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Comprehensive Review on Fuel Cell Technology for Electricity Generation

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Abstract: The world has been experiencing energy-related issues constantly. Scientists and researchers are actively searching for innovative, affordable, effective, and sustainable energy sources. A cost-effective, 'green', and environmentally friendly method of producing and generating power is necessary for an eco-friendly society. By 2040, fossil fuels will still produce approximately eighty percent of the world's primary energy, meeting today's global energy demand. Traditionally the fossil fuels are mainly converted into electricity and the world net electricity generation is likely to rise by 93% in 2040, due to the fast-developing countries and growing population. Thus, there is a demand to increase the efficiency of electricity production.

In addition, it is necessary to develop additional energy production resources along with current renewable energy resources. Among various technologies used nowadays, Fuel Cell (FC) appears as a promising alternative technology for electricity generation for residential and commercial sector. In recent year fuel cell (FC) technology are considered as credible energy resources on the basis of being clean, pollution-free, and efficient, including their potential to store, in the form of hydrogen, compared to other existing technologies. Based on above background, the goal of this paper is to perform the comparative analysis between different types of fuel cell and select best of them for electricity generation as well as for other commercial purposes. This review paper discusses about the potential of FC technologies for Distributed generation system. FC seems to be a good energy source to provide reliable power at a steady rate.

Keywords: Fuel Cell, Fuel Cell technology, Power generation, Renewable Energy

I. INTRODUCTION

Fuel cells, which are alternative solution for electricity generation, have attracted extensive research interest because of its potential to be an efficient, clean and pollution free energy conversion technology [1]. Fuel cell technology is a possible alternative to fossil fuels for providing electricity in rural areas where there is no connectivity to the public grid or the cost of installation and transmitting electricity is too expensive [2]. Distributed generation systems are being employed both for grid connected and commercial purposes in several developed countries and are using multiple resources like solar, wind, biomass, and hydro. The issue of reliability of some of the existing Distribution Generation systems in developing countries, especially the solar photovoltaic system Fuel cells has recently been identified as a key technological option on route to a low carbon-built environment. This is because of the ability of fuel cells (based on hydrogen production technique), to produce electricity with small or no emission of harmful pollutants such as CO_2. The static nature of fuel cells also allows for quiet operation with no noise or vibration, while its inherent flexibility allows for simple fabrication and a wide range of applications. In short, fuel cells enable a cleaner, more efficient, and potentially more adaptable chemical-to-electrical energy conversion. FCs can provide continuous operation, making them a highly reliable energy option that can serve as a backup for fluctuating characteristics in renewable energies.

Fuel cell systems for stationary applications offer the promise of substantial benefits for end users, more power and heat for the same amount of fuel with lower emissions [3]. FC technology does not depend on natural resources (such as wind and sunlight) for the electricity generation, which allows quick access to the electric power with uninterrupted service. To maintain the power demand of the load and solve the power storage problem with clean energy fuel cell are better option compare to any other available source. This technology is intended to be environment friendly solution without intermittent nature. Fuel cells have a number of advantages that give them a bright future. Thus, their characteristics favour their integration into Distributed Generation systems, and Hybrid technologies as well as in the design of isolated or interconnected Electric Microgrid [4]. A review of FC technologies is done, focusing on the principle and operating temperature in FCs. This paper is motivated towards development in distributed generation system and the possibility of powering them by FCs. Such efforts can help achieve energy security by growing a diversified energy system for various applications.

II. HISTORY AND BACKGROUND OF FCs

Scientist William R. Grove discovered the idea of Fuel Cell in 1839. This technical break through was achieved while reversing water electrolysis to produce direct current (DC) output from hydrogen (H_2) and oxygen (O_2). The electrochemical process involved in FCs is essentially a reversed electrolysis reaction. A fuel cell was initially called a gaseous voltaic battery (GVB) before it was eventually named “fuel cell”. Platinum electrodes, a sulfuric acid electrolyte, and hydrogen and oxygen reactants were used in the GVB technology. The platinum material in this arrangement was used to catalyze the reaction between H_2 and O_2. Fuel cells are devices that convert fuel into energy using an electrochemical method that does not include combustion. This conversion technique gives much higher conversion efficiency than conventional thermo-mechanical methods [6]. Table-1 summarizes the major turning points in the development of fuel cells. A single fuel cell consists of an anode and a cathode with an electrolyte in between. Fuel, such as natural gas, biogas, or hydrogen, is introduced into the anode side, while an oxidant is introduced into the cathode side, resulting in a reaction that transports electrons through the fuel cell's circuit, producing electricity [7].

