

Fuel Parameter and Quality Constraints for Fuel Cell Distributed Generators

Phanikrishna Gomatom, *Student Member, IEEE*, and Ward Jewell, *Fellow, IEEE*

Abstract--Distributed generation (DG) technologies are being discussed as the new paradigm for the electricity infrastructure, owing to growth in electric loads, deregulated markets, reliability constraints, emission control limitations, and the huge capital investments with minimal rates of return associated with central station generation. Some DG technologies are critically dependent on the fuel quality and supply parameters for optimal power delivery and overall economic operation. Currently, most DG technologies are expensive to install, operate and maintain. One of the factors that will affect feasibility and economic viability of fuel cells is the supply of fuel with the characteristics appropriate to fuel cell designs [1]. This paper deals with fuel performance indices for fuel cell DG units and analyzes their dependency on fuel characteristics for economical and optimal performance.

Index Terms-- Distributed Generation, Distributed Resources, Fuel Cells, Fuels, Natural Gas.

I. INTRODUCTION

Fuel cell Generators are stacks of fuel cells, each cell capable of producing a low electric DC voltage. Fuel cells consume hydrogen extracted from a hydrogen-rich fossil fuel (e.g., natural gas) and draw oxygen from air. In the fuel cell, oxygen and hydrogen combine at the molecular level, in the presence of a catalyst but under controlled temperature and pressure. This results in the oxidation of hydrogen, sometimes referred to as "no flame combustion." The by-product of this "combustion-like" phenomenon is H_2O at high temperature, generally in the form of steam. The oxidation of hydrogen, carried out in the presence of the electrolyte, produces a charge that drives a direct current flow from the cell's anode to its cathode. Depending on the electrolyte, a single fuel cell can generate about 1-1.5 V, and the magnitude of current depends predominantly on the surface area of the plates exposed to the electrolyte.

Based on the design, fuel cells can be external-reforming or self-reforming. External-reforming fuel cells run on pure hydrogen and hence require an external reformer that is fed with hydrogen-rich fuel. The reformer strips off the hydrogen molecules from the fuel, and the pure hydrogen is admitted

into the fuel cell after contaminants and other fuel contents are filtered out. . The self-reforming fuel cells are designed with a built-in catalytic converter and a catalytic oxidizer, combined together into one single unit that enables fuel to be pumped directly into the fuel cell. In spite of the complicated design, self-reforming fuel cells are expected to find a prominent place in most commercial applications in the future. Based on the electrolytic material and the type of chemical operation involved, fuel cells are broadly classified into five types: Alkaline, Proton-exchange Membrane, Phosphoric acid, Molten Carbonate and Solid oxide fuel cells [2].

II. ADVANTAGES AND DISADVANTAGES OF FUEL CELLS

A. Advantages

- Higher efficiency than any other fossil fuel based DG technology.
- Modular and easy to install.
- Portable and consume less surface area per unit power produced.
- In most cases fuel cells are zero-emission devices.
- Appreciable amount of useful exhaust heat, thus fuel cells are well adapted for CHP operation.
- Zero or very low noise except for occasional vibrations.
- Fuel cell stacks can be connected in parallel with batteries, enabling fuel cells to operate as base-load generators, under varying load conditions.

B. Disadvantages

- Highly expensive due to exotic materials, and complicated design and assembly.
- Highly sensitive to fuel contamination. Mandatory additional expense for procurement and maintenance of effective filters and cleaners.
- Skilled personnel needed for maintenance and overhaul.
- Fuel cell technology has an unproven record, though cost-effective and reliable materials/technologies are under research and development for commercial power generation applications [3, 4].

III. FUEL CONSTRAINTS ON FUEL CELL OPERATION

While fuel cells are one of the most promising DG technologies, they are today too expensive for extensive installation in most domestic and commercial applications. One of the primary constraints is the efficiency, cost, size and

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maintenance of auxiliary equipment to maintain the desired physical properties of fuels. These costs are in addition to costs incurred due to possible chemical and particulate contamination of fuel.

