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Materials and Power Management Systems in Fuel Cell Applications

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Abstract

The increasing reliance on electrical energy has become indispensable across diverse sectors, encompassing housing, public infrastructure, industry, lighting, transportation, and healthcare. However, this reliance has prompted the use of fossil fuels for electricity generation, leading to significant environmental challenges. Consequently, there is a continuous exploration of alternative energy sources that are more environmentally sustainable. Fuel cells have emerged as promising systems for electricity generation because they can produce electricity while emitting water vapor as waste. Hydrogen, the fuel source for fuel cells, is not naturally available in its pure state on Earth, necessitating its extraction from various sources. The production of hydrogen poses environmental challenges as it requires specific methods. Fuel cells can be broadly classified into two categories: chemical and biological. These cells are fabricated using a variety of materials, including metals and carbon. To ensure the efficient utilization of the electrical energy generated by fuel cells, power management circuits are employed. This study aims to provide comprehensive insights into the essential features, types, applications, environmental implications, and power management circuits associated with fuel cells.

Keywords: Fuel cell, materials, electrode, power, electrical devices

1. Introduction

Fuel cells are briefly defined as devices or systems that convert chemical energy into electrical energy. The chemical energy in question here is hydrogen, which is utilized as a fuel in fuel cells. The important features that distinguish a fuel cell from a battery are that there is no need for charging for electricity generation and that electricity production continues as long as fuel is provided.

In recent studies, the following benefits have been cited as the reason why fuel cells have been identified as one efficient energy conversion device:

- They are environmentally friendly.
- They only release water as a by-product.
- They do not contain moving parts.
- They work silently

Topics covered in this study are given below:

- Information about the basic properties of fuel cells.
- Types of fuel cells.
- Application areas of fuel cells.
- Environmental effects of fuel cells.
- Power management circuits of fuel cells.

2. Fuel cells and essential properties

A fuel cell essential consists of an anode, cathode, and electrolyte. Membranes that act as electrolytes are used in some fuel cells. Fuel cells with a membrane consist of two parts, the anode segment and the cathode segment. In a conventional fuel cell, fuel (hydrogen) is continuously supplied to the anode. In other words, the anode is fed with hydrogen. Usually, oxygen from the air or any oxidant is continuously supplied to the cathode. That is, the cathode is constantly supplied with oxygen or another oxidant. The electrochemical reactions required for the fuel cell to produce electrical energy take place at the electrodes (anode and cathode). Electrical charge movements occur due to the reactions taking place at the electrodes. Thanks to these charge movements, electrical energy is produced by the fuel cell.

The reaction occurring at the anode of fuel cells is given in equation (1).

Anode reaction: $H_2 \rightarrow 2H^+ + 2e^-$ (1)

The reaction occurring at the cathode of fuel cells is given in equation (2).

Cathode reaction: $H_2 + 2e^- + \frac{1}{}O_2 \rightarrow 2H^+ + 2e^-$ (2)

The total reaction of the anode and cathode are given in equation (3).

Total reaction: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{Energy}$ (3)

Explanation of equations (1), (2), and (3) in a little more detail reveals the following information:

Hydrogen gas reacts at the anode, it releasing hydrogen ions and electrons. Hydrogen ions migrate to the cathode through the electrolyte or membrane. The membrane does the task of the electrolyte. Electrons migrate to the cathode via the external circuit. At the cathode; hydrogen ions, electrons and oxidant combine. As a result of this union, water is released and energy (electricity and heat) is produced as the electrical charge balance is achieved. Electrons are in a stable state and they are particles that perform electrical and chemical interactions [5]. Hydrogen ions in fuel cells duty as protons. The proton is in a stable state, that is, when the particle retains its protecting properties for a long time without undergoing physical and chemical changes.

