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Modeling and Simulation of Electric Vehicle fed by PEM Fuel Cell

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ABSTRACT: *This paper presented the modeling and simulation of electric vehicles fed by PEM fuel cell. The proposed system consists of a PEM Fuel Cell, a 3-phase induction motor, an inverter dc/ac and a speed controller. The purpose of this study was used to determine the response of an induction motor with a PEM Fuel Cell as an electric energy source. The models developed in this paper using the neural network model for PEM Fuel Cell and the vehicle model. The simulation was done using the vehicle speed as input to the speed controller and the load torque as input to the induction motor. The simulation result of the rotor speed was compared with the reference speed at the speed controller.*

KEYWORDS: *PEM Fuel Cell, Vehicle Model, Neural Network (NN) Model*

I. INTRODUCTION

One of the means of transportation used for the mobility of people in the cities and villages is a vehicle. In Indonesia, the vehicle is used mostly with oil fueled. Oil is fossil fuel. Fossil fuels are very precious resources because they are non-renewable. Consumption of fuel for the vehicle is more increasing, while the fuel reserves is slowly dwindling [1]. The other problem of the internal combustion engine (ICE) vehicle is gas emissions. The ICE vehicles produce gas emissions that potentially generate air pollution, as presented by the Environmental Protection Agency (EPA)[2]. Electric vehicles are being developed as solution to eliminate oil use and emissions[3]. Electric vehicles require batteries as the energy source. The battery powered electric vehicles have very limited range[4]. Batteries need to be recharged after electric vehicles operate continuously for a few hours. Depending on the type of battery pack, they require an 4 or 8 hour recharge. To charge with 80% capacity , we need 30 minutes[5].

The hydrogen and the fuel cells can represent a solution to the problem of the emissions due to the transport vehicles. Fuel cell vehicles have the potential to address all of the problems surrounding the ICE vehicle [6]. A fuel cell is a source of electrical energy using hydrogen and oxygen to generate electricity. This technology uses hydrogen as fuel and oxygen as oxidant. Outputs of fuel cells are heat and water that don’t pollute the environment. A fuel cell can continuously provide electricity as long as hydrogen, is continuously supplied [7,8,9]. Hydrogen can be stored in a tank. By using a spare tank, refueling quickly resolved, so that the fuel cell can drive the vehicle for a long time. Polymer Electrolyte Membrane Fuel Cell (PEM Fuel Cell) is popular and suitable used in vehicles. It operates within a range of relatively low temperatures, has higher efficiency than combustion engines, is very quiet and produces no emissions [10].

A mathematical model that simulates is an important tool to improve the possibility of utilizing PEM Fuel Cell in vehicles. The models used in this paper consist of the Neural Network model of the PEM Fuel Cell [11], the vehicle model, the inverter block and the induction motor block. The setpoint value of the speed controller and the load torque are obtained by the vehicle model. The purpose of this study is to see the performance of the induction motor that fed by a PEM fuel cell.

II. PROPOSED SYSTEM DESIGN

The proposed system is shown in Fig.1. The system consists of a PEM Fuel Cell, an Inverter dc to ac, an induction motor, a speed controller and a vehicle. PEM Fuel Cell using NN model is connected to the induction motor via the inverter dc/ac. The inverter is pulse-width modulated (PWM) to produce a three-phase 50 Hz sinusoidal voltage to the induction motor. The load torque T_m applied to the machine's shaft is constant. The load torque is obtained from the vehicle model. The speed controller is used to generate pulses to the inverter. The reference speed value $\square_m$ is obtained by the vehicle model.