Fuel cell performance and emissions are dependent on fuel properties and fuel composition, although efforts are underway to build fuel cells that are less sensitive to fuel parameter deviations. If achieved, however, these will increase design costs.

These problems are reduced if the fuel supply and distribution systems deliver the right kind and the right quality of fuel. With existing constraints and a wide range of safety norms already in place for the fuel distribution infrastructure, it may not be feasible to provide the quality of fuel needed by fuel cells.

This paper deals with the analysis of some of the critical fuel cell performance indices that are directly or indirectly dependent on fuel characteristics. The analysis relates performance and economics of fuel cell DG to variations in fuel characteristics and chemistry.

IV. ANALYSIS

The functional diagram and basic components of a fuel cell are shown in Fig. 1 and Fig. 2, respectively. These will be used in the development of the analysis and performance indices for hydrogen fuel cells.

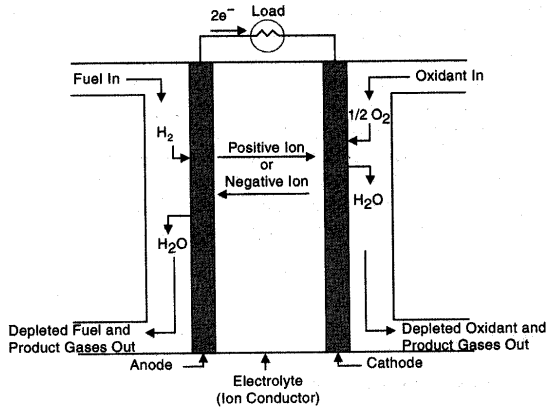


Fig. 1. Magnetization Functional Diagram of a Basic Fuel Cell [3].

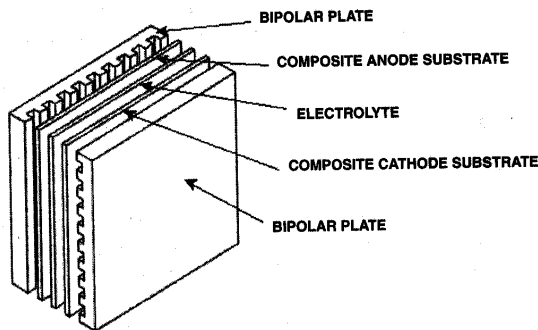


Fig. 2. Basic Components in a Fuel Cell [5].

A. Open Circuit Voltage (E_{OC})

The ideal (reversible) open circuit voltage for a fuel cell is the electrical work done in moving charge through the fuel cell circuit, and is equal to the electrical work done per unit

charge on one mole of electrons.

$$E_{OC} = (\text{Electrical work}) / 2F \quad (1)$$

where F is the Faraday constant, 96,485 C. The “2” in the denominator represents the number of electrons that flow for one mole of Hydrogen.

For an ideal system the electrical work is equal to the Molar Gibbs free energy released, $-\Delta g_F$, during the reaction. Hence

$$E_{OC} = -\Delta g_F / 2F \quad (2)$$

The negative sign is due to Gibbs free energy that is liberated.

When fuel is burned, the energy released is the change in the molar enthalpy of formation (Δh_F), sometimes called the “calorific value” of the fuel. Because the thermal energy in the fuel is converted to electrical energy in the fuel cell, Δh_F can be substituted for the Molar Gibbs free energy in the open circuit voltage equation:

$$E_{OC} = -\Delta h_F / 2F \quad (3)$$

Typical values for E_{OC} are 1.25 V to 1.48 V. The higher value uses the high heating value (HHV) for oxidation of hydrogen, 285.84 kJ/mole, which includes the molar enthalpy of vaporization of water. The lower value uses the low heating value (LHV), 241.83 kJ/mole, which does not include the vaporization of water.

