MODELING AND CONTROL OF A PROTON EXCHANGE MEMBRANE FUEL CELL WITH THE AIR COMPRESSOR ACCORDING TO REQUESTED ELECTRICAL CURRENT

by

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The aim of this paper is to design and investigate the dynamic behavior of a proton exchange membrane fuel cell system. Dynamic analysis of a proton exchange membrane fuel cell system has been done in Matlab/Simulink software according to electrical current that has been applied from hybrid system. In addition, dynamical fuel cell system has been explained according to oriented control that is started from air injection compressor model. Also hydrogen valve actuator has been controlled according to the compressor model. The results of the fuel cell dynamic model as well as the applied compressor model are fully validated based on the available results in the open literature. The effects of several operating parameters of the fuel cell system such as anode and cathode pressures, cell voltage, compressor voltage, compressor mass flow rate variation with respect to inlet pressure ratio, net and stack powers on the dynamic behavior of the hybrid system are investigated. The results show that the model can predict the dynamic behavior of the fuel cell system accurately and it can be used directly for any control purposes.

Key words: *hybrid system, proton exchange membrane fuel cell, dynamic behavior, battery*

Introduction

According to increasing production of automobiles, environmental pollutant's is increasing. Factories are investigating in order to decreasing pollution for their products but in spite of the fact that factories do this, the pollutant's problem has been remained. Removing this problem completely can be done by using electrical automobile because the efficiency for electrical system is high [1].

High power and energy density and low work temperature, cause to be used proton exchange membrane (PEM) fuel cell as the best kind of fuel cell for automobile factories [2]. Since PEM fuel cell include some various problem such as low response (considering the time constant for response) and unsteady voltage output, according to current variations. In order to eliminating these problems, secondary energy resource (battery) has been used. This action is

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accomplished for good performance and fast response of system to a load variation. In this kind of system called hybrid, two kinds of energy resources have been used for increasing efficiency and preventing the probable delay. Therefore, receive electrical power from energy systems in order to increasing efficiency and supplying produced energy in the safe mode for operational case of vehicle in dynamical conditions is desirable [3].

In many papers, fuel cell losses equations is considered to predict the polarization curve characteristics of the fuel cell in various conditions [4, 5]. The different conditions include partial pressures, stack temperature, relative humidity of input gases, amount of membrane water content, concentration of reactive materials, and semi empirical equations that have been used for losses.

The effects of the different kinds of membrane as well as the inlet relative humidity on the output voltage have been investigated [6]. Results show that any decreasing in the inlet relative humidity ratio increases the cell ohmic losses and subsequently it has high effect on the output voltage.

In addition to the operating parameters, the size of the hybrid system and its components, the degree of hybridization and amount of the consumed fuel are investigated in several papers. Barbir *et al.* [7] are developed a dynamic model for the whole of hybrid system. In their study, the effects of some parameters as operational pressures, temperature, anode and cathode relative humidity, output voltage, were investigated. The effects of the fuel cell operating temperature has been evaluated dynamically [8]. The obtained results show that the temperature variation is in the limit of 349 to 353 K. At the most papers (which have been studied) the time constant considered for this parameter is high because of a little variation in the temperature and relative humidity. Time constant shows the variations of the parameter in the extent of time. Hence, in the most papers this parameter has been considered steady.

According to the electrical current that requested from the fuel cell system, the rate of anodic and cathodic mass flows must be adjusted and controlled. In PEM fuel cell, the inlet oxidant and fuel to the fuel cell systems are oxygen and hydrogen, respectively. Air is usually supplied with a compressor and normally the rate of the fuel control follows the pressure ratio of the air compressor by using a control valve. An oriented control is developed based on the anode and cathode mass flow rates [9]. Reactant materials to the anode and cathode sides have been controlled with applied electrical current from the hybrid control unit [9].

An investigation on the hybrid systems has been done in [10]. In this study, the dynamic of the whole system is investigated and a comprehensive control achieved based on the drive cycle [10].

To bridge the still existing gap of more sophisticated dynamic PEM fuel cell models, the main object of this investigation is to develop a complete dynamic model for both the fuel cell system and the hybrid system. The model is implemented in the Matlab-Simulink software. In this paper, the fuel cell system model is fully described and the results of this model are presented in the next sections.

Model description

Figure 1 shows the hybrid system considered in this study. Subsystems of the PEM fuel cell and battery collections are also included in this figure *i.e.* The PEM fuel cell system, battery, hybrid control unit, and power requested signal. According to this system, the amount of electrical current can be obtained according to the hybrid control unit algorithm.