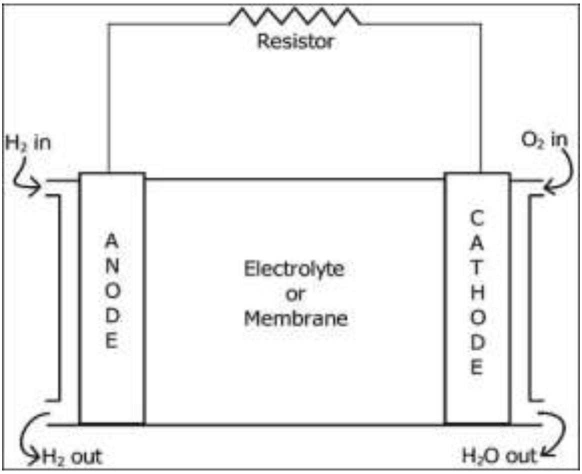


Fig 1: Example schematic diagram of fuel cell

Fuel cells were classified according to their application areas as follows

- Applications with high power reliability.
- Applications related to emission minimization or elimination.
- Applications covering locations with insufficient access to the electricity grid.
- Biological waste gas management applications.

Activities establishing the principle of “high power reliability” include:

- Facilities of high technology fabricating.
- Activity of data processing and call centres.
- Action of telecommunication.

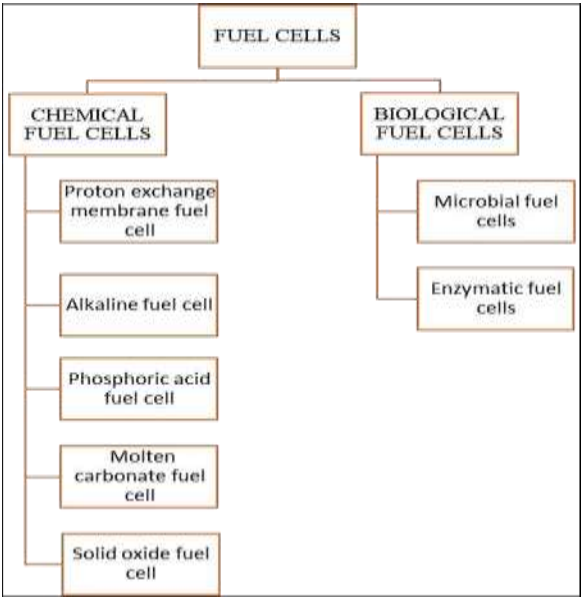


Fig 2: Fuel cells and their subcategories

Applications related to emission minimization or elimination following covered :

- Town like locations
- Vehicles
- Industrial foundations
- Air stations

Applications for areas with limited access to the electrical grid following contain :

- Portable applications.
- Remote areas.

The biological type waste gas governance practices have prioritized only one thing :

- Waste treatment plants.

Fuel cells are divided into two main categories, chemical and biological. The most mentioned chemical fuel cells in the literature are alkaline fuel cell, proton exchange membrane fuel cell, molten carbonate fuel, phosphoric acid fuel cell and solid oxide fuel cell. Biological fuel cells have been mentioned in the literature in two basic categories, these are enzymatic fuel cell and microbial fuel cell .

Microbial fuel cells are fuel cell systems that convert the chemical energy stored in the chemical structures of organic substances directly into electrical energy through microorganisms. While hydrogen is employed as fuel in fuel cells, the fuel source of biological (microbial and enzymatic) fuel cells is biomass (organic substances). Enzymatic fuel cells are systems that turn the chemical energy of organic materials straight into electrical energy through enzymes. Various biomass is utilized as fuel sources in enzymatic fuel cells. Because biomass is an abundant and renewable resource and it contains approximately 66% (w/w) sugar.

3. Environmental impact of chemical fuel cells

The main factor that reveals the need for fuel cells is the increase in the want for energy due to the increment in inhabitants. The need for energy has paved the way for the rapid depletion of energy resources. Most of the energy is still supplied from fossil sources. However, there are many harmful aspects of fossil fuels, which are given below:

- Their prices fluctuate erratically and unstable.
- It causes global warming and other more serious health problems.
- It is a limited resource that harms the environment.

