Simulation analysis of fuel cell integration in a hybrid car

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Abstract. Fuel cell is one of the green technologies that can help reduce toxic gas and decreasing effect of greenhouse gases in the world. This paper attempts to improve simulation model of fuel cell system that is easy to use and at the same time have an acceptable accuracy. The simulation model is developed through Matlab/Simulink software using Energetic Macroscopic Representation method which accuracy is compared with an established model. Simulation analysis of fuel cell integration is conducted by using experimental data from a real hybrid car. There are two potential types of system that were considered for the hybrid car in term of electricity generation and power produced to move the car, a full fuel cell car or a hybrid of fuel cell and battery. Analysis reveals that the hybrid car using combination of fuel cell and battery system is more effective compared to the car using fully fuel cell system due to factors that prevents fuel cell wide utilization for the vehicle.

1. Introduction

Research and development in fuel cell system gives hope in reducing emission and pollution from combustion engine vehicle that can affect respiratory system of mankind [1]. In some application, fuel cell have become a main power supply to new and modern transportation technologies and become an alternative to more eco-friendly and emission free transportation [2]–[5]. This progress is accelerated by fast simulation and modeling which is safer and can save cost in the realization process [6], [7]. A propos, simulation and modeling is the easiest way to overlook, optimize, and achieve highest performance for certain design since we have the capabilities to monitor and adjust parameters and constraint through various possibilities [3], [5], [8]. Simulation software like Matlab/Simulink, Femap, ANSYS and SimulationX give the opportunity to engineer and designer to make changes and adjustment to their design after looking at results of the simulation [2], [8].

The beneficial qualities of fuel cells such as high efficiency, low environmental pollution, fuel diversity, reusability of exhaust heat and modularity leads to power generation for various applications [2]. In hybrid electric vehicle (HEV) system, proton exchange membrane fuel cell (PEMFC) has become the choice because it can operate at low temperature, has high-power density, compact in size, lightweight, and need relatively short time for start-up [9]. The drawbacks of fuel cell with limited operating voltage range and load handling capability during transients are usually backed up by

combining a sufficient battery power. This combination can provide a good dynamics and can provide peak loads increasing the lifespan of fuel cell and keeping the battery state of charge (SOC) within safe limit [10].

The aim of this paper is to improve simulation model of fuel cell system that is easy to use with an acceptable accuracy in order to integrate a fuel cell pack in a HEV. Load fluctuations in HEV will cause fuel starvation, blooding, and drying membrane of PEMFC if the fuel cell pack is to be used alone to supply power [3]. Analysis through modeling and simulation can provide perspective for the integration and optimize parameters of the HEV design. The flow of this paper is as follow, the next section will present the fuel cell model development, followed by discussion in section three, before finally the conclusion in the last section.

2. Simulation model development

The modeling of fuel cell system has been applied by using energetic macroscopic representation (EMR). The connection of each part in this system is corresponding to arrows that represented the action and reaction principle between each part. The action and reaction variables in each part will produce a product which equals to instantaneous power exchanged between each subsystem.

Table 1 shows the list of parameter used for the simulation and Figure 1 shows the simulation model of the fuel cell using the EMR method.