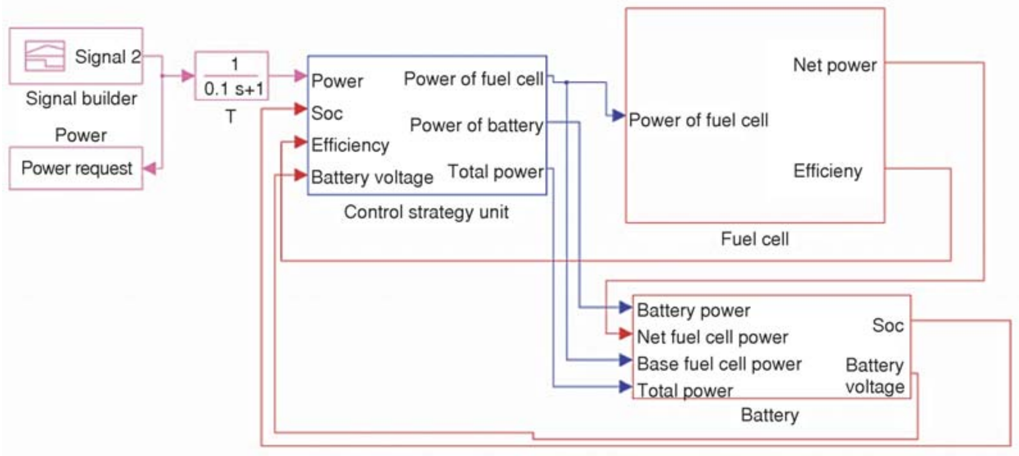

Figure 1. Simulink model of hybrid propulsion system

The PEM fuel cell subsystems have been modeled according to the governed equations. In continuous, the governed equations have been referenced for each subsystem. The main assumptions considered for the PEM fuel cell system are:

– during the operation, the stack and inlet stream temperature are considered constant (350 °K) *i.e.* isothermal condition,
– the relative humidity of the inlet flows are also considered constant (90% and 100% for the cathode and anode sides respectively),
– rate of reaction at anode side is more rather than the rate of reaction at cathode side,
– the anode pressure is followed from the cathode pressure, and
– the dead-ended model is used for the anode reservoir.

As shown in fig. 1, according to applying an arbitrary power to system, the electrical current of each energy resources can also be obtained with regards to the considered control strategy. Whereas this model is very comprehensive, only model of the PEM fuel cell system has been presented in this paper and the other subsystems as control strategy, requested power from hybrid system, and battery, are not explained. Therefore, the fuel cell system is the goal model for this paper.

For the fuel cell system, an accurate dynamic model has been presented according to the applied electrical current. For the battery system, according to demanded electrical current, harvested electrical power from battery or storage power in it can be calculated. In the storage state, the power of battery is supplied with fuel cell. In this paper only the electrical current, which is obtained from the hybrid unit, has been applied to the fuel cell system and the result of this system has been shown in the next sections.

Hybrid control system

Due to the requested power from the electrical motor of the vehicle, the electrical current of the PEM fuel cell system can be determined from the hybrid control unit. As the control unit must divide the amount of the electrical current between both energy systems *i. e.* PEM fuel cell and battery, it must be integrated with the model as well. The inputs of the hybrid control unit are the quantity of drawn electrical power from the electrical motor, fuel cell efficiency, and the state of the charge of battery. In this study and according to the designed model, activation

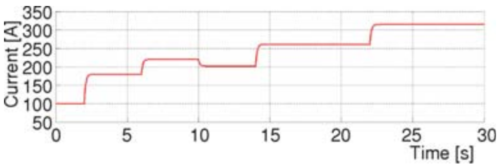

Figure 2. Applied electrical current

signals and quantity of drawn electrical currents for both battery and fuel cell systems can be obtained from the hybrid unit. Whereas, this model is so comprehensive and sharing the amounts of power between energy resources is in the outside of the argument of this paper, it is not explained. Hence, the electrical current that applied to the PEM fuel cell system is shown in fig. 2 (according to embedded control strategy model).

The PEM fuel cell system and auxiliary component

The main focus of this paper is on the fuel cell system model. Fuel cell system has been modeled by Matlab-Simulink software. As can be seen in fig. 3, the fuel cell system model involved a PEM fuel cell stack with 381 cells (that are connected in series), air injection compressor, air cooler, air humidifier, fuel cell radiator, hydrogen tank valve, hydrogen humidifier, supply manifold, return manifold, and separator of water in cathode output. The dynamic model of the air injection system is designed based on the amount of electrical current requested from the control unit.