Table-I: Milestones in the history of fuel cell [5]

Year(s)	Milestone
1839	W.R.Grove and and C.F. Schönbein demonstrated the principles of hydrogen fuel cell
1893	F.W. Ostwald described the functions of different components and explained the fundamental electrochemistry of fuel cells
1896	W.W. Jacques built the first fuel cell with a practical application
1937–1939	E. Bauran and H. Preis developed SOFC technology
1955-58	T. Grubband and L. Niedrach developed PEMFC technology at General Electric
1958-61	G.H.J. Broersand and J. A. A. Ketelaar developed MCFC technology
1960	NASA used AFC technology based on Bacon's work in its Apollo space program
1962-66	The PEMFC developed by General Electric used in NASA's Gemini space program
1990s	Worldwide extensive research on all fuel cell types with a focus on PEMFCs
2000s	Early commercialization of fuel cells

2.1 Hydrogen

Hydrogen can be used as an alternative to non renewable energy for domestic & commercial sector. Hydrogen's physical and chemical properties are widely understood, and manufacturing processes are subject to safety regulations. Due to global shortage of fossil fuels, renewable and environmentally acceptable energy sources are receiving more attention. These requirements are most definitely met by hydrogen fuel cell technology. Hydrogen can be used as a fuel to produce and store for future energy sources [8].

III. DESCRIPTION OF FUEL CELL SYSTEMS

Research and development that eventually led to a functional fuel cell goes back to the early1800s. Sir William R. Grove, a chemist and patent lawyer, is broadly considered to be the father of fuel cell science due to his famous water electrolyser /fuel cell experimental demonstration. Grove was successful in creating a device that uses oxygen and hydrogen to produce energy based on reverse electrolysis process (instead of separating them using electricity). The device, initially known as a gas battery, was renamed a fuel cell. Further in 1959, Francis Thomas Bacon, an English engineer, demonstrated the first fully-operational fuel cell. His work was impressive enough to get licensed and adopted by NASA [9].

A fuel cell is a type of "electrochemical" technology that works to continuously transform chemical energy into electrical energy, while the thermal energy developed and the water formed in the process are the products, or a steady supply both fuel and oxidizer are required for ongoing production of energy. All fuel cells have the same basic configuration, an electrolyte sandwiched with two electrodes (Fig.1). However, fuel cell technologies can be classified by electrolyte, fuel source, operating temperature, or application, but the operating temperature is presumably the most important distinguishing feature as it affects all the other characteristics [9, 10]. The fuel cell reaction at the anode, i.e., negative or hydrogen electrode, is described by eq. (1), whereas the reaction at the cathode or positive or oxygen electrode of the FC is represented by eq. (2) and the overall reaction is described by eq. (3).

$$2H_2 \rightarrow 4H^+ + 4e^- \quad (1)$$

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (2)$$

$$2H_2 + O_2 \rightarrow 2H_2O + \text{Energy (Electrical and Thermal)} \quad (3)$$

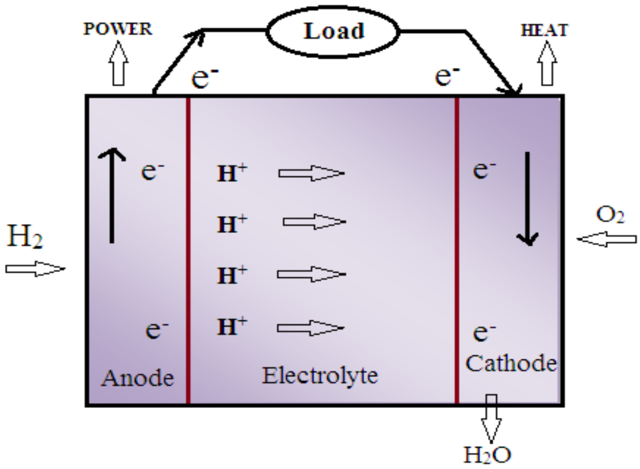

Fig.1. Schematic diagram of a fuel cell

IV. TYPES OF FUEL CELL

The fuel cells are traditionally categorized based on their electrolyte material, power output, operating temperature, electrical efficiency, applications and costs [11, 12]-

