

Fuel Cell System and Their Technologies: A Review

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ABSTRACT

Renewable energy generation is quickly rising in the power sector industry and extensively used for two groups: grid connected and standalone system. This paper gives the insights about fuel cell process and application of many power electronics systems. The fuel cell voltage drops bit by bit with increase in current because of losses related with fuel cell. It is difficult to control large rated fuel cell based power system without regulating tool. The issue associated with fuel based structural planning and the arrangements are extensively examined for all sorts of applications. In order to increase the reliability of fuel cell based power system, the combination of energy storage system and advanced research methods are focused in this paper. The control algorithms of power architecture for the couple of well-known applications are discussed.

KEYWORDS: Distributed generation; Renewable energy sources; Fuel cell systems; Power-conditioning units; dc/dc converters; dc/ac inverters

I. INTRODUCTION

The price of fossil fuel is increasing step by step because of absence of accessibility. The power system industries are restructuring to renewable energy based power generation as an alternate solution. By considering environmental factors, the fuel cell based energy generation is a most suitable renewable system than solar and wind energy system [1]. Recently, fuel cells are rapidly developed and commercially available with high, medium and low power range applications. In order to reduce the cost of fuel cell, researchers have been focused to improve the reliability and efficiency of the fuel cell based power system [2]. The analysis report shows that the fuel cell market is increasing every year [3].

The first fuel cell was accidentally invented in 1839 by Sir William Robert Grove, however, no down to earth's utilization was found for one more century [2]. General Electric Company (GE) started creating fuel cell in the 1950s and was granted the agreement for the Gemini space mission in 1962. The 1 kW Gemini energy unit framework had a platinum stacking of 35 mg Pt/cm² and execution of 37 mA/cm² at 0.78 V [3]. In the 1960s enhancements were made by joining Teflon in the impetus layer specifically contiguous the electrolyte, as was finished with the GE fuel cell unit at the time. Extensive upgrades were made from the mid-1970s, forward to the reception of the completely fluorinated Nafion layer.

The department of energy (DOE) and national energy technology laboratory (NETL) are mainly concentrated on developing fuel cell based power plants for standalone and grid connected applications [4].

The overall commercialization of fuel cell has not yet come. The two biggest obstructions for commercialization is life time and expense [5]. The lifetime needed by a commercial fuel cell is more than 5000 working hours for light-weight vehicles and more than 40,000 working hours of stationary power with not as much as a 10% decay [6], [7]. At present, most power devices display real execution rot after around a thousand hours of operation [8], [9]. The DOE targets are to

accomplish an existence time of 40,000 h by 2011 with 40% effectiveness for distributed power and 5000-h life by 2015 to 60% efficiency for transportation. Fuel cell technology has many advantages as compared with the other conventional renewable energy sources.

II. TYPES AND OPERATION OF FUEL CELLS

Water electrolysis to produce hydrogen and oxygen gases is a well-known established process. Basically, the principle of a water electrolyser is to convert water and DC electricity into gaseous hydrogen and oxygen, that is to say the reverse of a hydrogen fuel cell. This process was firstly demonstrated by Nicholson and Carlisle in 1800. In the 1820s Faraday clarified the principles and in 1934 he introduced the word "electrolysis". Electrolysis was not used commercially to produce hydrogen from water until 1902 by the Oerlikon Engineering Company. During the same period, Nernst developed the high-temperature electrolyte ZrO₂ with 15% Y₂O₃, this being the basis for solid oxide electrolysis (SOEC) and solid oxide fuel cells (SOFC). In 1951, the first commercially available high pressure electrolyser (30 bar) was presented by Lurgi. Nowadays, low temperature electrolysis technology is available with at least 13 manufactures (3 using alkaline electrolysers and 10 using polymer membranes). On the other hand, SOEC technology is still under development. This technology attracted great interest in the 1980s because of the studies carried out by Donitz and Erdle [3], where they reported the first SOEC results within the HotElly project from Dornier System GmbH using electrolyte supported tubular SOEC. In this program, single cells have been operated during long-term periods with current densities of -0.3 A cm^{-2} and 100% Faraday efficiency at a voltage as low as 1.07V. In addition, Westinghouse Electric Corporation Research and Development Centre contributed to the development of SOEC. They reported Area Specific Resistance (ASR) values of about 0.6 cm² per cell in a seven-cell stack at 1003 °C [4]. Research in high temperature electrolysis has increased significantly in recent years, as will be described in the present review.