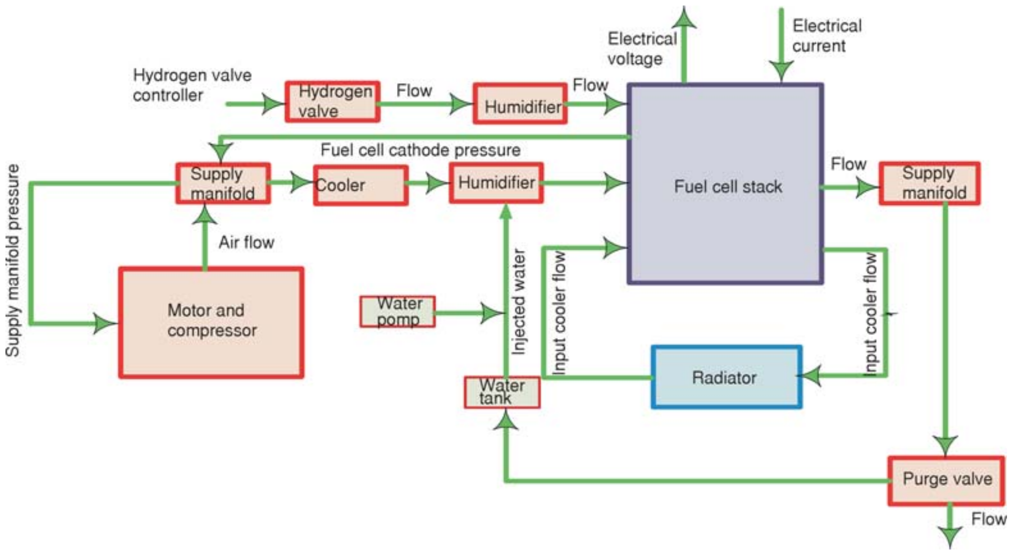

Figure 3. The PEM fuel cell system

In this paper, the inertia model of the air compressor has been considered, with a nonlinear curve. This model is considered according to the lumped-volume manifold filling dynamics. Static models of the cooler and humidifier in the cathode side are developed based on the lumped approach and conservation equations. In the next sections, the models of the main components are described.

Air injection compressor

As the main auxiliary power consumption in the fuel cell system is belongs to the air compressor, a comprehensive model must be considered for it. In this part, the mass flow rate of

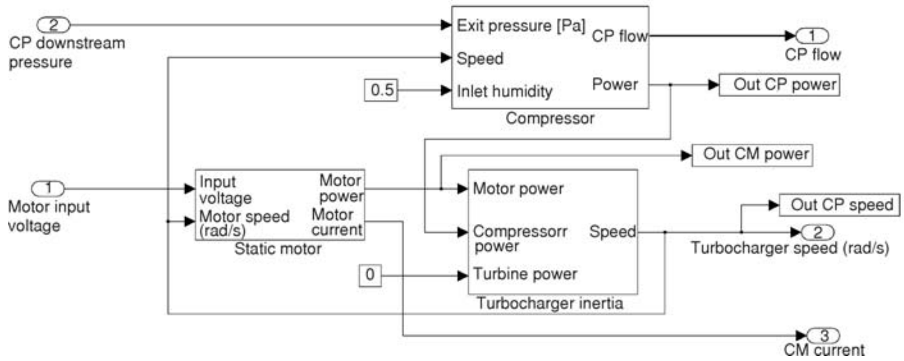

Figure 4. Simulink model of the air compressor

reacting materials has been regulated according to the requested electrical current. To prevent any damage or pin hole, the pressure difference in both side of the membrane must be equal. As can be seen in fig. 4, three subsystems are considered for the air compressor.

In the first subsystem, the dynamic of compressor motor can be considered with regards to the voltage and electrical current of the compressor which can be calculated [11]:

$$v_{\mathrm{cm}} = 0.672 \times I + 33.5541156 \tag{1}$$

$$i = \frac{v_{\mathrm{cm}} - K_{\mathrm{v}} \omega_{\mathrm{cp}}}{\mathrm{R}_{\mathrm{cm}}} \tag{2}$$

$$K_{\mathrm{v}} = 0.0153 \left[\frac{v}{\frac{rad}{s}} \right], \quad \mathrm{R}_{\mathrm{cm}} = 0.82$$

As can be seen, the compressor voltage is in relation with a linear function of PEM fuel cell electrical current.

The second subsystem is related to the compressor static model. This subsystem is used in the third subsystem in order to determine the angular velocity of the air compressor. Therefore, Jensen and Kristensen's model is used for this collection [11]. In this model, non-dimensional parameters have been used to provide a dynamic model of compressors. The equation considered in this research based on this model is:

$$P = \tau \omega_{\mathrm{cp}} = J_{\mathrm{cp}} \frac{\mathrm{d}\omega_{\mathrm{cp}}}{\mathrm{d}t} \omega_{\mathrm{cp}} = P_{\mathrm{cm}} - P_{\mathrm{cp}} \tag{3}$$

where P_{cm} can be calculated according to the electrical current and voltage; P_{cp} can also be calculated from the mass flow rate that passing through the compressor according to Jensen and Kristensen's model. This model is used for gaining a method for the status that the quantity of mass flow rate is changing.