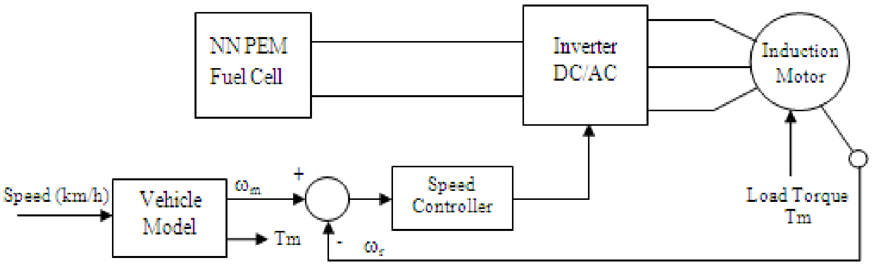

Fig.1 Proposed system model

2.1 Vehicle Model

This vehicle model is used to calculate the total power that used to drive the wheels of the electric vehicle. The total power (P_m) is obtained by multiplying the total force (F_{tot}) and vehicle speed (v), is given by [12,13]

$$P_m = F_{tot} \text{ x } v \qquad (1)$$

Total force (F_{tot}) is sum of wheel friction force (F_{wf}), air friction force (F_{af}), slope friction force (F_{sf}) and acceleration force (F_a), as follow:

$$F_{tot} = F_{wf} + F_{af} + F_{sf} + F_a \qquad (2)$$

These forces are:

$$F_{wf} = C_{rr}.m.g \qquad (3)$$

$$F_{af} = 0,5\, C_d\, \rho\, A\, v^2 \qquad (4)$$

$$F_{sf} = m\, g \sin\psi \qquad (5)$$

$$F_a = m\, a \qquad (6)$$

where m is the weight of the vehicle, kg; g is the gravitational acceleration, m/s^2; C_{rr} is the coefficient of wheel friction, dimensionless; C_d is the coefficient of form, dimensionless; ρ is air density, kg/m^3; A_f is shape of the surface of the vehicle, m^2; v is the vehicle speed, m/s; ψ is the slope of road; a is the acceleration, m/s^2.

Wheel friction force (F_{wf}) is caused by the friction of tires on the road. Wheel friction force is constant, and almost does not depend on the speed of the vehicle. Slope friction force (F_{sf}) is force on the vehicle to move up or move upward with slope (ψ). Air friction force (F_{af}) is caused by the friction of the vehicle body moving through the air. Acceleration force (F_a) is required to increase the speed of vehicle.

The torque at the wheels of the vehicle can be obtained from the power relation:

$$P_m = T_{TR}.\omega_{wh} = F_{tot} \text{ x } v \qquad (7)$$

$$T_{TR} = \frac{P_{mech}}{\omega_{wh}} \qquad (8)$$

where T_{TR} is the tractive torque in N-m, and ω_{wh} is the angular velocity of the wheel in rad/s. F_{tot} is in N, and v is in m/s. Assuming no slip between the tires and the road, the angular velocity and the vehicle speed are related by

$$v = \omega_{wh} \cdot r_{wh} \qquad (9)$$

$$\omega_{wh} = \frac{v}{r_{wh}} \qquad (10)$$

where r_{wh} is the radius of the wheel in meters. If G is the gear ratio of the system connecting the motor to the axle, and ω_m is the motor angular speed (rad/s), then we can say that:

$$\omega_m = G \,.\, \omega_{wh} \qquad (11)$$

and the motor torque T_m is

$$T_m = \frac{P_{mech}}{\omega_m} \qquad (12)$$

If the vehicle speed v is expressed in km/h then the motor angular speed (rad/s) is

$$\omega_m = G \cdot \frac{v}{r_{wh}} \cdot \frac{1000\ m}{3600\ s} \qquad (13)$$

A rotation of motor (n) in rpm can be calculated as

$$n = \frac{60 \cdot \omega_m}{2\pi} = \frac{30}{\pi} \cdot \omega_m \qquad (14)$$

2.2 Neural Network (NN) Model of The PEM Fuel Cell

The model used in this paper is the NN model of the PEM Fuel Cell. These models have been developed using feed-forward neural network with the back propagation (BP) algorithm. The neural network contains 24 nodes in the hidden layer and one node in the output layer [11], Fig.2. shows a diagram of the architecture used in our case. The NN model was trained using the motor current and the temperature as an input and the fuel cell stack voltage as an output.