B. Fuel Utilization Coefficient (μ_F)

In practical situations not all the hydrogen that enters the fuel cell is used in the electrochemical reaction. The fuel utilization coefficient, μ_F , is hence defined as

$$\mu_F = \frac{\text{Mass of fuel reacted in cell}}{\text{Mass of fuel input to cell}} \quad (4)$$

The mass of fuel reacted in the fuel cell is improved with fuel containing a high percentage of hydrogen [11].

C. Fuel cell Efficiency (η):

The fuel cell efficiency depends on the actual voltage generated in the fuel cell. V_C , the actual fuel cell output voltage, can be written as

$$V_C = E_{OC} - V_{drop} \quad (5)$$

where V_{drop} is the voltage drop within the fuel cell. The cell efficiency η is then

$$\eta = (\mu_F V_C) / E_{OC} \quad (6)$$

The voltage drop in the fuel cell is mostly due to polarization losses, which include concentration polarization, activation polarization and ohmic polarization losses [5].

D. Hydrogen Consumption

The hydrogen consumption in a fuel cell depends on the type of fuel cell and the concentration of hydrogen at standard temperature and pressure (STP).

$$H_2 \text{ consumption} = (2.02 \times 10^{-3} * P_d) / (2 * V_c * F) \text{ kg/s} \quad (7)$$

where 2.02×10^{-3} kg/mole is the molar mass of hydrogen at STP and P_e is the electrical power output of the fuel cell in W.

E. Heating Rate

When Hydrogen is oxidized in a fuel cell, the ideal open circuit voltage is generated only if the entire heat energy of combustion is converted to electrical energy. But some heat energy is lost in the by-products that result from the electrochemical reactions at the anode and cathode. For example, steam is released in most hydrogen fuel cell reactions. Using the LHV value of hydrogen-based fuel, the open circuit voltage for a fuel cell is 1.25 V [6].

$$\text{Heating rate} = n I (1.25 - V_c) W \quad (8)$$

where I is the rated current for a stack of n cells.

F. Net Power Output ($P_{O(NE T)}$)

The fuel cell's net power output ($P_{O(NE T)}$) is the electric power output available to the connected load. Net power output is equal to the electrical power output P_e minus the summation of parasitic power and conversion losses. The auxiliary systems in a fuel cell based DG unit depend on the type of the fuel cell (self- or external-reforming), the operating temperature range, and the nature of electrochemical reactions at the cathode and the anode.

$$P_{O(NE T)} = P_e - \sum [\text{parasitic losses} + \text{conversion losses}] \quad (9)$$

G. Total efficiency (η_{tot})

The total efficiency of the fuel cell generator system, η_{tot} , is the ratio of the sum of the net power output plus the net heat released at the exhaust, $P_{Exhaust}$, to the total system LHV fuel input, $P_{F(1)}$:

$$\eta_{tot} = (P_{O(NE T)} + P_{Exhaust}) / P_{F(1)} \quad (10)$$

V. DEPENDENCY ANALYSIS

Most of the performance indices discussed above are dependent on the ideal open circuit voltage E_{OC} . E_{OC} is dependent on a variety of fuel-specific parameters and on the temperature of the reactions involved.

The open circuit voltage of a fuel cell varies with the concentration of hydrogen supplied. The reforming process affects the concentration and pressure of hydrogen.

The Nernst equation expresses the dependence of the Molar Gibbs free energy on reactant pressure and concentration, in addition to the dependence on reaction temperature. This is shown in Fig. 3.

This dependence can be expressed as [7,8]:

$$E_{OC} := E_{STP} + \frac{RT}{nF} \ln \left(\frac{\Pi(\text{reactant activity})}{\Pi(\text{product activity})} \right) \quad (11)$$

where E_{STP} is the maximum open circuit voltage generated under standard conditions (one atmosphere and $77^\circ F$). R is the universal gas constant, 8.314 J/K mol , and T is the actual temperature in K. Reactant and product activity are dependent on the molar concentration of

reactants/product.[7,8].

