Fuel Cells for Distributed Generation: Opportunities and Challenges

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Abstract: **Fuel cell technology is attracting a lot of attention for distributed generation (DG). This is so because fuel cells are efficient, simple, silent and strictly conform to emissions norms for distributed generation. There are various types of fuel cells, each with different techno-economical pros and cons. This paper attempts to make a comparison of fuel cell technologies based on appropriate parameters and hence assess their suitability for application in distributed generation. Side-by-side, challenges posed by each type of fuel cell are also discussed.**

Index terms: **Distributed energy resources, distributed generation, fuel cells.**

I. INTRODUCTION

Energy determines growth of a society and past few decades have seen huge growth in demand of various types of energy. It is estimated that as of now the current population on the planet consumes 15 terawatts of power [1]. According to the World Coal Institute [2], at the current rate of consumption, reasonably recoverable coal reserves will run out in 130 years, natural gas in 60 years and oil in 42 years. Of all the forms of energy, electricity is considered most flexible and hence it has been abused substantially leading to further exhaustion of precious fuels used to generate electricity. Moreover, the demand for electricity continues to grow very rapidly. Forecasts show total worldwide electricity consumption rising from 12 trillion kilowatt-hours in 1996 to almost 22 trillion kilowatt-hours in 2020. Also by 2020, developing nations are expected to account for 43 percent of the world's total energy consumption as compared to only 28 percent in 1996. Solutions are being sought out to secure long term viability of our future.

This endeavor has led to the concept of Distributed Generation (DG) of electricity. Conventionally, electricity has been generated with what is called 'Centralized Generation' where chief sources have been fossil fuels to generate electricity. There have been many issues with such kind of approach. Apart from major concerns like limited supply of fossil fuels and pollution and subsequent climate changes, there are other important issues like fluctuations in fuel prices, insecurity, high transmission losses and large gestation periods [3].

Distributed Generation (DG) can be defined as an electric power source connected directly to the distribution network or even on the customer side of the meter [4-5]. These are *often* (but not necessarily) small-scale renewable energy sources, such as photovoltaic panels, biomass or wind turbines. The localization of the DGs can be used beneficially for both the consumer and the producer. Distributed generation also gives benefits like emergency back-up, improved system performance, increased reliability, potential utility capacity deferrals, ancillary service power, improved security and economics [3]. Hence, distributed generation has received a lot of attention from engineers and researchers.

The most popular distributed generators include microturbines, fuel cells, biomass, diesel, small wind plants and photovoltaic (PV) generators [6].

Power generation from sources like wind turbines and PV cells are intermittent in nature and depend on wind and solar radiations. They are significantly affected by the changes in climate. As for the diesel generators, they emit polluting gases leading to climate changes. Among different types of DG technologies, fuel cells are very appealing because of their high efficiency, high power quality, very less pollution (if any) and continuous power generation without being effected by weather conditions. There are types of fuel cells which can generate electrical power ranging from milliwatts to megawatts[7].

Some types of fuel cells are at the stage of commercialization , still the most significant challenge is the high cost of production and efforts are on to reduce it. In the following sections a general working of fuel cell and its types have been explained, comparisons have been made on various parameters appropriate for application in distributed generation and based on comparison, conclusions have been presented.

II. FUEL CELLS

The first practical demonstration of a fuel cell was made by lawyer and scientist William Grove in 1839 [8]. A hydrogen fuel cell is an electrochemical device that uses hydrogen (H_2) as fuel and oxygen from the air to produce electricity with water and heat as the by-products. That is, the chemical energy contained in hydrogen can be directly converted into electrical power by a fuel cell, thus eliminating the intermediate steps of converting fossil fuel energy first into heat and then using heat for mechanical motion used for generation of electricity [8].

In fact, a fuel cell combines the best features of IC engines (they can operate as long as fuel is supplied) and batteries (they can produce electricity directly from *fuel*, without combustion and thus reducing emissions and noise and increasing the efficiency). Two of their major benefits are their ability to provide power and heat at different scales and in locations not currently accessible; and their ability to operate on fuels ranging from fossil fuels through biomass based fuel to renewable sources [1].

There are different types of fuel cells, but they all are based on a simple design which consists of two electrodes: a negative anode and a positive cathode. These electrodes are separated by an electrolyte which can be solid or liquid and it carries the electrically charged ions between the two electrodes, the electrons released flow through the external circuit. To speed up the rate of these reactions, a catalyst such as platinum is used [9]. A typical schematic of fuel cell is shown in figure 1 [8]. Fuel is fed continuously to the anode and oxidant is fed continuously to the cathode, while driving electrons through the external circuit thus performing work on the load.

