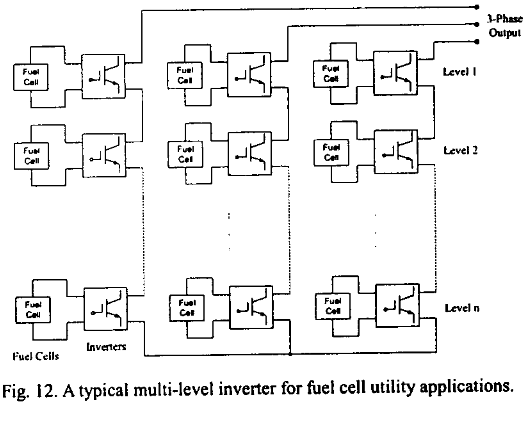

Fig. 12. A typical multi-level inverter for fuel cell utility applications.

V. AUTOMOTIVE APPLICATIONS

Various advantages of fuel cells including reliability, simplicity, quietness of operation, and most importantly low pollution have made them attractive in different low and medium power applications. One of the main applications is the automotive industry, where all the above-mentioned factors play a vital role. Generally, hydrogen is considered as the primary fuel to be used for automotive fuel cell based applications. Yet, due to the danger of carrying hydrogen aboard the vehicle, automotive industry is considering alternate fuel sources. These alternate fuels are generally natural gases, which can be reformed to get nearly pure hydrogen.

A. Passenger Cars

Conventional cars have electrical load demands of approximately 1kW. A 14V DC power system with 12V batteries is sufficient to satisfy these loads. With the gradual increase in the amount of electrical loads in conventional automobiles up to 10kW, 42V DC power systems have been proposed to handle the high power loads. In hybrid electric cars, higher voltages such as 300V or 140V with electrical systems capable of delivering tens of kilowatts are required to drive traction and non-traction electrical loads. Fuel cells can replace the high voltage batteries. They can also be used with batteries in hybrid systems to provide electric power in more electric and hybrid electric cars in order to improve fuel economy and emissions.

Fuel cells could also be considered as an advanced version of the battery powered vehicles in automobiles with all-electric drive train. They can be refueled quickly and, at the same time, provide longer operating range. Research results show that the fuel economy of a Direct Methanol Fuel Cell Vehicle (DMFCV), which is considered the best option for a fuel cell powered car, is approximately 2 times greater than that of a conventional car with Internal Combustion Engine (ICE). In addition, compared to ICE efficiencies of about 10-30%, fuel cells have shown efficiencies ranging between 30-40% for automobile applications. Even higher efficiencies are attainable when fuel cells make use of direct hydrogen as a fuel source. In this case, efficiencies as high as approximately 50% are attainable. Thus, compared to an ICE powered car, the fuel cell car can do about twice the amount of work and, hence, can cover almost double the distance [12], [13]. A typical schematic diagram of the power system of an automobile with a fuel cell based drive train is shown in Fig. 13. The fuel cell is fed with fuel and air at the anode and cathode, respectively. A low voltage DC is produced, which is made useable by an electric machine by passing it through a power electronic converter. The electrical machine output is a mechanical output used to drive the wheels of the vehicle. Arrangement shown in Fig. 13 includes a battery pack making it a hybridized arrangement and, hence, making regenerative braking possible [13].

A block diagram representation showing an on-board fuel processor system is shown in Fig. 14. A feedback from the fuel processor is given to the system controller, which, in turn, controls the fuel cell based system. This controller also receives a feedback from the vehicle and accordingly gives control signals to the fuel cell stack. Power conditioner provides the appropriate power to the vehicle loads.

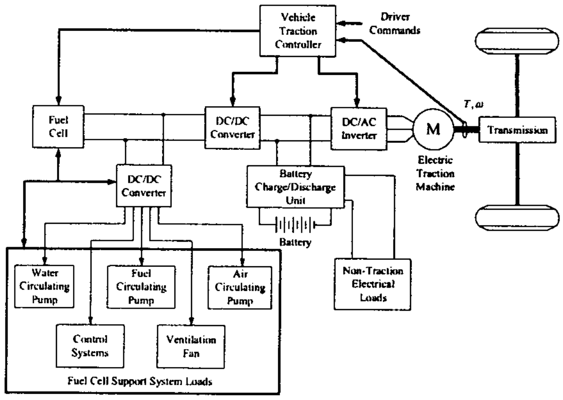

Fig. 13. Power system of an automobile with a fuel cell based drive train.

