Review on Selection of Fuel Cell for Powering Electric Vehicle

Mahesh Bodke
PG Scholar
Dept. of Electrical Engineering
M.C.O.E.R.&C, Nashik

Dr. Rakesh.G. Shriwastava
Professor
Dept. of Electrical Engineering
M.C.O.E.R.&C, Nashik

Prof. Rajesh U. Shelke
Head of Department
Dept. of Electrical Engineering
Govt Polytechnic, Nashik

Abstract-The scientific world of automotive technology in present state is more concerned towards eradication of the fossil fuel based Internal combustion engine, and the traction system needs a substitute which is both eco-friendly and economical. These concerns have mounted due to issues of pollution and finite status of fossil fuel, and conventions related to global climate change. Engineers have focused into seeking a clean and sustainable energy source for our ever increasing energy demands. Alternate fuel systems like Hydrogen, Ethanol from Biomass, and others are looked around for the optimal replacement of fossil fuels, particularly in the domain of transportation sector which houses the quantum consumption globally.

Fuel Cell Technology is seen as good option for supporting the Electric vehicle scenario, which also acts as a replacement for the internal combustion engine system. There are many Fuel cell technologies based on different cell configuration and fuel used. The best design for Electric vehicle is still a point of debate, and it is likely to be different for various combinations of operating conditions, working loads and desired sizes.

Keywords-Fuel cell, Electric Vehicle, PAFC, PEMFC.

I. INTRODUCTION

A fuel cell is an electrochemical reactor that converts the chemical energy of a fuel and an oxidant directly to electricity. Fuel cells are seen by many people as key solutions for the 21st century, enabling clean efficient production of power and heat from a range of primary energy sources. Fuel cells are electrochemical devices that use hydrogen (H_2), or H_2-rich fuels, together with oxygen from air, to produce electricity and heat. However there are many variants of this basic process, depending on the Fuel Cell type and the fuel used. This technology is very interesting for a many different applications including micro power generators, auxiliary power generators, stationary power generators, distributed power generators and portable power generators for transportation, military projects and the automotive market. These are all applications that will be used in a large number of industries and environments on a worldwide scale. The first time fuel cell vehicles were in the international spotlight was during the oil crisis in the 1970s. In the next few decades, carmakers from different countries spent various degrees of efforts developing fuel cell vehicles. The year 2014 was marked by the world’s first commercialized fuel cell vehicle by Toyota, representing a culmination of years of R&D efforts. From then on, in the eyes of the public, fuel cell vehicles were no longer experimental, but were recognized as one of the key driving technologies of the future of mobility.

In the next 5 years (till now), countries such as China, US, Japan, and various countries in Europe focused their efforts on driving this technology forward. Through a combination of governmental policy, technology advancement and industrial involvement, fuel cell applications are now entering into a golden era of advancement.[1]

II. LITERATURE STUDY

Fuel cell technology has escalated slowly with major focus on its application in modular devices and space technology. The history of Fuel cell technology can be traced to the discovery of the working principle which major contribution from German scientist C. F. Schönbein in 1838. Based on this work, the first fuel cell was demonstrated by Welsh scientist Sir W.R. Grove in 1839.

Based on these works as benchmarks, further research was carried out to improve this technology and develop it to commercialize the setup. Several German, Japanese and US vehicle manufacturers and their partners began to experiment with FCEV in the 1970s, increasing the power density of PEMFC stacks and developing hydrogen fuel storage systems. By the end of the century, all the world's major carmakers had active FCEV demonstration fleets as a result of these early efforts. The focus by then had shifted back to pure hydrogen fuel, which generates zero harmful tailpipe emissions.
In Germany, Japan and the UK, there began to be significant government funding devoted to developing PEMFC and SOFC technology for residential micro-CHP applications. Government policies to promote clean transport also helped drive the development of PEMFC for automotive applications. PEMFC and DMFC auxiliary power units (APU) were commercialized in leisure applications, such as boats and campervans, with similarly large numbers of micro fuel cell units being sold in the portable sector in toys and educational kits.