1. Alkaline fuel cell (AFC)
2. Phosphoric acid fuel cell (PAFC)
3. Solid oxide fuel cell (SOFC)
4. Molten carbonate fuel cell (MCFC)
5. Proton exchange membrane fuel cell (PEMFC)

The chemical reaction between the fuel (i.e., hydrogen) and oxidant (i.e., oxygen) differ in them according to fuel cell systems. All of them have their own advantages, limitations and potential applications.

1. Alkaline fuel cell (AFC)

The AFC produces 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 complete and electrical energy could be extracted. 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 as in eq. (4)-

$$\text{(Oxidation) } 2H_2 + 4OH^- \rightarrow 4H_2O + 4e^- \qquad (4)$$

At cathode, oxygen molecule and two water molecules combined and absorbed four electrons to form four negatively charged hydroxyl ions. The occurring redox reaction is reduction as shown in eq. (5) [13]-

$$\text{(Reduction) } O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \qquad (5)$$

AFCs generally perform below 100°C temperature (Table-II), hence they are classified as low operating temperature fuel cell. Electrical Efficiency of AFC is approximately 60%.

2. Phosphoric acid fuel cell (PAFC)

Phosphoric acid fuel cells (PAFC) utilize carbon paper electrodes and liquid phosphoric acid (H_3PO_4) electrolyte. H_3PO_4 (3.09% H, 31.6% P, 65.3% O) is a clear colourless liquid used in fertilizers, detergents, food flavouring and pharmaceuticals. The ionic conductivity of phosphoric acid is low at low temperatures, so PAFC can work at the range of 150–200 ◦C temperature [14]. The hydrogen expelled at the anode splits into four protons and four electrons. The redox reaction taking place in anode is oxidation as in eq. (6); while at cathode the redox reaction is reduction as in eq. (7), where four protons and four electrons combine with the oxygen to form water [15].

$$\text{(Oxidation)} \quad 2H_2 \rightarrow 4OH^- + 4e^- \qquad (6)$$

$$\text{(Reduction)} \quad O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \qquad (7)$$

$$\text{(Overall Reaction)} \quad 2H_2 + O_2 \rightarrow 2H_2O \qquad (8)$$

The PAFCs are costly to manufacture due to the need for finely dispersed platinum catalyst coating the electrodes.

Table-II: Comparison of Fuel Cell Technologies [16], [17]

Fuel Cell Type	**Operating Temp.**	**Electrical Efficiency (LHV)**	**Applications**	**Advantages**	**Challenges**
Polymer Electrolyte Membrane (PEM)	80^0C	60% direct H_2, 40% reformed fuel	•Backup power •Distributed generation •Transportation Specialty vehicle	•Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up and load Following	• Expensive catalysts • Sensitive to fuel impurities
Alkaline (AFC)	<100°C	60%	•Military •Space •Transportation	•Wider range of stable materials allow lower cost components •Quick start-up	•Electrolyte management (aqueous) •Electrolyte conductivity (polymer)
Phosphoric Acid (PAFC)	150 - 200°C	40%	•Distributed generation	•Suitable for CHP •Increased tolerance to fuel impurities	•Expensive catalysts • Long start-up time • Sulphur sensitivity
Molten Carbonate (MCFC)	600 - 700°C	50%	•Electric utility •Distributed generation	•Fuel flexibility •Suitable for CHP •Hybrid/gas turbine cycle	•High temperature corrosion •Long start-up time •Low power density
Solid Oxide (SOFC)	500 - 1000°C	60%	•Auxiliary power •Distributed generation	•Fuel flexibility •Solid electrolyte •Hybrid/gas turbine cycle	•High temperature corrosion •Long start-up time