2.1. Types of fuel cell

Fuel cells are mainly classified according to the electrolyte and types of fuel used. The main categories of fuel cells available in the market are explained below.

2.1.1. Proton Exchange Membrane Fuel Cells (PEMFC)

Acid polymer is used as the electrolyte and pure hydrogen is used as fuel. The operating temperature of the PEMFC is below 100°C. Now a day, this fuel cell is popular and widely used in vehicle application.

2.1.2. Direct Methanol Fuel Cell (DMFC)

In DMFC, the polymer membrane used as an electrolyte, and the fuel used is methanol. The operating temperature of DMFC is below 60 °C and it is mainly used for portable power applications below 259 W.

2.1.3. Phosphoric Acid Fuel Cell (PAFC)

In PAFC, The liquid phosphoric acid is used as the electrolyte and pure hydrogen is used as the fuel. The operating temperature is around 180 °C. These types of fuel cell are

particularly used as stationary power generators and which is not efficient electrically.

2.1.4. Alkaline Fuel Cell (AFC)

Here, alkaline solutions are used as electrolyte of fuel cell and pure hydrogen is used as fuel. The operating temperature is about 70 °C and which is more stable. This type fuel cell is mainly used as standalone power generators.

2.1.5. Solid Oxide Fuel Cell (SOFC)

This type of fuel cells is widely used as stationary power generator and its operating temperature is around 1000 °C. The solid ceramic electrolyte like zirconium oxide and syngas type of fuels are used in this fuel cell.

2.1.6. Molten Carbon Fuel Cell (MCFC)

Here, Molten carbonate salt suspended in a porous ceramic matrix is used as the electrolyte and hydrocarbon is used as fuel. The operating temperature is around 650 °C and which is mainly used for high power application.

Table 1 Different types of Fuel cell technology

Types of fuel cell	Electrolyte	Operating Temperature	Fuel	Oxidant	Efficiency
Alkaline (AFC)	potassium hydroxide (KOH)	50–200°C	pure hydrogen, or hydrazine	O ₂ /Air	50–55%
Direct methanol (DMFC)	polymer	60–200°C	liquid methanol	O ₂ /Air	40–55%
Phosphoric acid (PAFC)	phosphoric acid	160–210°C	hydrogen from hydrocarbons and alcohol	O ₂ /Air	40–50%
Sulfuric acid (SAFC)	sulfuric acid	80–90°C	alcohol or impure hydrogen	O ₂ /Air	40–50%
Proton-exchange membrane (PEMFC)	polymer, proton exchange membrane	50–80°C	less pure hydrogen from	O ₂ /Air	40–50%
Molten carbonate (MCFC)	molten salt such as nitrate, sulphate, carbonates	630–650°C	hydrocarbons or methanol	CO ₂ /O ₂ /Air	50–60%
Solid oxide (SOFC)	ceramic as stabilised zirconia and doped perovskite	600–1000°C	natural gas or propane	O ₂ /Air	45–60%
Protonic ceramic (PCFC)	thin membrane of barium cerium oxide	600–700°C	hydrocarbons	O ₂ /Air	45–60%

2.2. Fuel cell operation

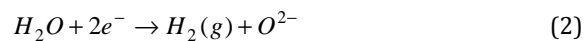
The working principle of the fuel cell is simple, however, it has complicated design. Fuel cell essentially comprises of cathodes, electrolyte and fuel. The positive and negative terminals are known as cathode and anode, respectively. These are two terminals are contacted with the electrolyte inside and external electric circuit. The fuel is continuously fed to the anode while oxidant supplied to cathode. Generally, the fuel is pure hydrogen or contains some hydrogen gases like methanol, ethanol and natural gases. The oxidants are pure oxygen or contains oxygen gases like air or halogens like chlorine [20], [21], [22].