Chemical fuel cells need hydrogen to operate, that is, they need hydrogen for producing electricity. Hydrogen does not exist in nature in pure form. Therefore, it is necessary to purify hydrogen from various sources. For this, carbon-containing sources are generally preferred and special production methods are used. It is stated that proton exchange membrane fuel cells (PEMFCs), one of the chemical fuel cells, do not spread noxious gases to the nature due to their structure. However, it is obvious that there is a serious greenhouse gas emission due to the production functions of hydrogen used as fuel. Hydrogen production methods and greenhouse gas emissions are given in Table 1. As can see here, the hydrogen production employment has a significant effect on global warming. In addition, even if renewable resources (solar and wind) are used for hydrogen production, the emergence of greenhouse gas emissions is an indirect problem for fuel cells, although not directly.

Table 1: Hydrogen production sources and greenhouse gas emissions

Hydrogen production source	Greenhouse gas emissions quantity
Gasoline and crude oil	84 g/MJ
Solar energy	30.6 g/MJ
Wind energy	20.55 g/MJ

In a study in which the environmental effects of the molten carbonate fuel cell (MCFC) are investigated in detail, raw materials and energy cover of the following topics:

- Fuel

- Water
- Minerals
- Plastics
- Metals
- Solvents

In literature, considering the raw material and energy relationship, raw material and energy input flows were investigated in detail for the MCFC with a maximum power of 500 kW. Table 2 presents the various findings from this MCFC.

Table 2: Raw material and energy input events for MCFC

Fuel cell type	**Global warming potential (CO_2-eq/kWh)**	**Terrestrial acidification (kg SO_2-eq)**	**Water consumption potential (m^3)**	**Fossil resource scarcity (kg oil-eq)**	**Mineral resource scarcity (kg Cu-eq)**
MCFC (unit/kWh_{el})	5.49E-01	5.06E-04	8.54E-02	1.87E-01	6.12E-04

One of the application areas of fuel cells is automotive. The comparison of fuel cell automotive and other technologies in a study comparing the environmental impacts associated with automotive production stages is given in Table 3 [20]. As can be understood from here, fuel cell automotive technology causes higher greenhouse gas effect and higher air pollution than others. Therefore, more environmentally friendly production technologies should be developed for the materials that make up the fuel cells. In order to produce hydrogen, which is the fuel of the fuel cell, more environmentally friendly and sustainable technologies should be discovered.

Table 3: Automotive production stages and environmental impact relationship

Automotive (car) type	**Curb mass (kg)**	**Greenhouse gas emissions (kg)**	**Air pollution emissions (kg)**	**(a)100 km of vehicle travel (100 km)**	**100 km of vehicle travel (kg per 100)**
Conventional	1134	3595.8	8.74	1.490	0.00362
Hybrid	1311	4156.7	10.10	1.722	0.00419

Electric	1588	4758.3	15.09	1.972	0.00625
Fuel cell	1678	9832.4	42.86	4.074	0.0178
(a) During vehicle's life time (10 years), an average car drives 241,350 km					

4. Materials used in fuel cells

Although chemical fuel cells mainly consist of an anode, cathode, electrolyte or membrane, they also contain structures such as catalysts, gas diffusion layers and bipolar layers. The performance of the fuel cell decreases as mechanical, chemical or thermal degradation occurs over time. Therefore, the durability of the materials is a very important factor.

The gas diffusion layer is a microporous layer fabricated from a carbon fibre-based macroporous substrate. This layer is coated with carbon nanoparticles and a hydrophobic material (commonly polytetrafluoroethylene (PTFE)). The gas diffusion layer is situated between the coils of the bipolar sheet and the electrode. It operates both the water entering the cell with moistened reactants and the water produced by the electrochemical activities. Therefore, proper water management of fuel cells is critical to ensure their proper operation and continued efficiency. Gas diffusion layer’s chemical degradation can be caused by polymer degradation or carbon corrosion. Therefore, a slight decrease in hydrophobicity occurs. Concentration polarization losses must be minimized in order to limit the water production due to the anode and cathode reactions and to acquire higher overall efficiency. For this, low current density values should be preferred.

Bipolar sheets act as a barrier between the various cells that make up the fuel cell stacks. However, it prevents the reactants from mixing inside the cell and does its job to help remove heat. In this way, it prevents a local accumulation of thermal energy in the fuel cell. It is mostly made of stainless steel, copper, aluminium, and carbon-based materials (carbon black, graphite flakes or lumps, carbon fibres, graphene, expandable graphite, carbon nanotubes, expanded graphite, polymer-carbon composites, etc.). Corrosion products (for example metal ions) emerging in bipolar layers degrade the membrane and fuel cell anode and reduce fuel cell performance. Although coating the surfaces of the bipolar layer with a protective coating is one way to prevent corrosion, this process leads to a serious cost increase.