3. Solid oxide fuel cell (SOFC)

Solid oxide fuel cells (SOFCs) are very high temperature fuel cells with metallic oxide solid ceramic electrolyte. SOFCs usually utilize a mixture of hydrogen and carbon monoxide formed by internally reforming hydrocarbon fuel and air as the oxidant in the fuel cell. The solid oxide FCs are part of the high-temperature technologies, which use nonporous “solid ceramic”, namely, zirconium oxide, stabilized with Yttrium oxide as an electrolyte, under the working temperature between 500 and 1000^0C [16,17]. In this technique, oxygen air is fed to the positive electrode and the nonporous solid ceramic initiates the mobility of oxygen ions from the positive to the negative electrode; electrons then flow through an external circuit to generate current. Water is generated at the negative electrode by the interaction of oxygen ions with hydrogen. The anode, cathode, and overall reactions in solid oxide FCs are represented by eq. (9) - (11), respectively [18]:

$$H_2 + O^{2-} \rightarrow H_2O + 2e^- \quad (9)$$

$$0.5O_2 + 2e^- \rightarrow O^{2-} \quad (10)$$

$$H_2 + 0.5O_2 \rightarrow H_2O \quad (11)$$

4. Molten carbonate fuel cell (MCFC)

At present, molten carbonate fuel cells are being developed for various power plants in the area of electricity generation, industrial applications and in the military applications using natural gas and coal as a fuel. MCFC uses a ceramic matrix impregnated with carbonate-salt as an electrolyte suspended in a porous, chemically inert ceramic lithium aluminium oxide matrix [19]. The temperature of operation is 600–700°C, where the alkali carbonates form a highly conducting molten salt, with carbonate ions providing the means for ionic conduction. The increased temperature of operation means that precious metal electro catalysts are not needed, and generally nickel anodes and nickel oxide cathodes are used. The need for CO_2 recirculation is a design constraint with the MCFC, making it impossible to operate below the 100 kWe scale. The anode and cathode electrode materials in molten carbonate FCs are Ni-5Cr and NiO (Li), and the reactions at these two electrodes are represented by eq. (12) and (13) respectively, while the total reaction is defined by eq.(14) [20]:

$$H_2 + CO_3^2 \rightarrow H_2O + CO_2 + 2e^- \quad (12)$$

$$0.5\,O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-} \quad (13)$$

$$H_2 + 0.5\,O_2 \rightarrow H_2O \quad (14)$$

The issue of stability is one major short come of the molten carbonate FCs. This problem is attributed to the high temperature related with the operating of the cells, which leads to a decrease in the performance. In addition, MCFCs are not prone to carbon monoxide and carbon dioxide poisoning making them more attractive when gases generated from coal is used as a fuel. This fuel cell is mainly used in stationary applications.

5. Proton exchange membrane fuel cell (PEMFC)

As the name suggests, the operational part of the PEM fuel cell is the proton exchange membrane. PEMFCs are low temperature fuel cells with operating temperature between 60 and 100 ◦C. They are light weight compact systems with quick start-up process. The sealing of electrodes in PEMFCs is easier compare to other types of fuel cells because of solidity of the electrolyte. PEMFC systems are generally used in portable and stationary applications. They also require least amount of maintenance for the reason that there are no moving parts in the power generating stacks of the fuel cells. This type of cell technology uses hydrogen and oxygen gases as fuels. As a result of electrochemical reaction between hydrogen and oxygen in the cell, electricity, water and heat are produced. As Oxygen is found in air at a large number, we only need to produce hydrogen to run the cell. Hydrogen is produced through electrolysis process. PEM fuel cell uses a solid polymer as an electrolyte and porous carbon electrodes containing a platinum or platinum alloy catalyst. The materials used as anode and cathode electrodes in polymeric electrolyte membrane FCs are platinum or platinum-ruthenium and platinum and eq. (15) and (16) describe the reactions at the anode and cathode [21]-[23].

$$H_2 \rightarrow 2H^+ + 2e^- \quad (15)$$

$$0.5O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (16)$$

PEMFCs have the largest range of applications as they are extremely flexible. An overview of fuel cell technologies is demonstrated in Fig.2.