B. Heavy Duty Vehicles

As far as automotive applications for fuel cells are concerned, this is considered by far the most popular application. Most transit authorities in the USA and Europe have proposed usage of fuel cell powered buses. Again, as in cars, most buses will use either Direct Hydrogen Fuel Cells (DHFC) or DMFC. Furthermore, as a major step towards reducing emissions from heavy-duty vehicles, most transit authorities have also opted to use Compact Natural Gas (CNG) fueled buses.

The emission standards are of prime importance when fuel cells are considered for vehicular applications. These standards are set in terms of average emissions from the engine on a prescribed engine drive cycle. Standards set for NO_x, hydrocarbons, carbon monoxide (CO), and particulate materials. Over the years, bus manufacturers have significantly reduced the NO_x and particulate material emissions. In order to do so, conventional buses using diesel and CNG utilize an oxidation catalyst for controlling emissions. On the other hand, the diesel hybrid electric buses make use of additional regenerative particulate controls apart from the oxidation catalysts [14].

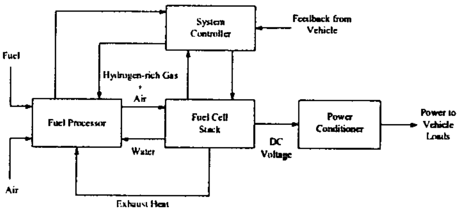

Fig. 14. Block diagram of a fuel cell system with fuel processor.

The diesel hybrid electric buses use batteries for electrical energy storage. These batteries are essentially lead-acid batteries, which provide the option of regenerative braking and, hence, energy recovery in the process. Research results have shown that this results in significantly reduced NO_x and hydrocarbon emissions. Moreover, their fuel economy is comparatively higher mainly due to the fact that there exists the energy recovery due to regenerative braking. Typical values of fuel economy of diesel hybrid electrical buses have been found to be 50–60% higher than those of conventional diesel and CNG fueled buses [14]. When direct hydrogen is used as a fuel, as compared to DMFC, the fuel economy value is found to be even greater. This is obvious due to the direct oxidation of the hydrogen fuel. Typically, the fuel economy of a DHFC bus is about 30% higher than that of buses using DMFC with a reformer. Thus, similar to smaller vehicles, heavy-duty vehicle manufacturers such as bus and truck developers also opt for either the DHFC or DMFC [15].

VI. AEROSPACE APPLICATIONS

Aerospace industry has been one of the first major applications of fuel cells. For long space missions, it has been identified that energy storage and conversion based on hydrogen technology is of critical importance [16]. Therefore, the fuel cell technology has gained considerable momentum for aerospace applications. The AFC, with an immobile electrolyte is considered one of the best options for powering space shuttles. This technology has been developed for space missions in the U.S. by NASA. In the immobile electrolyte AFC, the electrolyte is kept in a fixed position by capillary forces. Furthermore, for the water intake and removal, certain membrane techniques are used which are explained in [16].

In recent years, the PEMFC has gained favor over the AFC for space shuttle applications. As an example, NASA is considering upgrading its fuel cell program by replacing the existing AFC units with PEMFC units. This is being considered to provide power for the space shuttle orbiters [17]. According to the results, it has been proved that use of the PEMFC helps reducing lifecycle costs considerably. Moreover, the projected life of a PEMFC is comparatively longer. PEMFC units have also shown to have higher power densities, which enables them to produce approximately 1.5 times the power produced by an AFC unit. Apart from these advantages, the PEMFC has higher system stability and safety, thus, leading to significantly lower lifecycle cost of the power plants. In addition, the usage of PEMFC can improve flexibility of space missions. Therefore, missions that cannot be supported by the AFC can be undertaken by the PEMFC [17].

Similar to the other applications of fuel cells, in order to have a regulated DC voltage, a DC/DC chopper, as is shown in Fig. 15, is usually used. A DC/AC inverter, as is shown in Fig. 16, can also be used to achieve a simple single conversion AC power supply. However, in order to obtain better performance and flexibility, a double conversion AC power supply, as is shown in Fig. 17, might be used which utilizes a battery charge/discharge unit. Battery provides initial power during the warm-up period of the fuel cell. Therefore, the start-up time of the system is reduced considerably.

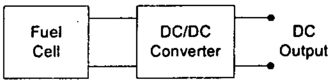

Fig. 15. A fuel cell based single conversion DC power supply.

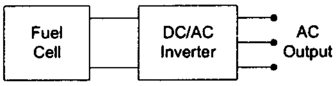

Fig. 16. A fuel cell based single conversion AC power supply.