In proton exchange membrane fuel cells, there is no liquid electrolyte, herein polymeric membranes such as solid Nafion/solid composite, Nafion is used. In solid oxide fuel cells, ceramics like solid yttria-stabilized zirconia is used as electrolyte. Liquid carbonate (lithium, sodium, potassium based carbonates, etc.) solution is used as the electrolyte in molten carbonate fuel cells. In phosphoric acid fuel cells, liquid phosphoric acid is used as the electrolyte. Liquid-state sodium hydroxide (NaOH) or liquid-state potassium hydroxide (KOH) is used as electrolytes in alkaline fuel cells. Recently, there has been talking of anion exchange membrane alkaline fuel cells introduced more contemporary.

Platinum is used as the anode material in proton exchange membrane fuel cells and alkaline fuel cells. While nickel is used as the anode material in alkaline fuel cells, nickel and yttria-stabilized zirconia cermet materials are used in solid oxide fuel cells. Nickel, chromium and aluminium alloys are used as anodes in molten carbonate fuel cells. Cathode materials used in proton exchange membrane fuel cells, alkaline fuel cells, solid oxide fuel cells and molten carbonate fuel cells are respectively; nickel, activated carbon, platinum, perovskite and porous nickel have been reported.

The catalyst is very important for efficient hydrogen oxidation reactions at the anode of fuel cells and for efficient oxygen reduction reactions at the cathode. Carbon-based materials, metal-based materials (platinum, palladium, ruthenium, gold, silver, cobalt, copper, iron, nickel, etc.) and various metal oxides (Co_3O_4, manganese oxides, nickel oxides, etc.) are widely used catalyst materials in fuel cells.

Carbon-based (graphite, carbon fiber, carbon felt, etc.) materials and metal-based (platinum, zinc, copper, aluminium, titanium, silver, etc.) materials are used as anode or cathode materials in microbial fuel cells.

Looking at recent studies, metal-based and carbon-based electrodes have been tested in enzymatic fuel cell research. The best example of metal-based materials used in the electrodes of enzymatic fuel cells is gold. In addition, carbon nanotubes have emerged as the best example of carbon-based materials used in the electrodes of enzymatic fuel cells.

5. Power management circuits used in fuel cells

Fuel cells produce direct current (dc) power. The power management of fuel cells can be done using a dc-dc converter. Besides the power management of fuel cells can be done without the need for a dc-dc converter. The fuel cell stack and ultracapacitor voltage level matching system are shown in Figure 3. It should be noted that the voltage provided by the fuel cell systems is equivalent to the ultracapacitor voltage. In this way, there is no need to use a bidirectional dc-dc converter .

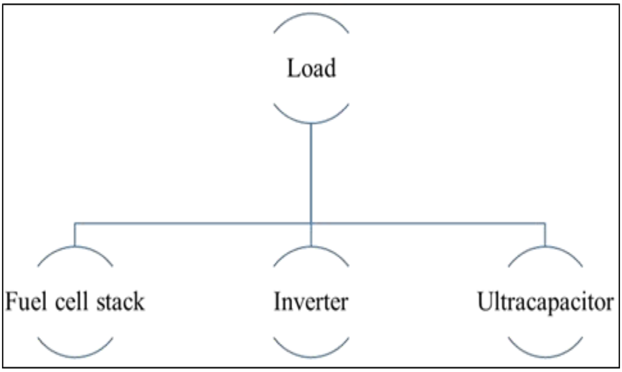


Fig 3: Example diagram of the energy management system of the energy produced by the fuel cell

The use of a bidirectional dc-dc converter is beneficial when a low-voltage battery and high-voltage fuel cell system are present. The circuit diagram in question is shown in Figure 4. Here, the bidirectional dc-dc converter does the duty as the core of the energy management system.