In most of the cases, the combustion of Hydrogen and oxygen produces the water and it will split into two electrochemical reactions at the electrode independently, which are termed as two cell reaction. The basic reaction taking place in a fuel cell is given in Eqs. (1), (2), (3).

The overall reaction of the water electrolysis is:



The reactions in the cathode and anode sides are:



III. RECENT DEVELOPMENT IN FUEL CELLS

The optimal selection of size of the fuel cell is important to locate the fuel cell in distributed system to meet the peak load demands for different applications of utilities [21]. The various intermediate ranges of different fuel cells available in markets from 0.5 kW to 2 MW are given in this classical paper [10]. Particularly the research is focusing on PEM,

MCFC and SOFC fuel cells, to reduce the cost of the fuel stacks and to increase their life span more than 40,000 h. At present a 7 kW capacity PEMFC development is carried out by plug power for residential applications and 250 kW capacity is under tested condition by Ballard power generation system. The Department of Energy (DOE) and Fuel Cell Energy, Inc. have researched MCFCs heavily for stationary power applications. A 1.2 MW system is largest distributed generation power plant located at Santa Clara, CA and for the commercialization purpose the development of 250, 300 and 400 kW capacity MCFC for cogeneration is researched in various countries such as Europe, Holland, Italy, Germany and Spain [5], [6], [7], [8], [9], [10], [13]. The SOFC has likewise achieved success in stationary power applications. Siemens Westinghouse has developed and tested a 250 kW hybrid system that has achieved efficiency of 52% and the efforts are also going on to develop the SOFCs in different ratings as 1 and 25 kW. They are also developing a high efficiency 5 kW SOFC-GT system to reduce its high installation cost. More over further research is focusing on PEMFC and PAFC systems for the combined heat and power generation [13], [17], [18], [19]. The research is also focusing on development of 100 kW to 1 MW DMFC and other fuel cell types such as DFAFC, DEFC, PCFC and DBFC for commercial applications [11], [12], [13], [14], [15], [16], [20].

3.1. I-V characteristics of fuel cells

The fuel cell voltage is usually very small, around 1.2 V. Due to their low output voltage it becomes necessary to stack many cells that need to be connected in cascaded series and parallel form to increase its power capacity. A typical fuel cell polarization characteristic with electrical voltage against current density is shown in Fig. 1[22]. It can be seen that a linear region exists because as the current density increases the voltage drops due to its ohmic nature. This region is called ohmic polarization, it is mainly due to internal resistance offered by various components. At low current level, the ohmic loss becomes less significant; the increase in output voltage is mainly due to activity of the chemical reactions (time taken for warm up period). So this region is also called active polarization. At very high current density the voltage fall down significantly because of the reduction of gas exchange efficiency, it is mainly due to over flooding of waters in catalyst and this region is also called concentration polarization.