Table 1. List of constants used in the simulation

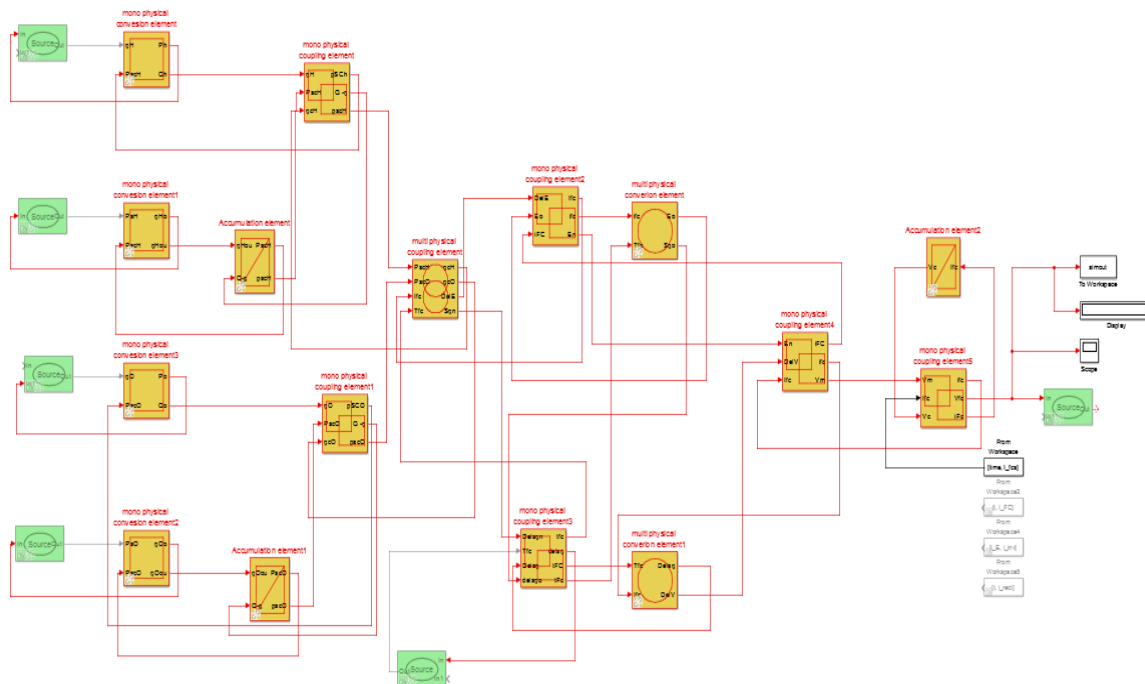| Constant	Denomination	Value	Unit
Faraday constant	F	96485.3329	s A
Perfect gas constant	R	8.314472	-
Exchange current	Io	0.01	mA
Internal current	In	0.01	mA
Limit current	Il	1000	A
Ohmic resistor of a cell	Rm	0.01	mΩ

Figure 1. Simulation model of the fuel cell using energetic macroscopic representation method.

2.1. Fuel cell mathematical model

The EMR of the fuel cell mathematical model are built in Matlab Simulink. Equations listed in equation 1 to 5 are the critical equations in the simulation model of fuel cell. Equation 1 is the fuel cell potential, with the voltage of fuel cell V_{fc} is obtained from the summation of cell voltage and charge double layer voltage V_c multiplied with number of cells, N because arrangement of the fuel cell stack is in series. The natural behavior of the fuel cell is capacitive called as 'charge double layer' situation where the $R_t C_{dl}$ is the transfer function. R_t is the resistance and I_{PAC} is the fuel cell stack current. This situation occurs because the interface between the layer of charge on electrode-electrolyte and it will be stored the charges like the capacitor. The thermodynamic potential E_o is modeled using equation 3 where T_{fc} is the fuel cell temperature with $\alpha, \beta, \gamma, \delta, \upsilon$ are constants obtained from the entropy of molar formation and Faraday constant. Voltage drop ΔV is a summation of activation, concentration and ohmic losses. Nernst potential E_N is the total of a potential variation, ΔE due to changes in partial pressure at electrodes and thermodynamic potential, E_o. These equations are related to thermodynamic, fluid, electric and electrolysis laws come from engineering principle like Gibbs law and Nernst equation. The constants used in the simulation model are given in Table 2.

Each input and output for an element can be identified from the physical equation and sometimes for certain element, the physical equation needs rearrange to gets their connection. This modeling is very straightforward and it can determine the control system by using inversion rule. Every block in EMR can directly be inverted steps by steps when there is no energy accumulation.

$$V_{fc} = N(V_M + V_c) \tag{1}$$

$$\frac{V_c}{I_{PAC}}(s) = \frac{R_t}{1 + R_t C_{dl} s} \tag{2}$$

$$E_o = \alpha + \beta T_{fc} + \gamma T_{fc}^2 + \delta T_{fc}^2 + \upsilon T_{fc} \ln T_{fc} \tag{3}$$

$$V_M = E_N - \Delta V \tag{4}$$

$$E_N = E_o + \Delta E \tag{5}$$

Table 2. The list of parameter for simulation model

Parameter	Denomination	Value	Unit
Temperature	T	55	^oC
Volume rate of Hydrogen, H2	q_{H2}	2	m^3s^{-1}
Volume rate of Oxygen, O2	q_{O2}	5	m^3s^{-1}
Number of stack	N	20	mA
Stoichiometry factor (Anode)	-	2	-
Stoichiometry factor (Cathode)	-	5	-

3. Results and discussion

All simulation for analysis are carried out in Matlab/Simulink by using 8th order solver. The fixed step size is 0.01 s and the volume flow rate is constant for 2 m^3s^{-1} hydrogen gas and 5 m^3s^{-1} oxygen gas.