Demand from the military also saw hundreds of DMFC and PEMFC portable power units put into service for infantry soldiers, where they provided power to communications and surveillance equipment and reduced the burden on the dismounted solider of carrying heavy battery packs.

A large-scale residential CHP program in Japan helped stimulate commercial stationary PEMFC shipments. These units began to be installed in homes from 2009, and more than 13,000 such units have been installed to date. Demonstration programs for backup power systems in the USA gave further impetus to the stationary sector. This was also driven by practical concerns over the need for reliable backup power for telecoms networks during emergencies and rescue operations.

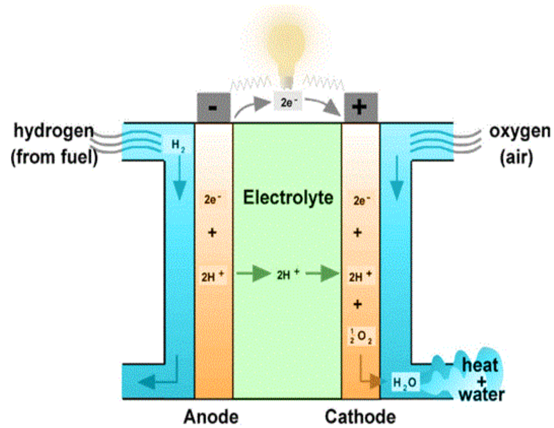

Fig 1.1 – Fuel flow in Fuel Cell

III. CONSTRUCTIONAL DETAILS OF FUEL CELL

A fuel cell is a lot like a battery. It has two electrodes where the reactions take place and an electrolyte which carries the charged particles from one electrode to the other. In order for a fuel cell to work, it needs hydrogen (H_2) and oxygen (O_2). The hydrogen enters the fuel cell at the anode. A chemical reaction strips the hydrogen molecules of their electrons and the atoms become ionized to form H+. The electrons travel through wires to provide a current to do work.

The oxygen enters at the cathode, usually from the air. The oxygen picks up the electrons that have completed their circuit. The oxygen then combines with the ionized hydrogen atoms (H+), and water (H_2O) is formed as the waste product which exits the fuel cell. The electrolyte plays an essential role as well. It only allows the appropriate ions to pass between the anode and cathode. If other ions were allowed to flow between the anode and cathode, the chemical reactions within the cell would be disrupted. The reaction in a single fuel cell typically produces only about 0.7 V. Therefore, fuel cells are usually stacked or connected in some way to form a fuel cell system that can be used in cars, generators, or other products that require power. The reactions involved in a fuel cell are as follows [2]:

Anode side (an oxidation reaction):

$$2H_2 \Rightarrow 4H^+ + 4e^-$$

Cathode side (a reduction reaction):

$$O_2 + 4H^+ + 4e^- \Rightarrow 2H_2O$$

Net reaction (the "Redox" reaction):

$$2H_2 + O_2 \Rightarrow 2H_2O$$

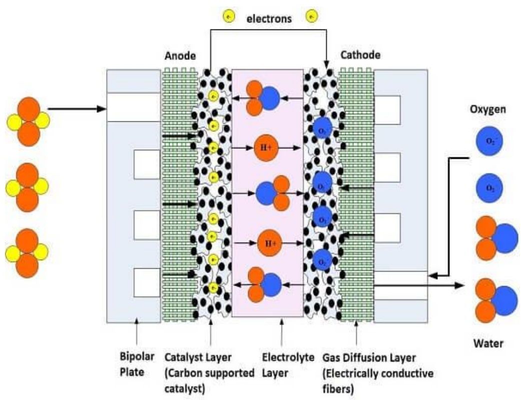

Fig 1.2 Overview of Fuel cell construction

The first step in building a fuel cell is to determine the power requirements needed to power the particular device or application. Fuel cells can be used to power anything including phones, laptops, automobiles, buses, houses, businesses and even satellites. A single fuel cell can be designed to achieve any current required for a particular application by merely increasing or decreasing the size of the active electrode area. The output voltage of a single cell is less than 1 V under realistic operating conditions, but most fuel cell developers use a voltage of 0.6 to 0.7 V at nominal power. However, fuel cell systems can be designed at nominal voltages of 0.8 V per cell or higher if the correct design, materials, operating conditions, balance-of-plant, and electronics are selected. For most applications, a fuel cell stack consisting of many individual cells connected in series is used. The number of cells in a stack is determined by the maximum voltage requirement and the desired operating voltage.