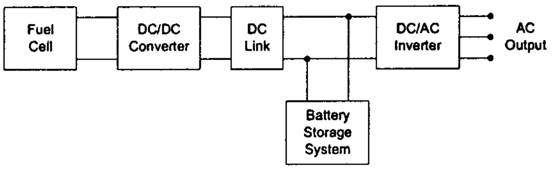

Fig. 17. A fuel cell based double conversion AC power supply with storage system.

VII. PORTABLE APPLICATIONS

Portable systems demand power supplies with long life, low mass, high energy density, and low start-up time. Based on these requirements, attention is being turned to the fuel cells in order to fulfill these needs. In the past, portable generators were used to supply power to various portable devices. Yet, they are problematic due to the fact that they are noisy and emit harmful gases. The solution to these problems was found in rechargeable batteries. However, they have their own disadvantages, when considered for portable applications. They show short life due to the time required to recharge the battery pack. Furthermore, they are heavy in weight and the initial investment required is high. All these factors have made portable power supply manufacturers focus their attention more towards the fuel cells. Based on the requirements for a portable power source, there exist three fuel cell options: PAFC, DMFC, and PEMFC.

The PAFC is used for portable applications in the range of 200-300W. It operates at a temperature of about 200°C and uses Metal Hydride (MH) as a fuel supplier. A typical PAFC based power unit is shown in Fig. 18. As is shown in Fig. 18, the unit consists of an air cooled PAFC stack, a fuel supplier, and a DC/DC converter [18]. The MH cylinder supplies pure hydrogen fuel to the anode of the PAFC.

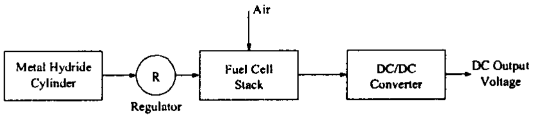

Fig. 18. Block diagram of a PAFC based portable power unit.

The DMFC has a much simpler construction as compared to other fuel cells. For portable applications, the liquid feed version of the DMFC is widely considered as a good option. The operation is based on the oxidation of an aqueous solution of methanol to CO_2 at the anode and reduction of O_2 to H_2O at the cathode. Thus, by using the DMFC, many issues concerned with the PAFC are solved. Furthermore, with the lack of an acidic solution, there is no concern of corrosion. This fuel cell can be operated at comparatively lower temperatures in the range of 60-100°C. Portable power sources using DMFC, in the range of 50-150W are being considered for various military applications [19].

As mentioned earlier, the operating temperature of the PAFC is approximately 200°C leading to longer warm-up time. This is a highly undesirable characteristic for a portable power source. As opposed to this, the PEMFC operates at a much lower temperature of approximately 100°C. This lower operating temperature allows a comparatively shorter start-up time. Furthermore, the PEMFC has a higher energy density; hence, system volume and weight is also low [20].

A. Back-Up Power Supply

Conventional back-up power supplies use engine generators and supply power to the load via a UPS system. Output waveform of an engine generator is generally distorted; therefore, through the UPS system, the quality of the supply voltage for the load is improved. In a system with fuel cell back-up power, the engine generator is replaced with a portable fuel cell system. A typical layout of a fuel cell based back-up power system used in conjunction with a UPS is shown in Fig. 19.

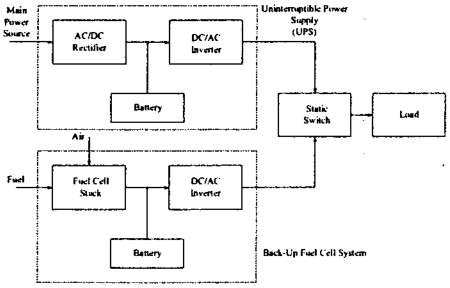

Fig. 19. Block diagram of a fuel cell back-up power supply.

In the case of a power failure in the system of Fig. 19, the UPS system supplies the load with the required AC power through the inverter. During this time period, the battery voltage reduces and upon reaching a pre-determined value, a signal is given to the control unit and the portable fuel cell system begins to warm up [20]. After completion of the warm-up period, the static switch connects the load to the fuel cell system. Therefore, load is fed by the suitable AC power from the fuel cell system.

A fuel cell back-up power supply can be used without the UPS. In fact, there is no need for the UPS when the fuel cell system provides the back-up power for the load. However, in the normal operating mode of the system when the fuel cell back-up power supply is disconnected from the load by the static switch, UPS system can be used to provide an uninterrupted voltage for the load. As is shown in Fig. 20, the UPS and back-up fuel cell based power system of Fig. 19 can be integrated to form a UPS with back-up fuel cell system. As the main advantage, the system of Fig. 20 has only one DC/AC inverter compared to the system of Fig. 19, which has two DC/AC inverters.