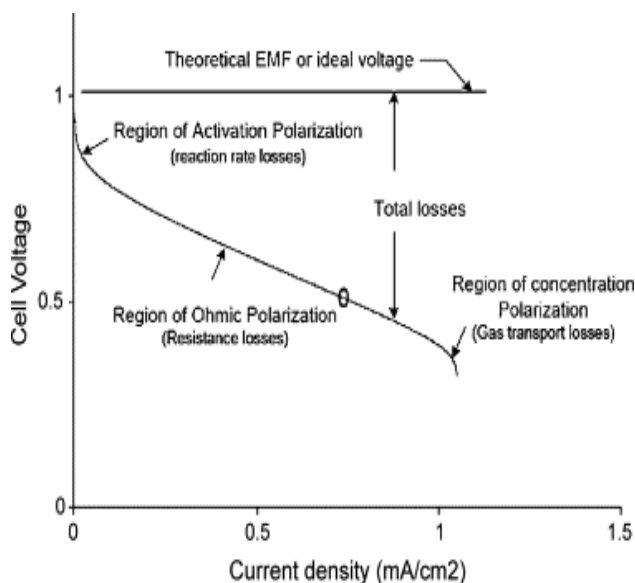


Fig.1. Typical fuel cell polarization curve

The performance of the fuel cell is improved by thermodynamics and electrical efficiency of the system. The thermodynamic efficiency depends upon the fuel processing, water management and temperature control of the system. But the electrical efficiency depends on the various losses over the fuel cells like ohmic loss, activation loss and concentration loss. In reality, the fuel cells differ in terms of characteristics, material used in construction and their suitability of applications. This includes military, space, portable devices, residential, stationary and transportation applications [5], [13].

IV. POWER-CONDITIONING UNITS (PCUS)

Looking to the drooping characteristics of fuel cell the development of power-conditioning units (PCUs) plays an important role to interface the fuel cell system with standalone/grid-connected system. The available fuel cell in the market is only in the range of 25–50 V due to its higher production cost. The generated fuel cell voltage is converted into directly ac supply by using single stage dc/ac inverter topologies or by a combination of a dc/dc converter in series with dc/ac inverter forming multistage conversion as shown in Fig. 2[35].

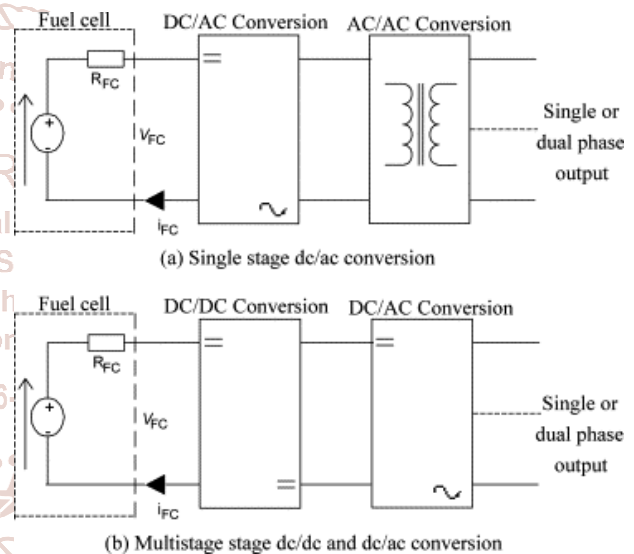


Fig.2. Schematics of fuel cell power electronic-conditioning systems

The selection of power-conditioning unit is based on some significant factors like lower cost, higher efficiency, electrical isolation, ripple free and reliable operation. The efficiency of the power-conditioning unit depends upon the conduction and switching losses. The conduction losses can be effectively reduced by reducing the usage of components and their operating ranges. The switching losses can be reduced by soft switching techniques either by zero voltage crossing (ZVS) or zero current crossing (ZCS) techniques. The major advantages of soft switching technique over hard switching conditions are to reduce the losses over the device by about 20–30% [36]. In order to reduce the cost and to increase their reliability the selection of topology must have reduced component count. More over an electrical isolation is required to protect the fuel cell stacks under overload conditions.