The fuel cell stack power output can be designed by calculating the highest possible power and voltage spike that may occur during device operation and then putting a safety factor into the power design calculation. The essential parts of a fuel cell are: [5]

1. *Proton Exchange Membrane, which helps the chemical reaction inside the fuel cell by allowing the flow of hydrogen protons through the membrane.*
2. *Electrode Backing Layers, which allow fuel and oxidant to travel to the catalyst while collecting electrons.*
3. *Catalyst, which breaks the fuel into protons and electrons.*
4. *Flow-field Plates, distribute the gases and liquids throughout the fuel cell.*
5. *Gaskets, which prevents fuel leakage and helps distribute pressure in the stack.*
6. *Current Collectors, which collect the electrons from the flow-field plates.*
7. *End Plates, provide support and apply compression to the components.*
8. *Clamping Mechanism, which holds the stack together*

IV. FUEL CELL BASED ELECTRIC VEHICLE

Direct combustion of fuel for transportation accounts for over half of greenhouse gas emissions and a significant fraction of air pollutant emissions. Because of growing demand, especially in developing countries, emissions of greenhouse and air pollutants from fuels will grow over the next century even with improving of technology efficiency. Most issues are associated with the conventional engines, ICEs (internal-combustion engines), which primarily depend on hydrocarbon fuels. In this contest, different low-polluting vehicles and fuels have been proposed to improve environmental situation [7].

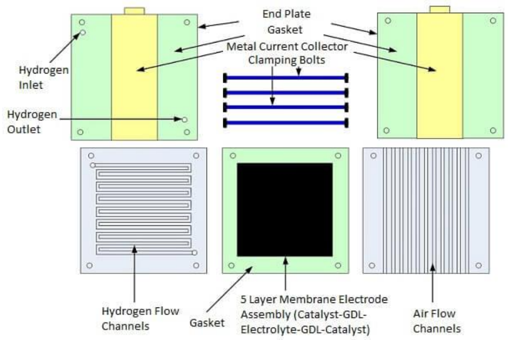

Fig 1.3 – Components in Fuel Cell

Some vehicle technologies include advanced internal combustion engine (ICE), spark-ignition (SI) or compression ignition (CI) engines, hybrid electric vehicles (ICE/HEVs), battery powered electric vehicles and fuel cell vehicles (FCVs). Fuel cell vehicles, using hydrogen, can potentially offer lower emissions than other alternative and possibility to use different primary fuel options.

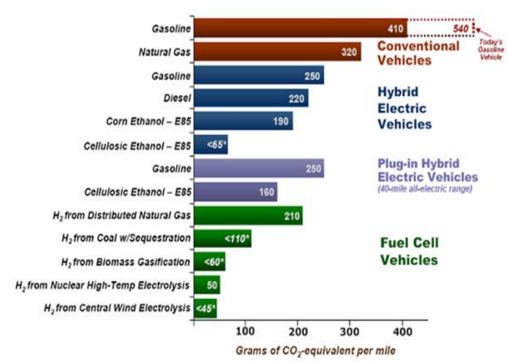

Fig 1.4-Source to Wheel fuel pollution ratings [8]

A fuel cell vehicles fed by pure hydrogen are a “zero emission vehicle”, in fact the only local emission are water vapor. But in this case it is important to consider the full fuel cycle or “source-to wheels” emissions, that includes fuel production, transport and delivery emissions. Primary source for hydrogen production is crucial for the environmental performance of vehicles. Hydrogen produced from renewable energy (i.e. wind or solar power connected with electrolysis process) and used in fuel cells can reduce significantly emissions. An analysis for reductions in emissions and petroleum use is reported in figure above.