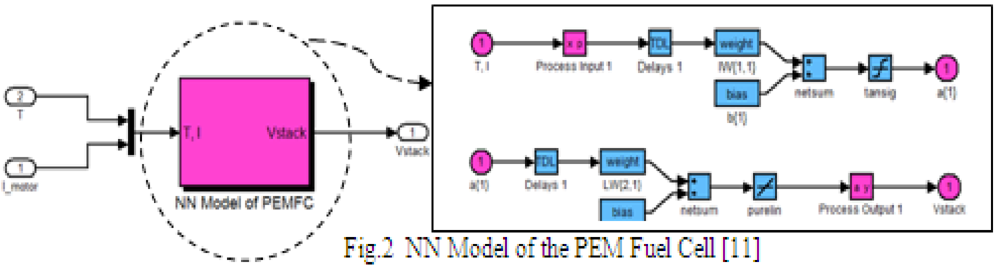

Fig.2 NN Model of the PEM Fuel Cell [11]

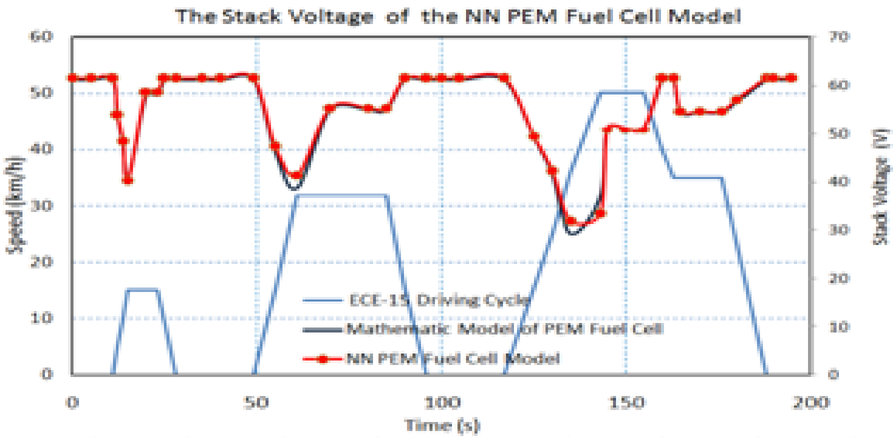

Fig.3 Stack voltage vs vehicle speed [11]

To calculate the output of the network can be done as follow[14]:

- The output of hidden layer (z_j) as follow:

$$z_j = f(z\_net_j) = \frac{2}{1+e^{-z\_net_j}} - 1 \qquad (15)$$

where $z\_net_j = v_{j0} + \sum_{i=1}^{n} x_i v_{ji}$, x_i is the input signal, v_{ji} is the line weights from input layer to hidden layer, v_{j0} is the bias in the input layer.

- The output of output layer (y_k) as follow:

$$y_k = f(y\_net_k) = y\_net_k \qquad (16)$$

where $y\_net_k = w_{k0} + \sum_{j=1}^{p} z_j w_{kj}$, x_j is the output signal of hidden layer, v_{ji} is the line weights from hidden layer to output layer, v_{j0} is the bias in the hidden layer.

The result of the NN Model is shown in fig.3.

III. ELECTRIC VEHICLE PARAMETERS

The proposed system design, the vehicle model and NN PEM Fuel Cell model have been explained. To simulate the proposed system we need the parameters of the electric vehicle. The electric vehicle parameters are reported in table 1.