Hydrogen valve model

In this model, according to the air pressure, mass flow rate of the hydrogen can be determined:

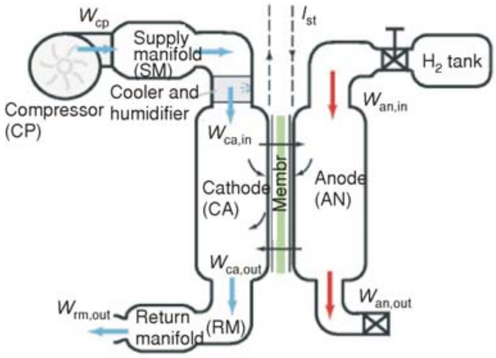

Figure 5. Manifold filling of the lumped model [12]

$$
\begin{aligned}
W_{\mathrm{an,in}} &= k_1 (k_2 P_{\mathrm{sm}} - P_{\mathrm{an}}) \\
k_1 &= 2.1\,[\mathrm{kg(sKPa)^{-1}}], \quad k_2 = 0.94
\end{aligned}
\tag{4}
$$

Manifold model

Figure 5 shows how hydrogen and air are injected into the system. As can be seen, the injected air passes through the supply and return manifolds. A schematic model of the supply and return manifolds has been shown in figs. 6 and 7, respectively [12].

Air cooler

The assumptions considered to the air cooler are:

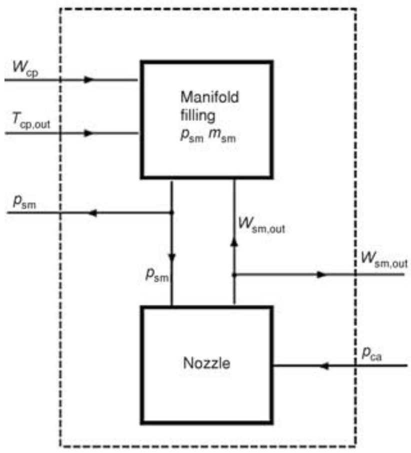

Figure 6. Schematic diagram of the supply manifold

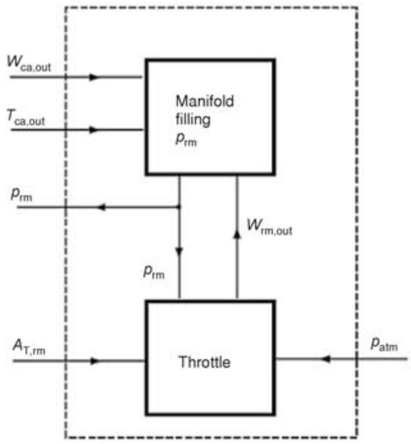

Figure 7. Schematic diagram of the return manifold

– the outlet temperature of the air cooler should be constant (80 K), and
– the operating pressures of the supply manifold and cooler are equal ($p_{cl} = p_{sm}$).

In the air cooler model, variations in the relative humidity and mass flow rate of the vapor have been considered with regards to any change in the air temperature. The equations those are considered for this subsystem is presented [12].

Humidifier model

In this subsystem, a static model is considered to preserving the quantity of relative humidity in the particular value. The full model is presented in [12].

Fuel cell stack

As shown in fig. 8, the stack model includes four subsystems. The stack voltage, anode mass flow, cathode mass flow, and membrane hydration have been included in these subsystems. In literature only stack voltage model has been explained. Other models are fully described in [12].

Model of stack voltage

The Nernst equation has been used in this study to calculate the stack voltage [4]. When the circuit is in the close status, the cell losses must be reduced from the open circuit voltage. These losses are mostly related to the ohmic and activation polarizations [13-15].