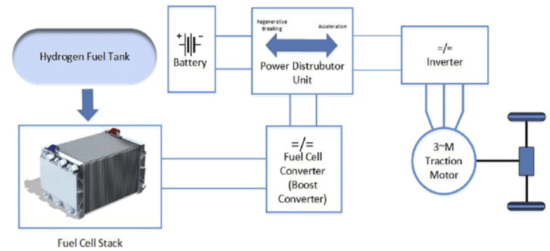

Fig.1.5- Block diagram of FCEV [9]

A. Key Components of a Hydrogen Fuel Cell Electric Car [10]

1. *Battery (auxiliary):* In an electric drive vehicle, the auxiliary battery provides electricity to start the car before the traction battery is engaged and also powers vehicle accessories.
2. *Battery pack:* This battery stores energy generated from regenerative braking and provides supplemental power to the electric traction motor.
3. *DC/DC converter:* This device converts higher-voltage DC power from the traction battery pack to the lower-voltage DC power needed to run vehicle accessories and recharge the auxiliary battery.
4. *Electric traction motor (FCEV):* Using power from the fuel cell and the traction battery pack, this motor drives the vehicle's wheels. Some vehicles use motor generators that perform both the drive and regeneration functions.
5. *Fuel cell stack:* An assembly of individual membrane electrodes that use hydrogen and oxygen to produce electricity.
6. *Fuel filler:* A nozzle from a fuel dispenser attaches to the receptacle on the vehicle to fill the tank.
7. *Fuel tank:* Stores fuel gas onboard the vehicle until it's needed by the fuel cell.
8. *Power electronics controller (FCEV):* This unit manages the flow of electrical energy delivered by the fuel cell and the traction

battery, controlling the speed of the electric traction motor and the torque it produces.

9. *Thermal system (cooling) - (FCEV):* This system maintains a proper operating temperature range of the fuel cell, electric motor, power electronics, and other components.
10. *Transmission (electric):* The transmission transfers mechanical power from the electric traction motor to drive the wheels.

B. Requirements of Power Source

The Fuel Cell power system is the vehicle's main power source, which is specifically installed for transforming the compressed hydrogen fuel chemical energy, to its electrical input energy form that is essentially used to feed-in the traction motor.

The design of the Fuel cell unit is completely dependent on the dimensions, configuration and operational parameters of the vehicle like [11]:

a) *Nominal power of the vehicle*
b) *The required Voltage range (V) for which the fuel cell unit stack needs to be designed.*
c) *The volume of Maximum Current (A) that the vehicle electric system can draw based on the mechanical load and safety limits*
d) *The Air flow per minute through the fuel cell system based on the volume of air passage provided which indirectly works with the space requirement criterion*
e) *The Hydrogen Flow per minute is also important criterion that defines the speed of chemical reaction and heat generation in the unit.*
f) *The purity limits of fuel that is being used (it is good to have high purity)*
g) *The available Volume of fuel cell stack*
h) *The allowable Weight (kg) of the stack*
i) *Air compressor: Designed to reduce size and consumption*
j) *Hydrogen recirculation pump: Designed to reduce size and consumption*

V. STUDY OF VARIOUS FUEL CELLS

Fuel cell classification based on Electrode Type:

1. *Alkaline Fuel Cell*
2. *Sulfur-Phosphoric Acid Fuel Cell*
3. *Proton Exchange Membrane Fuel Cell*
4. *Molten Carbonate Fuel Cell*
5. *Solid Oxide Fuel Cell*

In this paper, selection of Fuel cell for Electric Vehicle application is of major concern. As far as today's technology is concerned, Hydrogen fuel is the most probable fuel input that is certain to be used in Fuel cell. But the process of conversion is depending upon the design of electrode and material used there.