Figure 2 shows the simulation data of the developed model and experiment data from an experiment establish with parameters in Table 1. The maximum error between both data is 12%, but at other parts of the results, the simulation results follow the trend from the experiment.
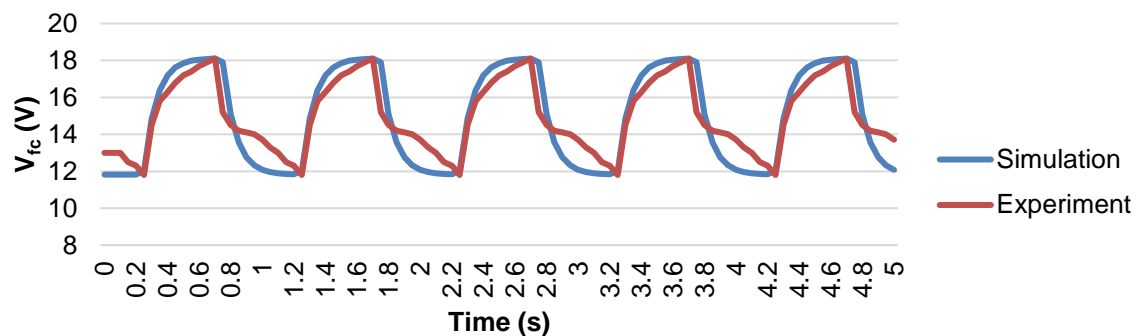
Figure 2. Validation of the model compared with experiment result.

In the experimental validation, the data for voltage fuel cell, V_{fc} was taken from previous paper to achieve simple validation for this project. The solver has been used for validation of simulation is Dormand-Prince which is 8th order, the fixed – step size is 0.05s and the parameter need to be defined is oxygen stoichiometry which is 4 and Nernst potential coefficients, A_{cd} and B_{cd} to calculate Nernst potential, E_N. Figure 2 shows the simple validation voltage of fuel cell produced from the experiment with data obtained from the simulation model. The model has good accuracy when voltage is more than 14 V, but less accurate when the voltage is less than that.

After consideration and following every parameter provided, the percent of error for voltage of fuel cell is 0.018% according to the calculation. The percentage was in the range 0% up to 5%, so data from the simulation model is very near with the targeted value.

The objective of the project is to improve the simulation model of fuel cell system that is easy to manipulate and simulate, so the parameter that needs improvement are the power generation and also the electricity generation between two systems of the hybrid car which is fully fuel cell and combination of the fuel cell and battery. Moreover, Figure 3 shows the transformation of voltage for hybrid car using fully fuel cell system and combination fuel cell and battery system against time.

After analysis, the hybrid car using combination of fuel cell and battery is more effective compared to the hybrid car using fully fuel cell system. This situation occurs because the battery has a special function called a reverse process known as regenerative braking. This process has reduced the power generation to move the car by 25% compared to other system suggested for the car.

The differences between these two systems are on the ability of the system to recharge the current inside the system. The captured regenerative braking is when the motor used to move the vehicle is rotated backward for the purpose to slow down the speed of the vehicle and the energy from the movement of the vehicle effect to the motor for running in reverse. So, the energy losses from that situation are captured by braking system and stored in the battery. However, this system does not available at the system if using fully fuel cell and this system needs a lot of energy to move the car whenever the car needs to move again and for start up the system.