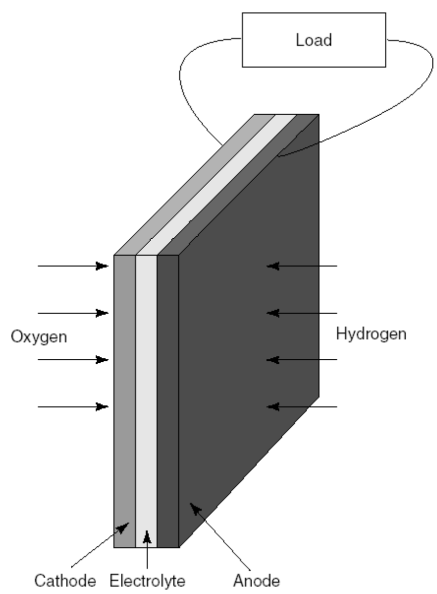

Figure 1. Schematic of a Fuel Cell

For an acid electrolyte fuel cell, the hydrogen gas ionizes, releasing electrons and creating H^+ ions (protons)

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

Energy is released in the above reaction. At the cathode, oxygen reacts with electrons taken from the electrode, and H^+ ions from the electrolyte, to form water.

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

The overall reaction, which is true for all types of fuel cells, is:

$$2H_2 + O_2 \rightarrow 2H_2O$$

A fuel cell achieves its highest output voltage only at open circuit conditions and as the current drawn is increased, the voltage drops. This behavior is similar to that of a voltage source with internal resistance. This behavior of a fuel cell is represented with a polarization curve [8], as shown in figure 2.

So-called *activation losses* are because of slow rate of reactions at the electrode surfaces and a proportion of the voltage generated is used in driving the chemical reaction that transfers the electrons to or from the electrode [8]. The resistance of the material of electrodes and various interconnections lead to voltage drop which is essentially proportional to current density and hence the resulting losses are called *ohmic losses*. The *concentration losses* result from the change in concentration of the reactants at the electrode surfaces as the fuel is consumed.

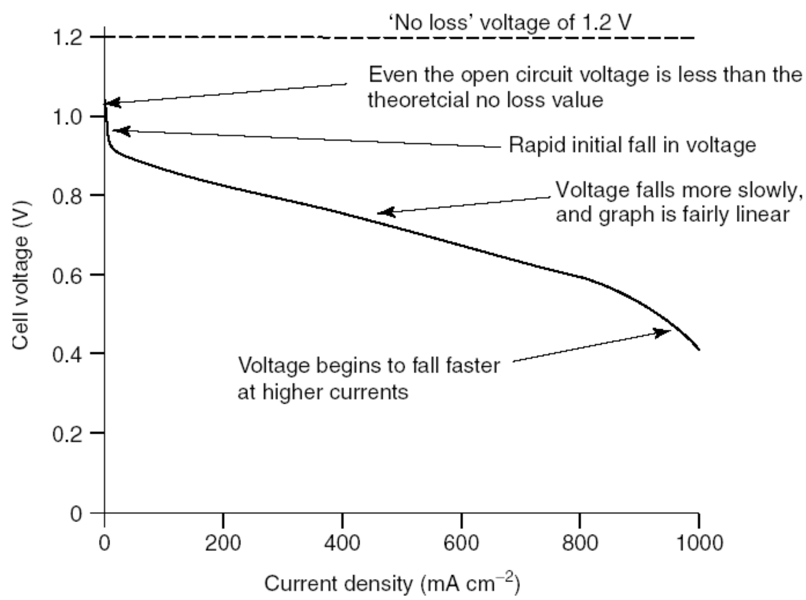

Figure 2. Polarization curve

If one leaves aside practical issues such as manufacturing and materials costs, following are the two fundamental technical problems with fuel cells [8] : (1) slow reaction rate, leading to low current and power, and (2) hydrogen is not a readily available fuel. To solve these problems, many different types of fuel cells have been tried, distinguished by the electrolyte used and operating temperature. As of now, six classes of fuel cells have emerged as viable systems for the present and near future. They are: (a) alkaline fuel cell (AFC), (b) proton exchange membrane fuel cell (PEMFC), (c) direct methanol fuel cell (DMFC), (d) phosphoric acid fuel cell (PAFC), (e) molten carbonate fuel cell (MCFC), and (f) solid oxide fuel cell (SOFC). Table 1 shows the operating temperature range for these fuel cells [8].