A. Phosphoric Acid Fuel Cell

The electrolyte in the PAFC is a paper matrix saturated with phosphoric acid, transporting the hydrogen ions. The operating temperature is around 200 °C. The operating temperature requires platinum as catalyst which is supported being dispersed on graphite material. But platinum at this temperature is sensitive to CO-poisoning. Cells which use hydrocarbons directly as fuel around 150 °C have low efficiency and current density, thus have been restricted to research investigations.[11]

Phosphoric acid fuel cells (PAFC) use carbon paper electrodes and liquid phosphoric acid (H3PO4) electrolyte. H3PO4 (3.09% H, 31.6% P, 65.3% O) is a clear colorless liquid used in fertilizers, detergents, food flavoring and pharmaceuticals. As shown in illustration, the hydrogen expelled at the anode splits into its 4 protons and 4 electrons. The Redox reaction taking place in anode is oxidation, while at cathode, the redox reaction is reduction where 4 protons and 4 electrons combine with the oxygen to form water:[12]

- (Oxidation) $2H_2 \rightarrow 4H^+ + 4e^-$
- (Reduction) $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

The electrons and protons pass through the external circuit and the electrolyte, respectively.

The result is generation of electrical current and heat.

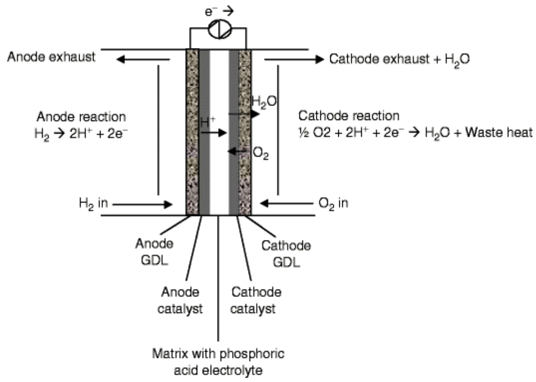

Fig.1.6 – Structure of PAFC[12]

Currently, PAFC systems are in commercial stage with capacity up to 200 kW and systems with higher capacities (11 MW) are already tested. Electrical efficiency of PAFC is between 40 and 50% and CHP efficiency about 85%. They are typically used for on-site stationary applications. [14]

B. Alkaline Fuel Cell

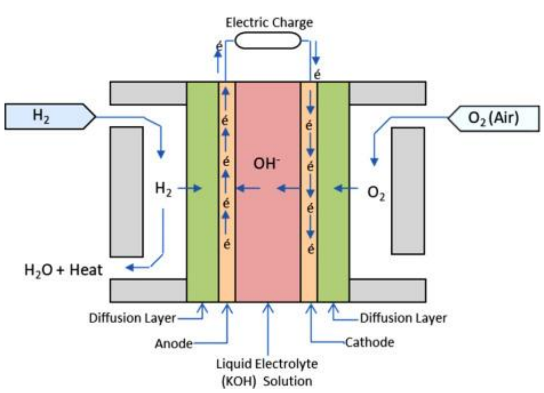

Fig.1.7-AFC Fuel Electron Flow [16]

The AFC generate electric power by utilizing alkaline electrolyte potassium hydroxide (KOH) in water based solution. The presence of the hydroxyl ions travelling across the electrolyte allows a circuit to be made and electrical energy could be extracted. Figure below illustrates an alkaline fuel cell. At anode, 2 hydrogen gas molecules are combined with 4 hydroxyl ions with a negative charge to release 4 water molecules and 4 electrons. The redox reaction taking place is oxidation and reduction is stated below [16]:

(Oxidation) $2H^2 + 4OH \longrightarrow 4H_2O + 4e-$

Electrons released in this reaction, reach the cathode through the external circuit and react with water to generate (OH−) ions.