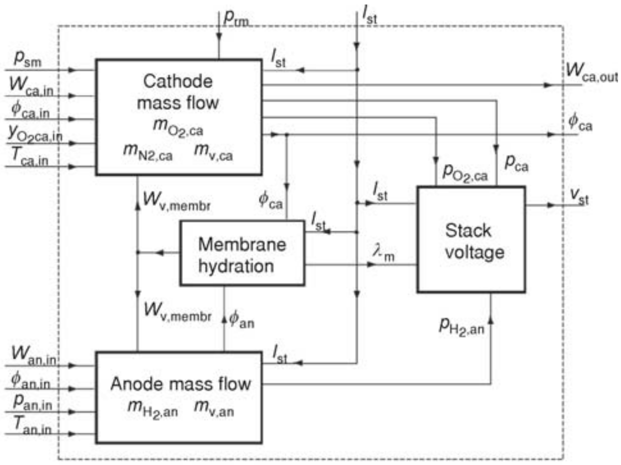

Figure 8. Block diagram of the stack model

Activation losses

Whereas reaction of activation in anode side is better than of cathode side, losses of cathode activation are more than anode section [13]. Therefore, activation voltage is presented:

$$v_{\mathrm{act}} = v_0 + v_{\mathrm{a}}(1 - e^{-c_1 i}) \tag{5}$$

where i is the input current density. The fuel cell active area is 280 cm^2, v_0 is the voltage drop in zero current density and other constants are empirical. The amount of activation voltage is related to temperature and pressure of oxygen in the cathode section. Other parameter has been gained from [13].

Ohmic losses

Resistance of polymer membrane in emission of protons and resistance of electrodes in electrical collector plates, show themselves as the shape of electrical resistance that they are depended to the temperature and relative humidity of PEM fuel cell [14].

$$R_{\mathrm{ohm}} = \frac{t_{\mathrm{m}}}{\sigma_{\mathrm{m}}}, \quad t_{\mathrm{m}} = 0.0125 \tag{6}$$

$$\sigma_{\mathrm{memb}} = (0.005139\lambda - 0.00326)\exp\left[350\left(\frac{1}{303} - \frac{1}{T_{\mathrm{f}}}\right)\right] \tag{7}$$

Concentration losses

Concentration losses can be obtained from the eq. (8) [15]:

$$v_{\mathrm{conc}} = i\left(c_2 \frac{i}{I_{\max}}\right)^{c_3}, \quad I_{\max} = 2.2, \quad c_3 = 2 \tag{8}$$

where $I_{\max}$ represent the maximum value of electrical current that could be extracted from the fuel cell.

Cell terminal voltage

Close circuit voltage earned from deducing the open circuit voltage from voltage losses. The complete Simulink model of the fuel cell system is shown on figs. 9(a) and 9(b). Be-

Table 1. Parameters of the fuel cell model

Parameter	Value	Unit
R	8.314	$kJkg^{-1}K^{-1}$
t_m	0.01275	cm
A_f	280	cm^2
V_{an}	0.005	m^3
V_{sm}	0.02	m^3
F	96485	coulomb
c_2	0.68	ohm
T_f	350	K
J_{cp}	$5\cdot10^{-5}$	kgm^2
N_{cell}	381	–
V_{ca}	0.01	m^3
V_{rm}	0.005	m^3

cause this model is so comprehensive, parts of this model are not explained and referred to references. The parameters used in this model are listed in tab. 1.

Results and discussions

The requested electrical current from the PEM fuel cell can be determined from the hybrid control unit. The applied current density as a function of time is shown in fig. 2. In future studies, the modality of sharing electrical current between energy resources can be described. This model can be produced according to the circumstances of the energy resources.

Voltage of the compressor motor, hydrogen valve controller, injection of humidifier water, and requested electrical current form the fuel cell (originated from hybrid control) are important parameters and devices for produced control model.

Figure 10 shows the cathode and anode pressures as a function of current density. As can be seen, the pressures in the both side of the membrane are almost same. Therefore, the hydrogen valve controller operates accurately and the anode pressure can be correctly regulated with regards to the pressure in the cathode side.

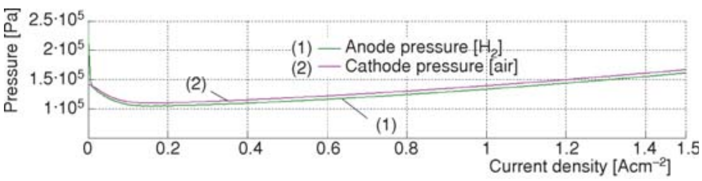

Figure 10. Distributions of cathode and anode pressures according to current density

As can be seen in fig. 10, hydrogen pressure has been controlled according to actuator that is in relation with the air pressure.

Additionally, the results of the dynamic model have been compared with the same model in the open literature. This model is in the same assumptions and conditions with respect to the produced model. Electrical current that requested from the fuel cell, subsystems, parameters used in tab. 1, applied assumptions *etc*. are the parts of similar assumptions and conditions for produced model and reference.