The operating temperature depends on the material and structure of the fuel cell. Of these, DMFC is a type of PEMFC, though it is called direct methanol fuel cell, 'direct' indicates they use methanol as the fuel in its liquid form and hydrogen need not be extracted from the methanol. Therefore, for comparison DMFC won't be considered as a separate class of fuel cells in itself. Moreover, as the AFC is restricted to space and military applications, it has been neglected in the comparison. AFC, though has powered hundred of NASA space missions since the 1960's, they never reached commercial potential [10]. This is so because it needs pure fuel and high reformation thus increasing the system cost and complexity. In AFC, the electrolyte is KOH solution and even a small amount of CO_2 , if present, reacts with KOH to form K_2CO_3, thereby altering the electrolyte. Hence, the corrosive nature of the electrolyte reduces the total life time of the fuel cell.

Fuel cell type	Operating temperature
Alkaline (AFC)	50–200°C
Proton exchange membrane (PEMFC)	30–100°C
Direct methanol (DMFC)	20–90°C
Phosphoric acid (PAFC)	~220°C
Molten carbonate (MCFC)	~650°C
Solid oxide (SOFC)	500–1000°C

Table 1. Operating temperatures of various fuel cells

AFC uses KOH solution as electrolyte, platinum being the reaction catalyst in it and H_2 acting as the fuel. O_2 acts as the oxidant and OH^- ions are mobile in the fuel cell.

PEMFC uses solid polymer membrane (Nafion, ®DuPont) as the electrolyte and the electrodes are made of graphite or metals. It also uses platinum as the catalyst with pure H_2 fed into the anode and O_2 fed into the cathode. H^+ ions are the mobile ions.

As for PAFC, the electrolyte is H_3PO_4 solution. The electrodes are made of nickel or other transition metals and platinum is used as a catalyst. Here, again, H^+ ions are mobile.

In MCFC, a mixture of alkaline carbonates is used as the electrolyte. With the operating temperature being high, nickel serves well as a catalyst. Anode is fed with H_2 , CO, CH_4 and other hydrocarbons. CO_3^{2-} ions are the mobile ions.

Ceramics (Perovskites) are used to make electrodes in SOFC and a solid electrolyte is used. O_2^- ions are the mobile ions.

A. Classification of fuel cells

Based on the range of operating temperature, the fuel cells can be categorized as: (1) low temperature fuel cells (AFC, PEMFC and PAFC) and (2) high temperature fuel cells (MCFC and SOFC).

In low temperature fuel cells, though generally have less complexity, the rate of reaction is slow and thus special catalysts like platinum have to be used to increase the rate. This, however, also increases the cost and thus the cost of production of electricity. In such fuel cells, impurities like CO act as poison for the anode.

As for the high temperature fuel cells, expensive catalysts are not required and impurities like CO don't act like poison (in fact, CH_4 can directly be fed into the stack and can be converted to H_2 there). However, high operating temperatures increase their start-up time (even up to some hours). Generally, these fuel cells have more complex structure as compared to the low temperature fuel cells.

III. COMPARATIVE STUDY OF FUEL CELLS

As for the manufacturing of fuel cells many techno-economical issues are inter-related. The biggest challenge remains to reduce their cost. In fact, two key figures are the cost per kilowatt and the power density [8]. The current internal combustion engine technology gives around 1kW per liter of power density at the cost of USD 10 per kW. Such a system is supposed to last about 4000 hours. For combined heat and power (CHP) systems, the cost is still important but a much higher figure of USD 1000 per kW is the target. At the same time, such systems are expected to last a minimum of 40,000 hours. In the fuel cell reactions, heat is also a by-product apart from the electrical energy and high-grade heat is used to form CHP systems.

To make comparison of fuel cells, various parameters can be chosen and appropriate trade-offs have to be made if contradictory conditions are present. Following parameters have been chosen to make comparison of fuel cells (not necessarily in the order of importance): design and structure, catalyst used, sensitivity to impurities, start-up time, efficiency, usage in CHP systems, cell-life and cost of production. They are hereby discussed one-by-one separately for low-temperature and high-temperature fuel cells.

i. Design and Structure:

(a) Low temperature fuel cells: PAFC is less complex than PEMFC. This is so because it needs proper water management in the membrane to perform efficiently. It must operate under conditions where the by-product water does not evaporate faster than it is produced (as the membrane must be kept hydrated) [11].

(b) High temperature fuel cells: High temperature fuel cells are more complex as compared to low temperature fuel cells. In the anode of MCFC carbon monoxide is produce and wanted for cathode consumption, so with a cycle the production and consumption of CO can be managed. This leads to high complexity in the design of MCFC stack and electrolyte management [11]. As for SOFC, higher contacts and cathode resistance limits its power density.

ii. Catalyst used:

(a) Low temperature fuel cells: Because of low temperature, the reaction rate is slow and expensive catalyst like platinum has to be used. Both PAFC and PEMFC use platinum as catalyst. Also, PEMFC uses more catalyst in its electrodes [8].