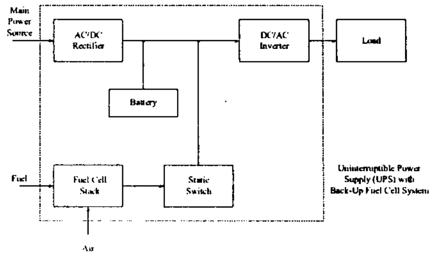

Fig. 20. Block diagram of a UPS with back-up fuel cell system.

VIII. OTHER APPLICATIONS

PAFC has found applications in the telecommunication industry for powering telecommunication equipment as well as for cooling them. This idea has been put to practice in Japan and has been proved to be feasible. These systems can also be used for the purpose of co-generation in telecommunication buildings. They can be operated in parallel with the commercially available power supplies as well [21].

In past years, an engine generator was used to provide power to the telecommunication equipment and cooling devices such as air conditioners in case of an emergency [21]. Approximately 40-50% of the energy consumed in a telecommunication building is by the main equipment, whereas about 30% is utilized by the cooling equipment [22]. The PAFC system, thus, helps in providing the power to both the main as well as the cooling equipment. A typical schematic diagram illustrating a telecommunication energy system based on fuel cells is shown in Fig. 21.

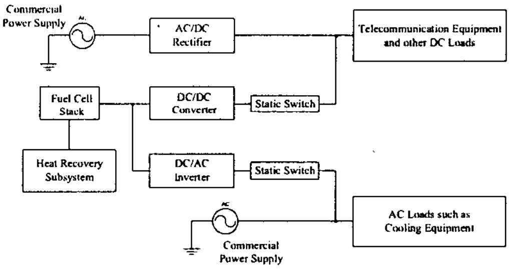

Fig. 21. Typical block diagram of a fuel cell based telecommunication power system.

As is shown in Fig. 21, the fuel cell operates in parallel with the commercial AC power supply. Hence, output can be held constant even under power stoppages due to the maintenance or failure of equipment since the commercial power supply provides the necessary power in absence of the fuel cell. In addition, there are two methods of parallel operation for DC and AC loads. The DC power is supplied to the telecommunication equipment, whereas the AC power output from the DC/AC inverter is fed to the AC loads and cooling devices that, in turn, cool the main equipment. The fuel cell output is kept constant by inverter voltage phase control and, hence, good interconnection characteristics can be observed during load changes [22].

Another application of fuel cells is for mobile power sources, which typically require quicker starts and have a larger number of start-ups, as compared to other commercial power sources [23]. Moreover, they must satisfy high efficiency, low noise, and low emissions requirements.

Fuel cells offer an attractive solution over batteries for underwater vehicles as well. This is because they are highly efficient, quiet, and can be easily refueled. The PEMFC systems have been developed for such applications ranging from 20-30kW. These power units consist of equipment for fluid handling, heat management, and control systems [24].

Another interesting application for fuel cells involves usage in medical devices and gadgets. Reference [25] presents a Micro Direct Methanol Fuel Cell (µDMFC) for medical devices to be implanted into the human body, such as cerebrospinal fluid shunt pump and micro-insulin pump. Some of the factors in favor of fuel cells for medical applications are the compact size, manufacturing simplicity, clean operating features, not producing hazardous materials, and comparatively high efficiency. They are also much more powerful than other related power sources.

IX. CONCLUSIONS

Fuel cells have emerged as one of the most promising technologies for meeting new energy demands. They are environmentally clean, quiet in operation, and relatively efficient for generating electricity. This new technology provides a cost-effective system with greater flexibility to meet the deregulated power generation market criteria, especially for distributed power generation. They also show a great promise to enhance aerospace and vehicular power systems in electric, hybrid electric, and more electric vehicles. They find applications in a variety of transportation systems as well. In addition, various new applications such as portable devices are now being considered wherein the conventional batteries are being replaced by fuel cells.

In this paper, major types of fuel cells, which are on the verge of commercialization or already being used for a variety of applications, have been explained. Basic structures and operating principles have also been described. Furthermore, we have presented that power electronics plays a vital role in improving flexibility of utilizing fuel cells. Common topologies of power electronic converters, which are used in conjunction with fuel cells, have also been studied.

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