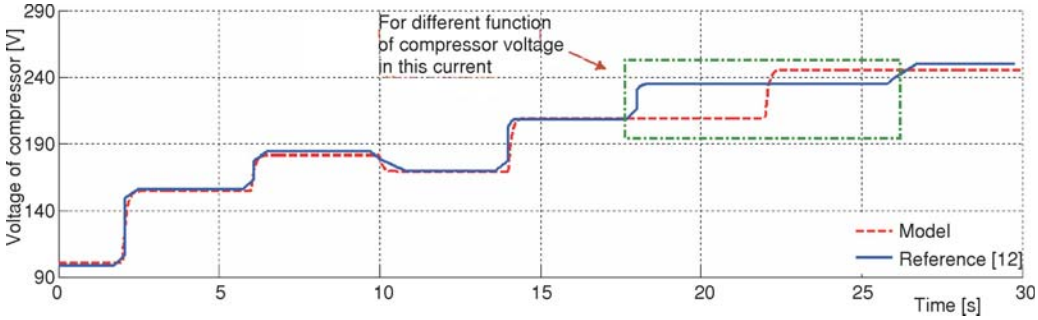

Figure 11. Distribution of compressor voltage for pressent and reference models [12]

Therefore, presented diagrams of the presednt model have been compared with the results of reference model. Applying the same electrical current to this model and based on the static feed forward equation of compressor, compressor voltage diagram has been obtained for present and reference models. Results for these two models follow each other, except in high electrical current. The reason is use of antoher equation for high electrical current for the compressor function in ref. [12]. As a consequence, at high electrical conditions, mass flow rate was higher, as well as the oxygen stoichiometric ratio and pressure of air for ref. model. Compressor voltage results for the these two models are shown in fig. 11.

As it is obvious, compressor voltage has a small difference in the time that is more than 18 seconds.

In addition, this influence has been shown in the results of dynamic polarization curves for this rang of time. Hence, this model can be validated with the reference model according to comparing these results in one diagram. In fig. 12, those models (reference and produced model) have been shown.

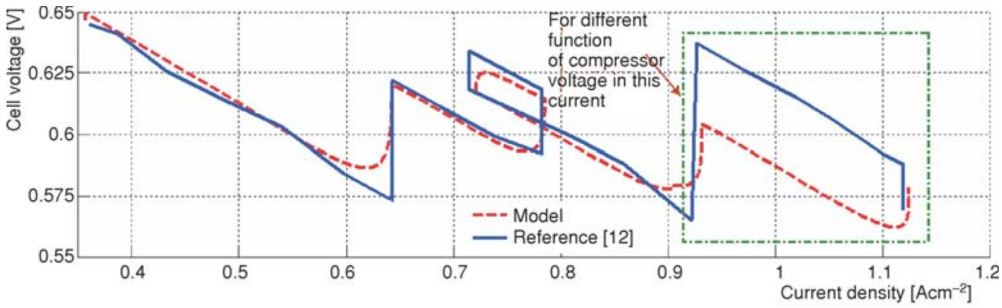

Figure 12. Dynamical polarization curve for pressent and reference models [12]

With increasing the requested electrical current from the fuel cell, the voltage quantity of the collection decreases but the electrical power increases. With increasing in electrical power, the fuel cell efficiency is reduced. If system responses which is being investigated synchronically, dynamic effects are visible on the stack and total power according to variable electrical current in the time steps of 2, 6, 10, 14, and 22 seconds. Therefore, the results of electrical power of the stack and final electrical power of the fuel cell system have been shown in fig. 13. This difference is originated from the parasitic power of air compressor motor (in order to inject of air to fuel cell).

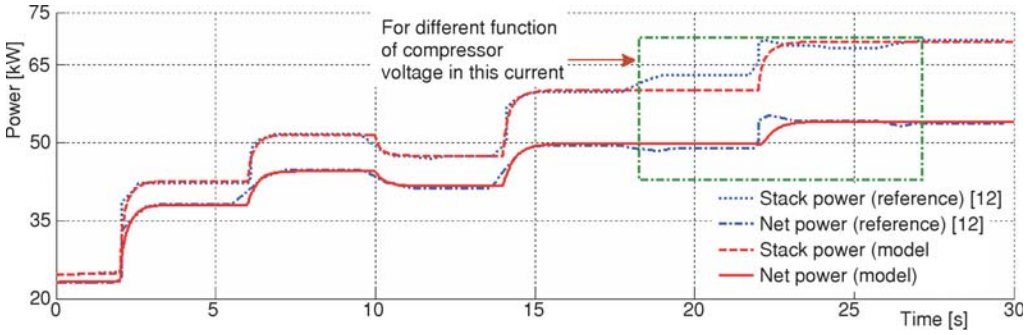

Figure 13. Net power of fuel cell and stack power pressent and reference for models [12]

The maximum power of the fuel cell stack is 70 kW. In this situation, about 15 kW of compressor power consumes for sending air to fuel cell.