Table 1: ELECTRIC VEHICLE PARAMETERS

Components	Parameters
Vehicle	Total vehicle mass : 1200 kg, Wheel friction coefficient C_{rr} : 0.013, Shape of the surface of the vehicle (A_f) : 1.8 m^2, Coefficient of form (C_d) : 0.23, Air density (□):1.25 kg/m^3 , Gravity (g): 9.81 m/s^2 , Gear Ratio (G): 3, Radius of wheel (r) = 0.3 m.
Three- Phase Induction Motor	20HP, 400V, 50 Hz, 1460 rpm
PEM Fuel Cell	2x 65V, 2 x 6 kW.
DC/AC Inverter	Input : DC bus voltage : 600V, output : 3 x 400 V AC, IGBT Inverter, Speed controller : vector control

IV. RESULT AND DISCUSSION

We use the models such as fig.1 to simulate this system. In simulation the dc/ac inverter is operating at 600Vdc. The inverter needs the power supply of 600V. While the fuel cell voltage is only 120V then required the voltage booster to increase the dc voltage. The set point value of the speed controller is obtained from equation (13) and the load torque value (Tm) is obtained from equation (12). Based on table 1, we can observe application PEM Fuel Cell for three-phase induction motor. The simulations to find out the performance of electric vehicle in starting conditions and running with constant speed. Following summarizes the result of simulations for the electric vehicle. It can be shown in fig.4 to fig.9.

On the vehicle speed of 30km/h the speed set point value of the speed controller is 83,33rad/s (795,8rpm). The load torque and power applied to the machine's shaft are 17.1 N.m and 1425 W. The simulation starts from starting conditions and running with constant speed. Fig.4 shows the rotor speed and the electromagnetic torque response of induction motor. When the motor reaches a constant speed, the stator voltage rms value decreases to 138V and the frequency to 63,57Hz. Stator voltage (phase AB) and phase A current waveforms can be seen in Fig.5. A current waveform of the simulation result is sinusoidal. Fig.6 shows the dc voltage and the dc current of the inverter.