At cathode, oxygen molecule and 2 water molecules combined and absorbed 4 electrons to form 4 negatively charged hydroxyl ions. The occurring redox reaction is reduction as below:

(Reduction) $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

They can generate electricity up to 20 kW. NASA has first used AFCs to supply drinking water and electric power to the shuttle missions for space applications. Currently, they are employed in submarines, boats, forklift trucks and niche transportation applications with a possible stack size of 10-100kW. AFCs are considered as the most cost efficient type of fuel cells since the electrolyte used is a standard chemical potassium hydroxide (KOH). They consume hydrogen and pure oxygen to produce portable water, heat and electricity sources. The by-product water produced by AFC is the drinking water which is very useful in spacecrafts and space shuttle fleets. They have no green house gas emissions and operate with a high efficiency. In spite of all the advantages of AFCs, [13]

C. Proton Exchange Membrane Fuel Cell

The proton exchange membrane (PEM) fuel cell consists of a cathode, an anode and an electrolyte membrane. Hydrogen is oxidized at the anode and the oxygen is reduced at the cathode. Protons are transported from the anode to the cathode through the electrolyte membrane and the electrons are carried over an external circuit load. On the cathode, oxygen reacts with protons and electrons producing heat and forming water as a by-product. The complete process of a PEMFC is shown in figure below.

Depending on the operating temperature, we can distinguish two different types of

PEMFCs. The first type, Low-Temperature Proton Exchange Membrane Fuel Cell, operates in a range of 60–80 °C. The second type operates in a range of 110–180 °C, therefore, it is called High-Temperature Proton Exchange Membrane Fuel Cell. The standard electrolyte material used in Low-Temperature PEM fuel cells is fully fluorinated Teflon based material for space applications, which is generally called Nafion. For High-Temperature PEM fuel cells, it is possible to Polybenzimidazole doped in phosphoric acid. Platinum is classically used in the catalyst for Low-Temperature PEMFCs, while Platinum–Ruthenium is used for High-Temperature PEMFCs catalyst. The electrical efficiency for Low-Temperature PEM fuel cells is about 40–60%, while for High-Temperature PEM fuel cells it is about 50–60%. [13, 14]

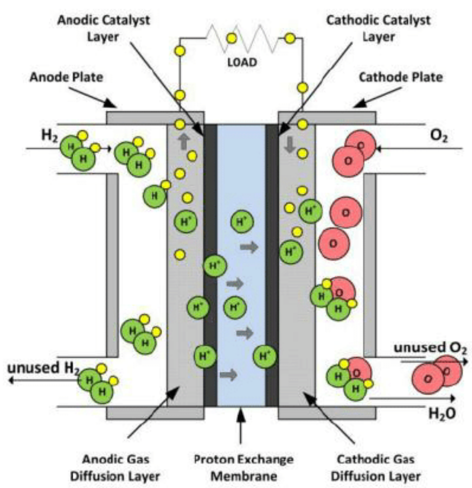

Fig.1.8 – Fuel flow in PEMFC [14]

In PEMFCs, the hydrogen is activated by catalyst to form proton ion and eject electron at the anode. The proton passes through the membrane while electron is forced to flow to the external circuit and generate electricity. The electron then flows back to the cathode and interact with oxygen and proton ion to form water. The chemical reactions occurring at each electrode are stated below.

$$\text{Anode: } H2\ (g) \rightarrow 2H^{+} + 2e^{-}$$

$$\text{Cathode: } (1/2)\ O_2\ (g) + 2H^{+} + 2e^{-} \rightarrow H_2O\ (l)$$

$$\text{Overall reaction: } H_2\ (g) + (1/2)\ O_2\ (g) \rightarrow H_2O\ (l)$$

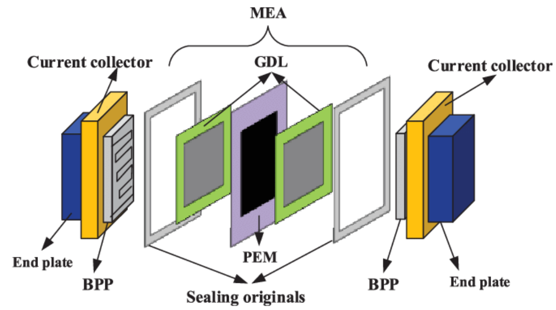

Fig.1.9 – Layers of Electrode in PEMFC [14]