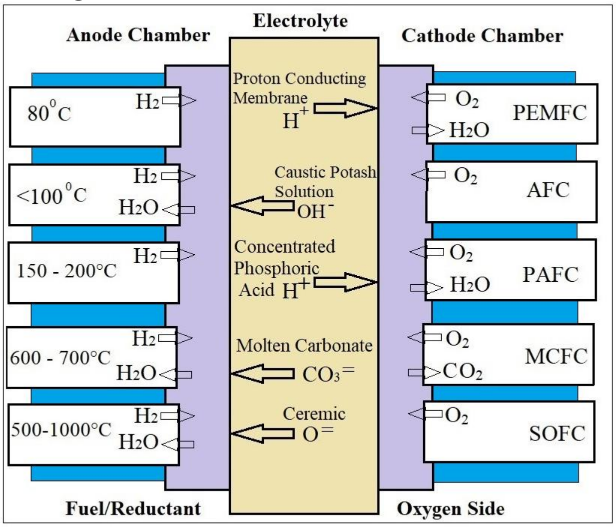

Fig.2. Fuel Cell Technology Overview

V. PROPOSED WORK

Prime motive of authors is to seek for long-term alternate energy solution to lower per capita energy expenses and to reduce the dependence on power transmission system. Two significant factors contribute to above are conventional energy resources are limited and their cost is dependent on international market. Another significant matter of concern here is, effect of global usage of fossil fuels for energy is the increased destruction of the environment. Fuel cells are a fantastic replacement for conventional methods of obtaining electricity from the grid because they significantly reduce long-term electricity costs while being environmentally friendly too. The previous sections have shown that fuel cells and other hydrogen-fuelled technologies have the potential to be low carbon options for electricity. It is also observed how fuel cell could be integrated into existing energy systems to support electricity generation and distribution.

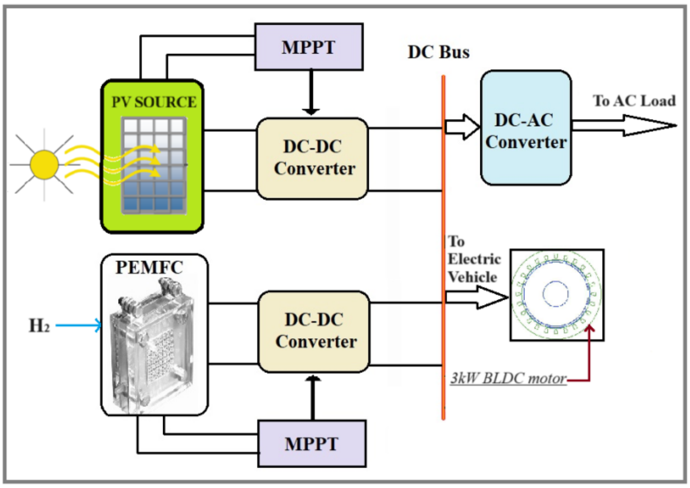

Fig.3. Proposed Hybrid PEM-FC model

Energy system models are used to study and update climate policy on periodic basis in global scenario. Significant energy demand from petroleum-based products would shift to electricity as a result of the use of electric vehicles. Electrification of transport system could also increase future electricity load. Therefore, there is a need to provide alternatives/ substitutes of conventional energy system which the transport sector would rely on. It is proposed to model and simulate a 3 kW PEM-FC hybrid power system in MATLAB Simulink environment. This PEM-FC Hybrid power system is expected to deliver electricity for Electric Vehicle as well as for residential applications. This application would be beneficial in terms of reducing the burden on public grid, and lowered expenditure on electricity bill of individual consumer in long term. This model is designed aiming at its application in public transportation