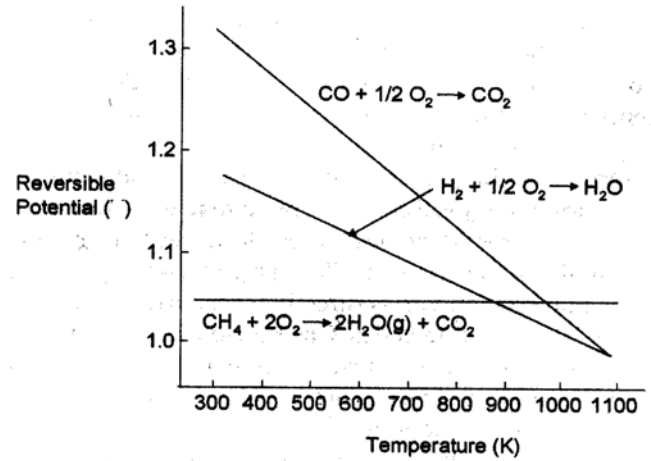


Fig. 3. Ideal Reversible Open circuit Potential Versus Temperature [6].

The Nernst equation for a hydrogen/oxygen based fuel cell can be written as [7,8]:

$$E_{OC} := E_{STP} + \frac{RT}{2F} \ln \left[\frac{\Pi(a - H_2) \cdot (a - O_2)^2}{\Pi(a - H_2O)} \right] \quad (12)$$

where "a" is the activity of the specific reactant or product and is synonymous to molarity(strength) of a solution with dissolved chemicals. Equation (12) assumes that the products of the electrochemical reactions at the anode and the cathode are mostly H_2O or water vapor.

Refer to Table I for maximum voltage (EMF) and thermodynamic efficiency limits.

TABLE I.
 ΔG_f , MAXIMUM EMF AND EFFICIENCY LIMIT (HHV) FOR HYDROGEN FUEL CELLS [7].

Form of water product	Temp °C	$\Delta \bar{g}_f$, kJ/mole	Max EMF	Efficiency limit
Liquid	25	-237.2	1.23V	83%
Liquid	80	-228.2	1.18V	80%
Gas	100	-225.3	1.17V	79%
Gas	200	-220.4	1.14V	77%
Gas	400	-210.3	1.09V	74%
Gas	600	-199.6	1.04V	70%
Gas	800	-188.6	0.98V	66%
Gas	1000	-177.4	0.92V	62%

Activity can be expressed as:

$$P' = \frac{\text{Partial pressure (or pressure)}}{\text{Standard Pressure}} = \frac{P}{P_{STP}} \quad (13)$$

The Nernst equation can then be written as:

$$E_{OC} := E_{STP} + \frac{RT}{2F} \ln \left[\frac{(P' - H_2) \cdot (P' - O_2)^{\frac{1}{2}}}{P' - H_2O} \right] \quad (14)$$

Partial pressure applies when the hydrogen gas is a part of a mixture (similar to the terminology used in the Dalton's law of partial pressures). This is true for self-reforming fuel cells where hydrogen enters the fuel cell as a part of a mixture of gases. For fuel cells with external reformers, hydrogen gas enters the fuel cell and P' is replaced with P , the pressure of the hydrogen gas.

The Nernst equation in the form of (14) provides a theoretical basis and a qualitative indication for a large number of variables in fuel cell design and operation. It will be used to begin a detailed analysis of natural gas characteristics as they relate to fuel cell performance and economics. This analysis will include development of a theoretical model, followed by analysis of actual natural gas characteristics correlated with fuel cell performance data. Thus verified, the model will then accurately estimate the effects of natural gas quality on fuel cell performance and economics, and will provide DG users, electric utilities, and natural gas suppliers and distributors with guidance in fuel needs of fuel cells.

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VII. ACKNOWLEDGMENT

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VIII. BIOGRAPHIES



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