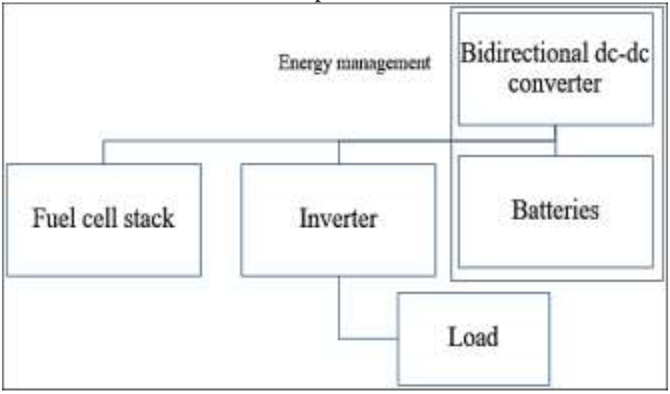


Fig 4: Use of a bidirectional dc-dc converter in fuel cells and energy management

DC-DC converters are very important for power management of fuel cells. Isolated major login range dc-dc converters are available for fuel cell power conditioning. The dc-dc converter operation, which can be an example of this, is given in Figure 5. Fuel cell systems demand an alternative energy source to provide energy in the face of sudden load demands. Ultracapacitors are of great importance in fuel cell power management circuits as they are a feasible aspirant for energy storage. The dc-dc converter developed for fuel cells and support for power conversion covers of two segments to power up the energy. The first segment includes providing low ripple as well as reducing voltage and current fluctuations of power devices. For this, it consists of two current-fed boost converters depended in parallel to have a smaller inductor dimension. Initial boost and regulation of the fuel cell module voltage is succeeding owing to the first boost part. Herein pre-regulation of the voltage to 80 volts is achieved. In these simulations, voltage of fuel stack is regulated in a wide range from 40 volts to 60 volts, up to about 70 volts, due to possible switching and conduction losses over the circuit components. The first boost stage was operated at a frequency of 100K Hz with less than 50% duty cycle for the power switches. Cum this design, approximately 97% efficiency was achieved for the first step-up converter. In addition, the efficiency of the converter has increased significantly, with a mission cycle almost 50%. An ultracapacitor is used after the first boosting stage to supply energy during spike load needs. If the module cannot supply the power required by the load, the ultracapacitor temporarily maintains the voltage of the first step-up converter. The second stage is the process in which the upgrading job takes place. Here it is used with an isolated two-inductor step-up converter covering of two coupled inductors L1 and L2 to provide a certain voltage boost with switches S5 and S6. At the output of the second boost converter, galvanic isolation with 1:3 turns for the firstly and secondary windings assures an additional signal boost. The rectification of the signal is provided by the synchronous switches S5' and S6' at the load end. A decisive high dc voltage is achieved. Synchronous switches are preferred over diodes. Because MOSFET turn-on voltage losses are much lower confronted to diodes. Thus, it helps to obtain higher efficiency. The second boost converter is used at frequencies of 20 KHz succeeding with a converter efficiency of almost 94%.

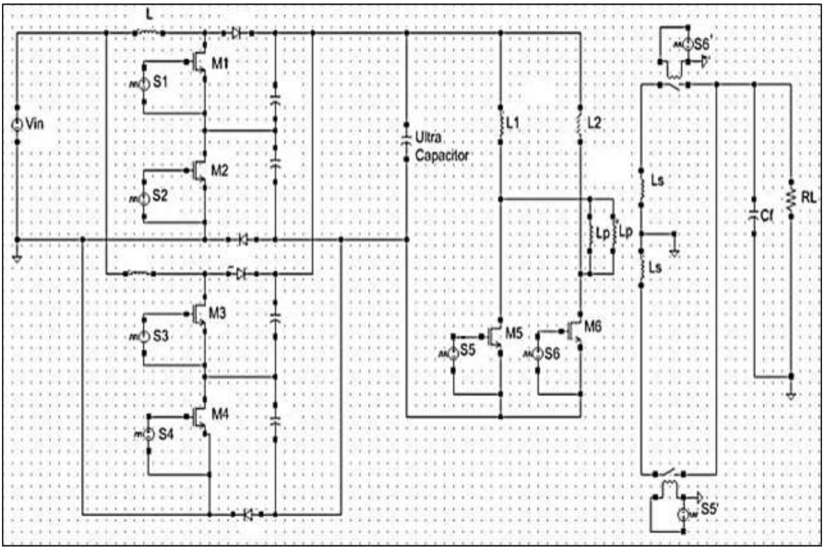


Fig 5: Example of equivalent circuit of major login range dc-dc converter [35]

The energy management strategy (EMS), which includes fuel cells, is divided into two main headings. These

1) Rule-based EMS.
2) Optimization-based EMS.

