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Effect of process parameters on the dynamic behavior of polymer electrolyte membrane fuel cells for electric vehicle applications

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Abstract This paper presents a dynamic mathematical model for Polymer Electrolyte Membrane "PEM" fuel cell systems to be used for electric vehicle applications. The performance of the fuel cell, depending on the developed model and taking the double layer charging effect into account, is investigated with different process parameters to evaluate their effect on the unit behavior. Thus, it will be easy to develop suitable controllers to regulate the unit operation, which encourages the use of fuel cells especially with electric vehicles applications. The steady-state performance of the fuel cell is verified using a comparison with datasheet data and curves provided by the manufacturer. The results and conclusions introduced in this paper provide a base for further investigation of fuel cells-driven dc motors for electric vehicle.

1. Introduction

The increasing demand for enhanced environmental performance is placing greater demands for the development of clean energy sources. Furthermore, there are increasing demands to reduce the global warming and ozone depletion processes related to the use of fossil fuel [1]. Moreover, oil reserves are depleting worldwide, while the demand on energy is increasing in large scales [2]. Therefore, it becomes a necessity to replace traditional fuels with new energy sources that depend on non-conventional fuels. Hydrogen is a good candidate to substitute conventional fuels by employing fuel cells to produce electricity from hydrogen with high efficiency and considerably lower environmental impact. A fuel cell system is characterized by low emission of nitrogen oxide and sulfur oxide, high generation efficiency, very low noise, fuel flexibility, and possibility of cogeneration [3].

Fuel cells are devices that utilize electrochemical processes to convert fuel into electrical energy, which can be used for

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Nomenclature

Symbol	description		
A	Tafel slope	E	ideal fuel cell potential (V)
C_B	bulk concentration	$E^o_{theor.actual}$	actual theoretical voltage (V)
E_{theor}	reference potential (V)	E_n	nernst voltage (V)
E_{losses}	loss voltage (V)	F	faraday constant (coulombs/mole)
E^o_{theor}	ideal standard potential at 298 K (V)	i_o	exchange current (A)
h	planck constant (J s)	I_{limit}	limitation current (A)
i_{fc}	fuel cell current (A)	K_r	modeling constant
K	Boltzmann constant (J/K)	P_{air}	absolute supply pressure of air (atm)
n	number of electrons participating in the reaction	P_{H2}	partial pressure of hydrogen inside the stack
P_{fuel}	absolute supply pressure of fuel (atm)	R	gas constant (J/mol K)
P_{O2}	oxygen partial pressure inside the stack	$U_{f\mathrm{O2}}$	rate of conversion (utilization) of oxygen (%)
$U_{f\mathrm{H2}}$	rate of conversion (utilization) of hydrogen (%)	$V_{\mathrm{lpm(fuel)}}$	fuel flow rate (l/min)
$V_{\mathrm{lpm(air)}}$	air flow rate (l/min)	V_{act}	activation voltage (V)
V_{cell}	cell voltage (V)	V_{ohm}	ohmic voltage (V)
V_{conc}	concentration voltage (V)	W_{el}	maximum electrical work of fuel cell (J)
V_{out}	output voltage of fuel cell stack (V)	$y\%$	percentage of oxygen in the air (%)
$x\%$	percentage of hydrogen in the fuel (%)	α	charge transfer coefficient
z	cell number of moving electrons	ΔG^0	gibbs free energy change of reaction at standard conditions
ΔG	change in Gibbs free energy (J/mole)	ΔS	entropy change
ΔH	enthalpy change		
C_S	surface concentration		

vehicles applications, portable-power applications, and stationary power generation [4]. Fuel cells are preferred compared to batteries and conventional heat engines. Fuel cells convert fuel into electrical power without storage devices within its structure, unlike batteries, which store energy. The operation of fuel cells is thus restricted only by the existence of fuel and it is capable of generating power as long as fuel is supplied [5]. On the other hand, battery operation depends on its size and stored energy [5]. Moreover, the absence of intermediate conversion compared to mechanical and combustion processes gives many advantages to fuel cell technology [6]. Fuel cell vehicles are now spreading all over the world in real utilizations not only as research or prototypes models [6].

There are many types of fuel cells that are generally defined according to their electrolyte [7]. Alkaline fuel cell (AFC) has an electrolyte of a liquid solution of potassium hydroxide [8]. AFCs cannot use normal outside air to extract the required oxygen since they are very intolerant of carbon dioxide. In addition, they use a corrosive electrolyte, which erodes its parts and contributes to shorten its operating life [8]. Phosphoric acid fuel cells (PAFCs) utilize a liquid phosphoric acid as an electrolyte. The high operating temperature requires a warm-up period and the relatively low current and power densities increase its overall size [8].

Solid oxide fuel cells (SOFC) are high temperature units that use an electrolyte of solid ceramic materials. The high operating temperature causes a high efficiency but speeds up the breakdown of cell components [8]. Molten carbonate fuel cells (MCFCs) operate at high temperature and thus they require large start-up time. The main application of these units is high-rating power generation. Recently, membraneless fuel cells showed many advantages that make them promising units [9]. The elimination of membrane reduces the cost and simplifies the structure. This structure, however, weakens the function of separating the two streams [9]. It is also not ensured that the unwanted mixing with impact of diffusional or convectional interfacial transport is prevented [9].

The polymer electrolyte membrane fuel cell “proton exchange membrane” (PEMFC) employs a solid polymer as the electrolyte. The main advantages of the PEMFC are its high power density, long life, lower corrosion, and lower operating temperature in addition to the use of a solid electrolyte. Thus, PEMFC has a quick start and compact size, which are very important for vehicle applications [1,2,7,9,10]. In addition, PEMFCs operate at low temperatures (50–100 °C), which allows for fast start-up. This characteristics make PEMFCs a strong candidate in transportation activities that require rapid start-up and fast dynamic response over transient times (start, stop, acceleration and deceleration) [3,4].

For real utilization of fuel cells for vehicle applications, many features should be considered, such as performance, reliability, durability, cost, and fuel availability. Since FC systems are large, complex and expensive, it becomes a must to have accurate models prior going through the process of design and building new prototypes. Also, system behavior has to be analyzed at the design stage under different operating conditions to ensure its suitability for the application. In addition, the effect of different operating parameters on the performance has to be investigated.

Several mathematical models of PEM fuel cells have been presented [2,10,11–13]. The majority of them succeeded to simulate the steady-state behavior [10,11], while in practical applications, the fuel cell output power undergoes large variations especially during acceleration and deceleration. During such processes, simple and steady-state models will not be enough to represent the transient dynamics and therefore the analysis under dynamic conditions cannot be carried out. Some dynamic models [2,12] are characterized by their high complexity