Besides that, the middle region for both graphs shows that the effect of acceleration and deceleration of the car to the voltage and power produce by the system. The middle region for the graph increase significantly from time 256s until 830s for combination fuel cell and battery. However, the hybrid car using fully fuel cell produces an unstable graph for voltage and power generation in the middle of the graph and it needs a lot of power and energy compared to other systems. The maximum value of voltage and power that produces from this system is 1289V and 686922.9 W.
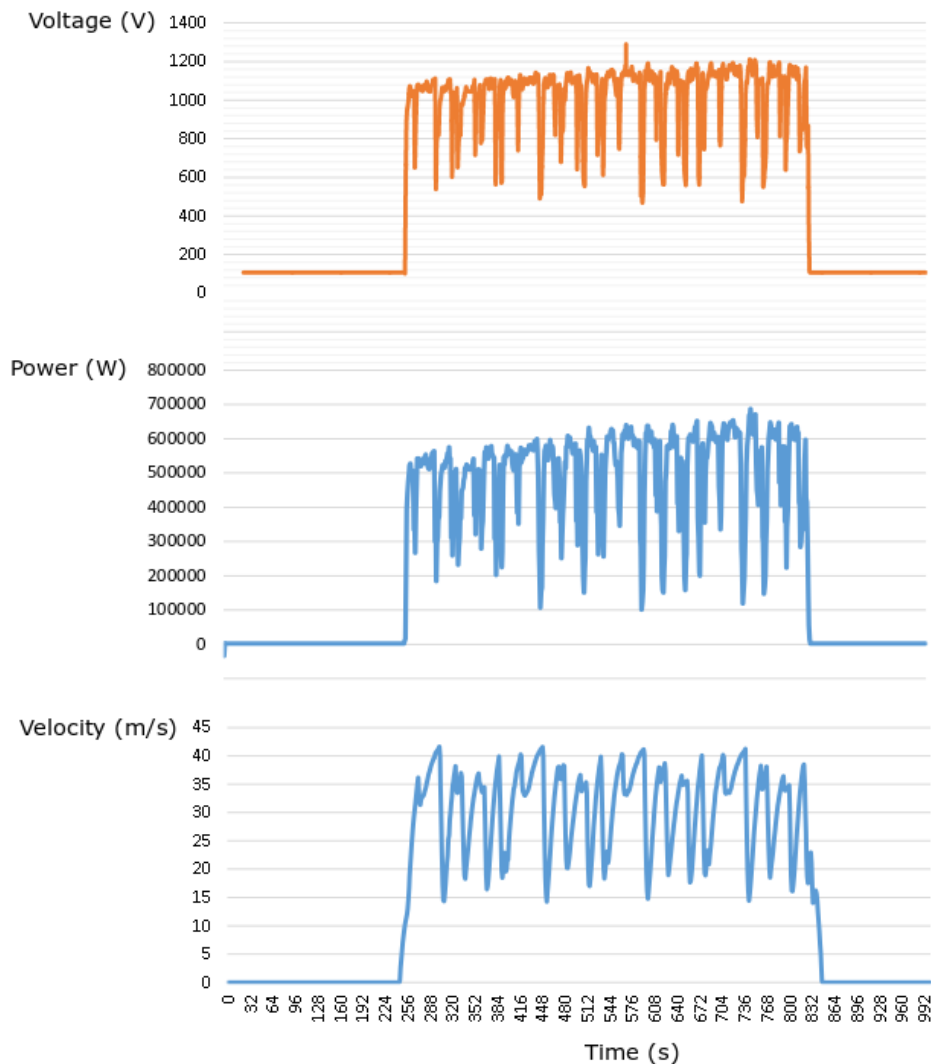
Figure 3. The transformation of voltage for hybrid car using fully fuel cell system and combination of fuel cell and battery system against time.

4. Conclusion and future works

As a conclusion, we can say that the hybrid car with the system using a combination between the fuel cell and the battery is more effective compared to the hybrid car using fully fuel cell system. This situation occurs because the battery has a special feature called a reversible process where it can capture regenerative braking. This process occurs when the motor rotates backward for decreasing the speed of the vehicle and the energy from the movement of the vehicle causes motor to rotate in different direction where the energy is captured by the braking system and transfer it to the battery. This process has reduced the power generation to move the car by 25% compared to other systems for the hybrid car. In addition, the accuracy of the simulation model can be seen through the percentage of error between experimental data and simulation data, the percent of error between both data is 0.018% only. Then, the value of percent of error is almost near with zero and it makes the data from simulation model almost the same with the actual data from the experiment.

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