With the ideologies of fuel cell requirements and operations, several dc/dc converters and dc/ac inverter topologies are researched [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51]. In dc/dc converters

the efficiency of the conventional boost converter is always greater than the other converter topologies like push pull, half bridge, full bridge, etc., because it has reduced component counts and simplicity in control. But for the protection point of view electrical isolation is not possible in boost converter as shown in Fig. 3. However for isolation and high boost ratio, push pull, half bridge and full bridge can be considered as candidate topologies [37]. Fig. 4 shows a push pull converter is used to reduce the conduction loss in switches by operating only one switch at any time to interface the fuel cell voltage to dc bus. But the major problem is the transformer saturation which results in converter failure because the two half portions of the center tap transformer windings cannot be equal or symmetrically wound. Therefore it is suitable for low and medium power applications only [38]. Though the half bridge converter as shown in Fig. 4 is suitable for high power applications, it requires large value of secondary/primary transformation ratio to deliver the desired output voltage or it requires large value of dc link capacitors to eliminate the transformer saturation that increases cost of the converter [36]. The full bridge converter as shown in Fig. 5 is suitable for high power applications compared to half bridge. Though it has more components, it has an advantage of reduced device current ratings, transformer turns ratio and the voltage and current stresses are small compared with other topologies [40], [41].

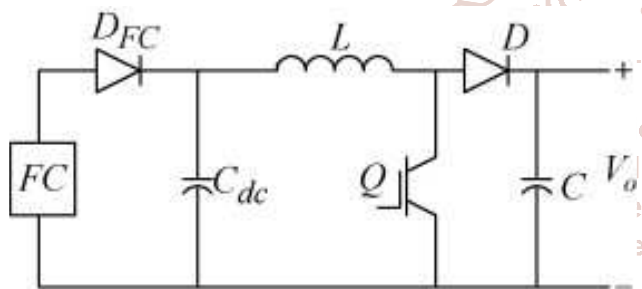


Fig.3. Non-isolated dc/dc boost converter.

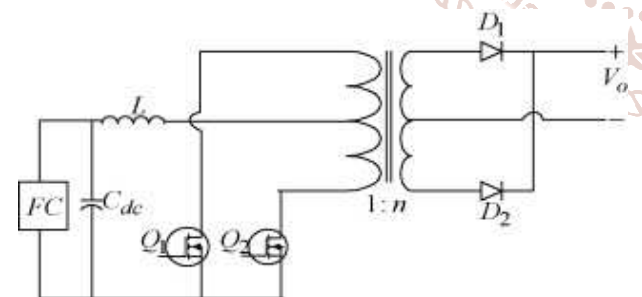


Fig.4. Push pull converter.

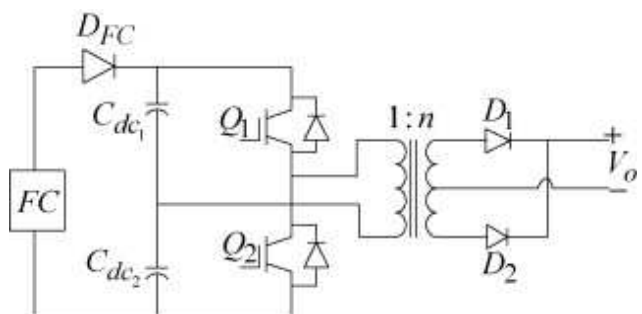


Fig.5. Isolated half bridge dc/dc converter.

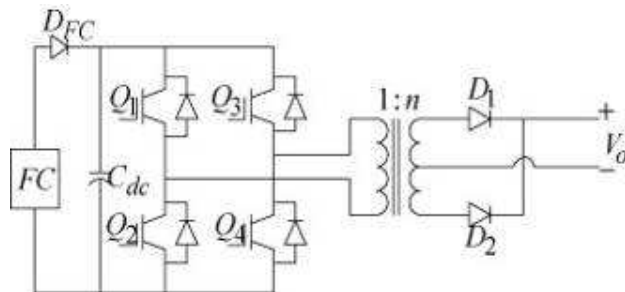


Fig.6. Isolated full bridge dc/dc converter.

Development of dc/ac inverters topologies are also studied based on their relative characteristics under operating conditions. From this paper [38], [42], it is clear that for single phase loads single phase 3 wire inverter shown in Fig. 7 is the best choice compared to single bus inverter with two paralleled half bridge inverter and dual bus inverter with two split half bridge topologies, because it satisfies the ultimate basic requirements of reduced components, simple design and control.