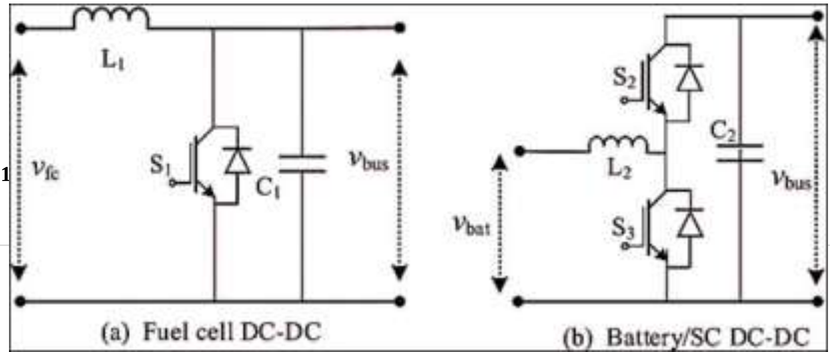
Rule-based EMS is again divided into two groups and is as follows [36]:

a) **Deterministic approach:** Thermostat on/off approach, filter-based approach, state machine approach and others.
b) **Fuzzy approach:** Conventional approach and adaptive fuzzy approach.

Optimization-based EMS is again divided into two groups and is as follows [36]:

a) **Global optimization:** Dynamic programming etc., stochastic search (genetic algorithms, particle swarm optimization, etc.).
b) **Real-time optimization:** Equivalent consumption minimization strategy, EDMS, etc., model predictive control, intelligence (neuro network, reinforcement learning).

Direct current to direct current (DC-DC) converters are used to control the output power of the fuel cell system. A unidirectional DC-DC converter that can control only one direction is generally preferred for fuel cells, electric machines or photovoltaic solar cells. There are DC-DC converters with the ability to control bidirectional power flow, usually applied to batteries or super capacitors (SC) and other energy storage devices. These are called bidirectional DC-DC converters. An example of a unidirectional DC-DC converter circuit is given in Figure 6(a) and an example of a bidirectional converter circuit is given in Figure 6(b). In Figure 6(a); L_1 is the inductor used in the fuel cell circuit, S_1 is a transistor used in the fuel cell circuit, C_1 is a capacitor used in the fuel cell circuit, V_{FC} is the fuel cell voltage (input) and



(a) Fuel cell DC-DC

(b) Battery/SC DC-DC

V_{bus} is the output voltage of the circuit. In Figure 6(b); L_2 is the inductor used in the fuel cell circuit, S_2 is a transistor used in the fuel cell circuit, C_2 is a capacitor used in the fuel cell circuit, V_{bat} is the battery input voltage and V_{bus} is the output voltage of the circuit.

Fig 6: Schematic examples of fuel cell and hybrid power systems DC-DC converters

Conclusion

In conclusion, materials and power management systems represent foundational aspects of fuel cell applications, critical for their efficiency, performance, and longevity. The selection of appropriate materials, including membranes, catalysts, electrodes, and bipolar plates, directly impacts the overall effectiveness of fuel cells in converting chemical energy into electrical energy. Moreover, power management systems play a pivotal role in regulating voltage, current, temperature, and gas flow within fuel cell systems. These systems ensure optimal operation, efficiency, and safety while also addressing challenges such as water and heat management.

As technology advances and research continues, further innovations in materials science and power electronics will likely lead to enhanced fuel cell performance, reduced costs, and broader adoption across various industries and applications. Ultimately, the integration of advanced materials and sophisticated power management systems will contribute to the continued evolution and success of fuel cell technology as a clean and sustainable energy solution.

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