Confirmation of the compressor status in dynamic mode and according to mass flow rate and pressure ratio is essential. This case shows the accuracy of the designed model. As it is visible, dynamic status of the compressor is situated in embedded space (between surge lines). In addition, this model has been compared with the same model of [12] (fig. 14). Small differences between the results of produced model and reference model show the accuracy of the compressor model.

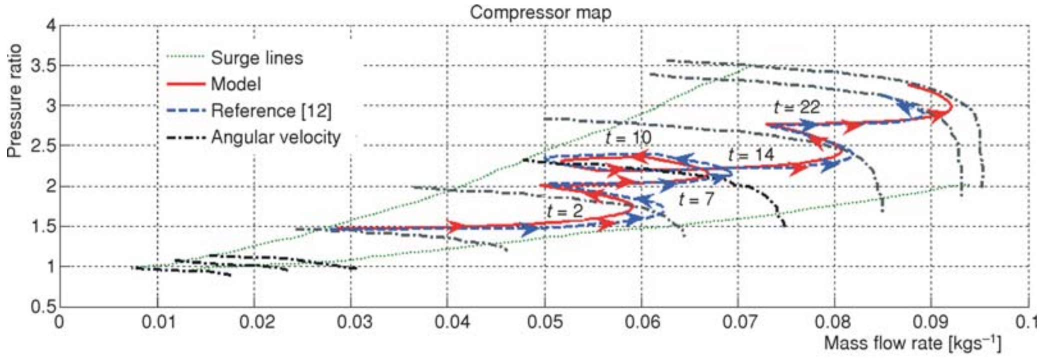

Figure 14. Validation of compressor for dynamic model [12]

Conclusions

To bridge the still existing gap of more sophisticated dynamic PEM fuel cell models, the main object of this investigation is to develop a complete dynamic model for both the fuel cell system and the hybrid system. Therefore, a dynamic analysis of a PEM fuel cell system has been done in Matlab-Simulink software according to electrical current that has been applied from hybrid system. In addition, dynamical fuel cell system has been explained according to oriented control that is started from air injection compressor model. Hydrogen valve actuator has been added to system. This system has been controlled with the pressures of compressor and anode side. As shown in fig. 10, it has been used to equalize the cathode and anode pressures. According to fig. 3, control of PEM fuel cell system originated from the subsystems that affect each other. Stack model consists of four subsystems that have been modeled exactly and accurately. The results of the fuel cell dynamic model as well as the applied compressor model are fully validated based on the available results in the open literature [12]. Thus, compressor voltage, polarization curve of the fuel cell and compressor dynamic curves have been validated. In addition, stack and net power of model have been obtained. Difference between these curves originated from compressor parasitic power. The results show that the model can predict the dynamic behavior of the fuel cell system accurately and it can be used directly for any control purposes and in the hybrid systems. Moreover, this model has been created, based on the lump method, and the general equation has been considered for this simulation; therefore, the benchmark is the survey of a comprehensive and actual system, with consideration of some reasonable and undeniable assumptions. As a result, it could be able to design a very comprehensive and complete model of fuel cell, with considering all details model. Meanwhile, by use of some approximation in governing differential equation, the complex set of equation would be decreased. As well as, results of the model, asserts the origins of the tradeoff between air flow control and system net power. Also the analysis suggests a multivariable control architecture where the power conditioning unit of the fuel cell and the traction motor controller proportionate for better performance.

Nomenclature

A – area, [m^2]
I – electrical current, [A]
i – input current density, [Am^{-2}]
J – inertia, [kgm^2]
m – mass, [kg]
P – power [Js^{-1}]
p – pressure, [Pa]
R – gas constant [Jmol^{-1}K^{-1}]
T – temperature, [K]
t – thickness, [mm]
V – volume, [m^3]
v – voltage, [V]
W – mass flow rate, [kgs^{-1}]

Greek symbols

λ – membrane water content, [–]
σ – membrane conductivity, [Ωcm^{-1}]
ϕ – relative humidity, [–]
ω – angular velocity, [rad·s^{-1}]

Subscript

act – activation
f – fuel cell
cl – cooler
cm – motor
conc – concentration
cp – compressor
in – input
memb – membrane
ohm – ohmic
out – output
sm – supply manifold
rm – return manifold
st – stack
v – vapor