VI. DISCUSSION

The application of FCs and heterogeneous energy storage systems was recently hot topic of discussion. Phosphoric Acid FCs is used for combined-heat-and-power (CHP) applications with high energy efficiencies. Molten carbonate fuel cells (MCFCs) and solid oxide fuel cells (SOFCs) are very high-temperature fuel cells suitable for cogeneration and combined cycle systems. Proton exchange membrane fuel cells (PEMFCs) have been used in small-scale renewable energy applications because they have a low operating temperature, a short start-up time, and a high-power density. However, they require cooling to release heat when generating electrical energy. For this reason, PEMFCs have been designed with both air- and water-cooling systems. The PEMFC has the advantage of use in small IoT devices because the power density per volume is high. Low temperature fuel cell helps to start fast and results in less wear on system components, resulting in better durability. For a single fuel cell working on hydrogen and air at atmospheric pressure, the theoretical open circuit voltage ranges from approximately 1.2 V for a Proton exchange membrane fuel cell at 80 °C to approximately 1.0 V for a SOFC at 700 °C. Table-III technically compares fuel cells for portable, stationary, and transportation application [18].

Table-III: Applications of fuel cell

Application	Portable	Stationary	Transportation
Power range	1 W–20 kW	0.5 W–400 kW	1 kW–100 Kw
Technology	PEMFC, DMFC	PEMFC, SOFC, MCFC, PAFC, AFC	PEMFC, DMFC
Examples	•Non-motive auxiliary Power units (campervans, boats, lighting) • Military applications • Portable products	•Large stationary combined heat and power (CHP) • Small stationary • Uninterruptible power supplies (UPS)	• Materials handling vehicles • Fuel cell electric vehicles (FCEV)

Fuel cell power systems have a variety of characteristics that make them appealing in stationary and transportation applications. Unlike other power sources such as PVs, the fuel cell system has a control system that manages the balance of plant and determines the static and dynamic characteristics of the power output. As long as the fuel cell system is connected to a reliable source of fuel, it can continuously provide power to the load making it more desirable for distributed generation than PVs or wind [24]. Furthermore, different fuel cell technologies can be chosen to align with the application requirements. For example, low-temperature fuel cells are suitable for both residential and commercial applications providing the low-grade heat.

Among the variety types, Proton Exchange Membrane Fuel Cell (PEMFC) has drawn much interest for both stationary and transportation application owing to its simplicity, viability and wide power range [25]. Polymer electrolyte membrane, also proton exchange membrane, fuel cells (PEMFCs) in particular are one of the most promising types already in the early commercialization stage. The authors in this paper demonstrate a fuel technology with renewable source for distributed generation. In addition, the authors demonstrate qualitative advantages of PEMFC based electricity generation by renewable fuel, the work mainly focuses on clean energy generation with low temperature fuel cell and small-scale applications. A promising source of renewable energy in the near future is the hydrogen fuel cell. Thinking about global warming and keeping in mind the fossil fuel shortage, fuel cell system can be a reliable option.

VII. CONCLUSION

The paper presents a detailed review of different types of FC technologies such as proton exchange membrane, alkaline, phosphoric acid, molten carbonate, and solid oxide FCs, which are engaged for stationary (Residential, commercial, and industrial stationary power generation) applications as well as transportation (fuel cell electric vehicles) application. The theoretical study finds that proton exchange membrane FCs have a comparatively very low temperature high specific power for distributed generation compare to other fuel cell technology. The paper demonstrated interests in the application of Fuel cells in Distributed generation systems based on some attractive features such as being clean, pollution-free, highly efficient, and promising energy resource for power generation applications that need more interest in research and development terms.

The review of different FCs technology is expected to provide useful insights into advancing research and developments in clean energy generation through Distributed generation systems based on FC technologies. Nonetheless, further development and research are required in order to reduce their costs, improve their stability, and further optimize and improve their performance and will be a function of better technologies to generate electricity for near future well as better business capabilities to global market. Most of the research currently being conducted on PEMFCs is on the individual cell-level and the general system-level, on the other hand, is an area that requires further research and development. Reducing cost and improving stability are the two most significant challenges to fuel cell commercialization. Fuel cell technology must be cost-competitive with, and perform as well or better than, conventional power technologies larger than the life of the system.

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