(b) High temperature fuel cells: MCFC operates at the range of 650^{o}C and SOFC in the range of 500-1000^{o}C. Such high temperatures reduce the need of expensive catalyst and nickel is used.

iii. Sensitivity to impurities:

(a) Low temperature fuel cells: PEMFC 's are sensitive to contaminations like carbon monoxide, compounds of suphur and ammonia and therefore they need highly pure fuel. PAFC, on the other hand, is less sensitive to fuel impurities and can stand up to even 1 percent of carbon monoxide in the fuel.

(b) High temperature fuel cells: Because of high operating temperature, fuel consumption is quite flexible in these fuel cells and fuel reformation can be ignored. Even CO can be directly fed into it.

iv. *Start-up time:*

(a) Low temperature fuel cells: Operating temperature of PEMFC is about 60-80^{O}C (because of presence of water, temperature can't be more than 100^{O}C). PAFC operates at around 150-200^{O}C. Hence PEMFC has lesser start-up time.

(b) High-temperature fuel cells: As the operating temperature of SOFC is higher (500-1000^{O}C) compared to MCFC (around 650^{O}C), its start-up time is higher.

v. Efficiency:

(a) Low temperature fuel cells: PEMFC gives efficiency of 25-35% in stationary applications (e.g back-up power) and 53-58 % in transportation [12]. Efficiency of PAFC is more than 40%.

(b) High temperature fuel cells: SOFC operates at the efficiency of 38.5 – 41% and MCFC operates at the efficiency of 45-47% [12].

vi. Usage in CHP:

(a) Low temperature fuel cells: Because of higher operating temperature, it is possible to utilize PAFC in the form of combined heat and power (CHP).

(b) High temperature fuel cells: Because of high operating temperature, waste heat is of high grade and they are suitable for combined heat and power (CHP) generation and efficiency more than 50% can be achieved.

vii. Cell –life:

(a) Low temperature fuel cells: With usage fuel cells loose the voltage under similar operating conditions. As discussed earlier, the desired life-time of a fuel cell system in around 40000 hrs minimum. The degradation of PEMFC is around 2-10µV/hr and that of PAFC is 2-4µ/hr [10].

(b) High temperature fuel cells: Degradation of MCFC is 5µV/hr and that of SOFC is less than 8µV/hr [8].

viii. Cost of Production:

(a) Low temperature fuel cells: Reducing cost of production remains an important challenge for wide spread application of fuel cells [1]. PEMFC's are thought to have better cost potential as compared to that of PAFC's [11]. A production cost of USD 300-600/kW is reached for PEMFC's whereas PAFC has the production cost of about USD 3000-4000/kW.

(b) High temperature fuel cells: As compared to MCFC, SOFC has lower cost of production as of now [10]. A production cost of USD 724-775/kW has been achieved and that of MCFC is around USD 1000/kW. As a result SOFC's are receiving lot of attention.

The comparison of fuel cells has been summarized in Table 2.

TABLE 2 COMPARISON OF FUEL CELLS

PARAMETER	LOW-TEMPERATURE FUEL CELLS		HIGH-TEMPERATURE FUEL CELLS	
	PEMFC	**PAFC**	**MCFC**	**SOFC**
Design and structure	Simple	Simpler	Complex	Complex
Catalyst	Expensive	Less expensive	Not expensive	Not expensive
Sensitivity to impurities	More sensitive	Sensitive	Not much	Not much
Start-up time	Lower	Low	High	Higher
Efficiency	Stationary application: 25-35% Transportation: 53-58%	More than 40%	45-47%	38.5-41%
Usage in CHP system	Not suitable	Suitable	Suitable	Suitable
Cell-life	2-10µV/hr	2-4 µV/hr	5 µV/hr	0-8 µV/hr
Production cost	High	Very high	High	High

IV. CONCLUSION

Concern for fast depleting fossil fuels and environmental awareness, apart from prices and security, has led to widespread interest in distributed generation (DG) of electric power. Of many technologies available (microturbines, fuel cells, biomass, diesel, small wind plants and photovoltaic

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(PV) generators) for DG, fuel cells are very attractive option because of their efficiency, simplicity low emissions and silence. This paper discusses a broad classification of fuel cells based on their operating temperature (high temperature and low temperature fuel cells) and further sub-type of both the types. A comparative study has been carried out based on definite important parameters. As for opportunities for application in DG, PEMFC scores over PAFC amongst low-temperature fuel cells and SOFC scores over PAFC amongst high-temperature fuel cells. Fuel cells offer bright prospective for use in stationary, portable and transportation applications, though their high costs still pose a significant challenge.

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