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Appendix

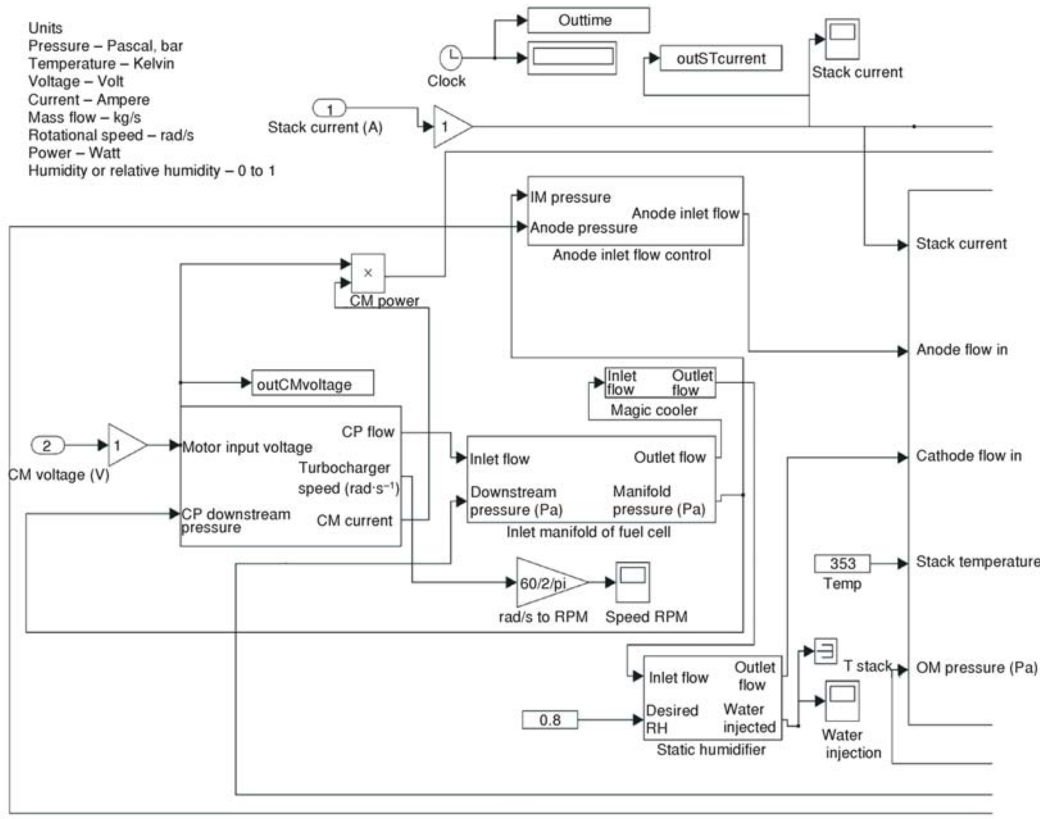

Figure 9(a). Simulink model of PEM fuel cell system – input part

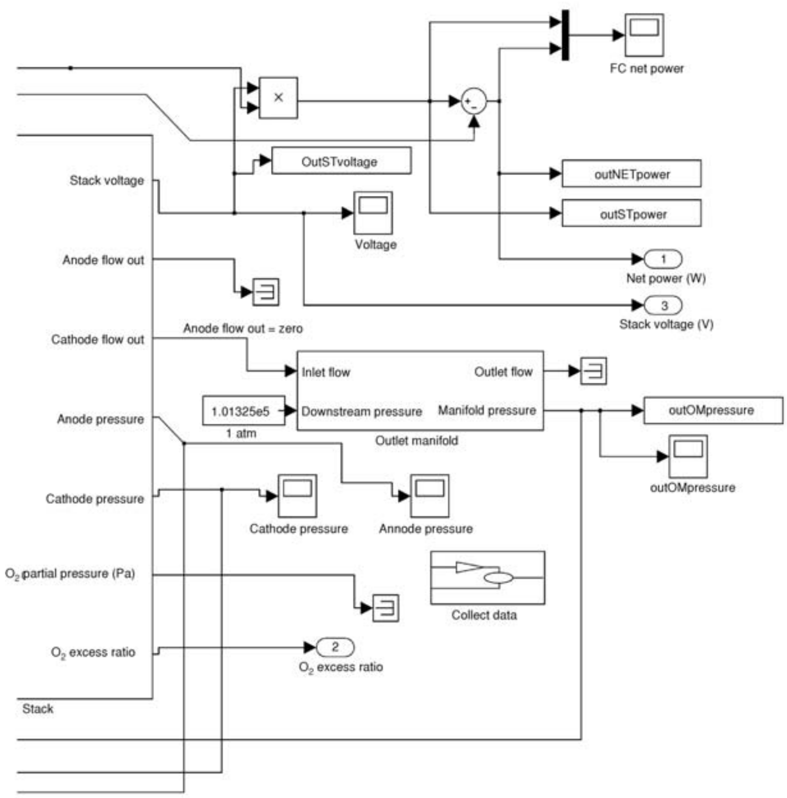

Figure 9(b). Simulink model of PEM fuel cell system – output part