The proton exchange membrane fuel cell is unusual in that its electrolyte consists of a layer of solid polymer which allows protons to be transmitted from one face to the other. It basically requires hydrogen and oxygen as its inputs, though the oxidant may also be ambient air, and these gases must be humidified. It operates at a low temperature because of the limitations imposed by the thermal properties of the membrane itself. The operating temperatures are around 90 °C. The PEMFC can be contaminated by carbon monoxide, reducing the performance by several percent for contaminant in the fuel in ranges of tens of percent. It requires cooling and management of the exhaust water in order to function properly [18].

a) *Advantages of PEMFC*
- Solid electrolyte reduces corrosion and electrolyte management problems
- Low temperature operation possible
- Quick start-up

b) *Disadvantages of PEMFC*
- Expensive catalysts
- Sensitive to fuel impurities
- Low temperature waste heat

There are a number of companies involved in manufacturing PEMFC. The main focus of current designs is transport applications, as there are advantages to having a solid electrolyte for safety, and the heat produced by the fuel cell is not adequate for any form of cogeneration. Daimler-Benz has taken a high profile in developing cars powered by Ballard fuel cells, while Toyota has recently presented a vehicle that is using a fuel cell of their own design. There is a strong possibility of using PEMFC in very small scale localized power generation, where the heat could be used for space heating. There is also the possibility of a heater/chiller unit for cooling in areas where air conditioning is popular. [21]

VI.CONCLUSION

The automotive industry is on the brink of a new era in alternative propulsion. Fuel cells are now being favored for the title "power source most likely to replace the internal combustion engine in the next generation of transportation vehicles." Though they were long believed to be nowhere near commercial viability, virtually all leading automotive manufacturers are producing sophisticated fuel-cell demonstration vehicles, and a number are unveiling concept vehicles. Use of Alkaline Fuel Cell is restricted in transport sector and can specifically be seen used in early systems.

In today's date, several units are installed in low loaded transport sectors such as motorbikes, forklift trucks, and can be seen in marine and space applications. The rest were installed in transportation development and demonstration vehicles. Proton Exchange Membrane Fuel Cells (PEMFC) are the most used technology in FCVs. In part, this dominance is due to large number of companies interested in PEMFC development. In technical terms, PEM fuel cells have high power density, required to meet the space constraints in vehicles, and a working temperature of about 70 ºC allowing a rapid start-up. The electric efficiency is usually 40-60% and the output power can be changed in order to meet quickly demanded load. Other characteristics of PEMFC systems are compactness and lightness. As a result of these characteristics, PEMFC are considered the best candidates for mobile applications. The disadvantages of this technology are sensitive to fuel CO impurities and expensive catalyst, higher CO levels result in loss of fuel cell performance. Furthermore, the electrolyte must be saturated with water and the control of the anode and cathode streams.

References

[1] Rembelski, D.; Viricelle, J.P.; Combemale, L.; Rieu, M. "Characterization and Comparison of Different cathode materials for SOFC: LSM, BSCF, SSC and LSCF", Fuel Cells, 2012, 2, 256-264.

[2] Hamilton, P.J.; Pollet, "B.G. Polymer Electrolyte Membrane Fuel Cell (PEMFC) Flow Field Plate: Design, Materials and Characterization" Fuel Cells, 2010, 4, 489-509

[3] Knauth, P.; Di Vona, M.L, "Solid State Proton Conductors: Properties and Applications in Fuel Cells", 1st ed.; John Wiley & Sons: New York, 2012

[4] Larminie, J.; Dicks, A, "Fuel Cell Systems Explained", 2nd ed, John Wiley & Sons: The Atrium, Southern Gate, Chichester, West Sussex, England, 2003

[5] Bose, S.; Kuila, T.; Nguyen, T.X.I.; Kim, N.H.; Lau, K, "Polymer membranes for high temperature proton exchange membrane fuel cell: Recent advances and challenges, Prog. Polym. Sci., 2011, 36(6), 813-843.