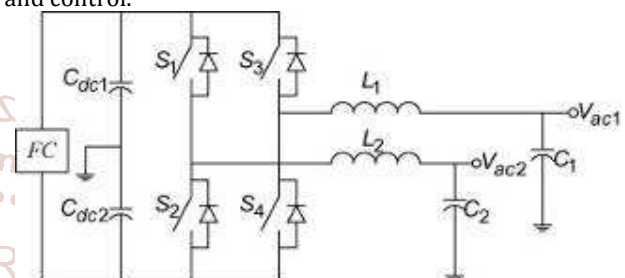


Fig.7. Single bus inverter with two paralleled half bridge topology.

V. FUEL CELL APPLICATIONS

Fuel cells are used in many applications including distributed generation (DG), automotive application and telecommunication application. In all these applications, the technical, economic and environmental advantages of fuel cells are exploited. Some of the specific applications of fuel cell are explained in the next subsections.

A. Fuel cell vehicle

Fuel cells are a promising innovation in transportation. The main objective of the automotive industry is to improve the fossil fuel efficiency and reduce the harmful gas emission. Because of this fact, the growth of fuel cell rapidly increases in e-vehicles applications [24]. A fuel cell vehicle is becoming popular and attracts more due to the absence of internal combustion engines. Also, it has the advantages of simple construction with more reliable and pollution free. The main challenge of fuel cell based vehicle is to convert and control of the electrical power to mechanical power. Fig. 3 shows the fuel cells are becoming more attractive in the automotive industry. The main challenge in using fuel cell for vehicle application is to convert the power generated to mechanical power and controlling of the generated electric power. Fig. 3 shows the generalized block diagram of a heavy duty fuel cell powered transit bus [25].

B. Telecommunication

Fuel cells are popular in telecommunication systems [31], [32]. The fuel cell framework is currently under test by the distinctive telecom organization in worldwide for backup application. Giuseppe Gianolo et al. have been proposed a new system named electro7 fuel cell power system for telecommunication application [33].

C. Underwater vehicle

Recently, the fuel cells are used in submarines and ships. In ships, the fuel cells can be used as an advanced electric ship demonstrator (AESD). However, the space occupied by a fuel cell system is large and it has to be taken care. Due to higher environment temperature caused by fuel cells, the special consideration needs to be provided for other sensitive major components and ship's crew. The choice of fuel cell must be able to withstand the under level temperature and humidity of ship fuel, however, such a fuel cells are industrially accessible [34]. PEMFC is appropriate for maritime applications in light of its low working temperature, quick switch-on/switch-off conduct, and long service life. PEMFC module could be incorporated into the Advanced Electric Ship Demonstrator. The combination of the energy unit modules into AESD obliges a strong force moulding framework [35].

VI. CONCLUSIONS

This paper presents a detailed review of the fuel cell, which includes the chemical and electrical aspects of the fuel cell. Moreover, the working principles of the fuel cells and the different types of fuel cells available in the market have been reported. The investigation has been made against different applications of the fuel cells. The current and research challenges in the fuel cells and its solutions are addressed with reference of the recent articles. Different typologies of the power electronic converters that can be used for fuel cell applications are discussed. The issues of standalone and grid connected fuel cell based power system are mentioned.

The literature review clears that the fuel cells are used in many applications which includes Electric vehicles, power generation and in space ships, etc. As addressed the research challenges in this paper are to be incorporated for better utilization of the fuel cell technology efficiently. In addition, it is identified that the low voltage output is the main drawback of fuel cell in electrical application and in order to mitigate this issue a higher gain and efficient power electronic converters has to be developed. Furthermore, it is evident that by the year of 2030, the fuel cell replaces the conventional internal combustion engines in all commercial vehicles.

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