[6] Asensio, J.A.; Sanchez, E.M.; Gomez-Romero, P. Proton conducting membranes based on benzimidazole polymers for high temperature PEM fuel cells. A chemical quest. Chem. Soc. Rev.,2010, 39, 3210-3239.

[7] Litster, S.; McLean, G. PEM fuel cell electrodes; Angstrom Power Inc.: North Vancouver, BC, Canada, 2003.

[8] Okada, O.; Yokoyama, K, "Development of Polymer Electrolyte Fuel Cell Cogeneration Systems for Residential Applications", Fuel Cells, 2001, 1(1), 72-77.

[9] Kirubakaran A, Jain S, Nema RK. A review on fuel cell technologies and power electronic interface. Renew Sustain Energy Rev 2009;13:2430–40.

[10] Zhang X, Shen Z. Carbon fiber paper for fuel cell electrode. Fuel 2002;81(December (17)):2199–201.

[11] Larrosa-Guerrero A, Scott K, Head IM, Mateo F, Ginesta A, Godinez C, "Effect of temperature on the performance of microbial fuel cells", Fuel 2010;89(December (12)):3985–94.

[12] Xu H, Kong L, Wen X. Fuel cell power system and high power dc–dc converter. IEEE Trans Power Electron 2004;19:1250–5

[13] Comparison of fuel cell technologies", US Department of Energy Hydrogen Program.

[14] Kordesch K. "Alkaline fuel cells applications, innovative energy technology", Austria: Institute of High Voltage Engineering, U Graz; 1999.

[15] Remick RJ, Wheeler D, Singh P. "MCFC and PAFC R&D workshop summary report", U.S. Department of Energy; 13 January 2010.
[16] D.N. Luta, A.K. Raji, Potential benefits of renewable fuel cell systems for rural communities' power supply, in: 2nd EAI Int. Conf. Res. Innov. Dev. Africa, European Alliance for Innovation, Victorai Falls, 2017. doi:10.4108/eai.20-6-2017.2270897
[17] A.K. Raji, M.T.E. Kahn, Can Fuel Cell Systems Be Efficient and Effective As Domestic Distributed Generation Units, in: Domest. Use Energy Conf., IEEE, Cape Town, 2003.
[18] M. Becherif, D. Hissel, MPPT of a PEMFC based on air supply control of the motor compressor group, Int. J. Hydrogen Energy. 35 (2010) 12521–12530.
[19] Nimat Shamim, Gina Marcela Munoz, David Reale, Mark Harral, Stephen Bayne, "Fuel Cell Power System Integration with Grid using Finite Set Model Predictive Control Technique", Telecommunications Energy Conference (INTELEC) 2018 IEEE International, pp. 1-5, 2018.
[20] Yudi Xiao, Zhe Zhang, Michael A. E. Andersen, Brian Engelbrecht Thomsen, "Partial Parallel Dual Active Bridge Converter with Variable Voltage Gain for SOEC/SOFC System", Applied Power Electronics Conference and Exposition (APEC) 2019 IEEE, pp. 1641-1646, 2019.
[21] Xiaoyong Ma, Yifeng Wang, Ping Wang, "A High Frequency 40kW Step-Up Converter for Fuel Cell Electrical Vehicles Based on SiC MOSFET", Electrical Machines and Systems (ICEMS) 2019 22nd International Conference on, pp. 1-6, 2019.
[22] Behnam Mohammad, Jiabin Shen, Jiacheng Wang, "An Auxiliary Converter for Fuel Cell Stack EIS using a Switched-Capacitor Converter Interfaced Supercapacitor as a Bidirectional Energy Buffer", Industrial Electronics Society (IECON) 2020 The 46th Annual Conference of the IEEE, pp. 5006-5011, 2020.