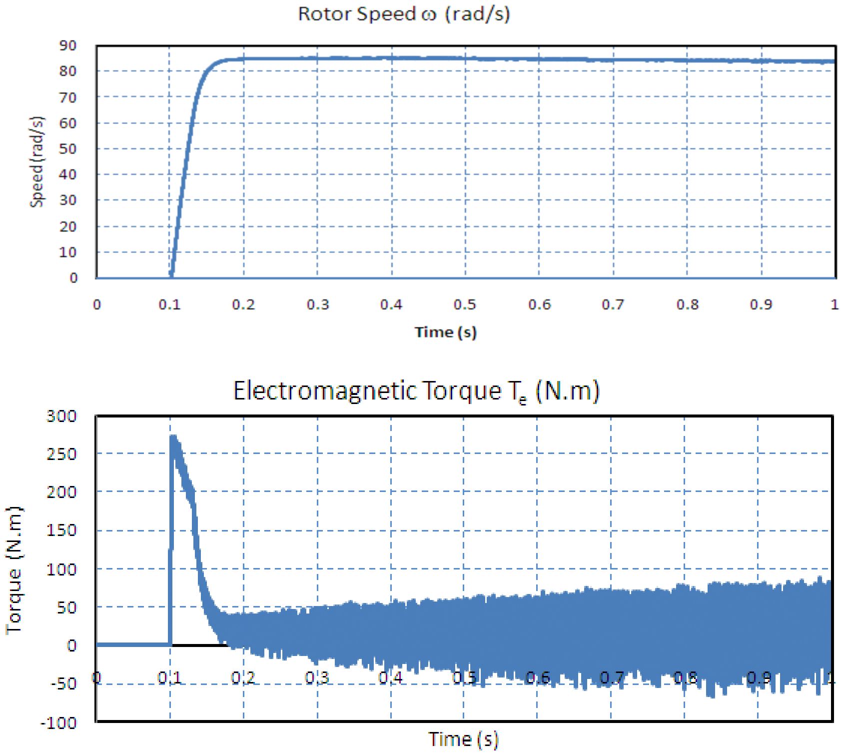

Fig.4 Response of induction motor

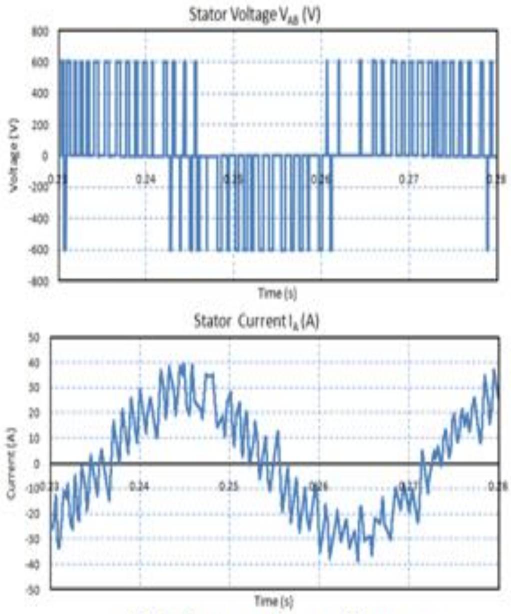

Fig.5 Stator voltage and current

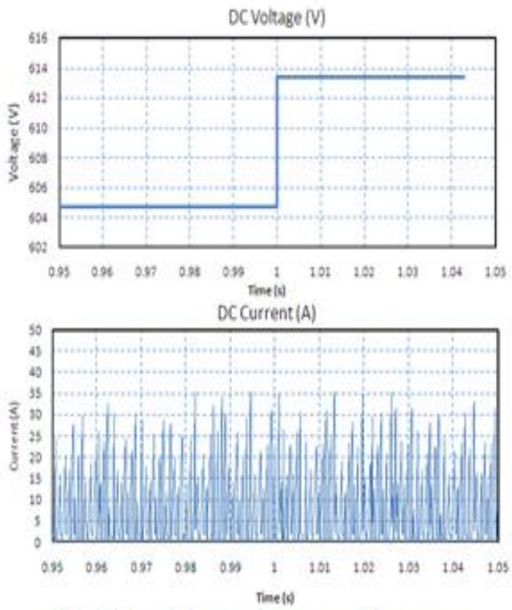

Fig.6 Dc voltage and current of inverter

Fig.7 show the response of induction motor from low speed (69.44rad/s) to the high speed (138.9 rad/s). After a start condition the system reaches a steady state during 20ms and speeds up to 139 rad/s (1326 rpm). The stator voltage rms value is 387.93V and frequency is 44.37Hz.

Fig.8 show the response of induction motor from the high speed (138.9 rad/s) to low speed (69.44rad/s). At 20ms, the vehicle speed is changed from 138.9 to 69.44 rad/s. After the system reaches a steady state, the stator voltage rms value is 186.62V and frequency is 18.84Hz.

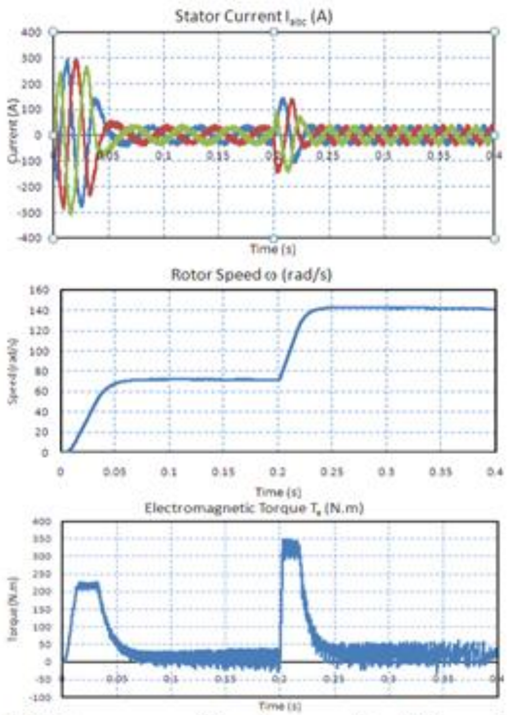

Fig.7 Motor response from low speed to high speed

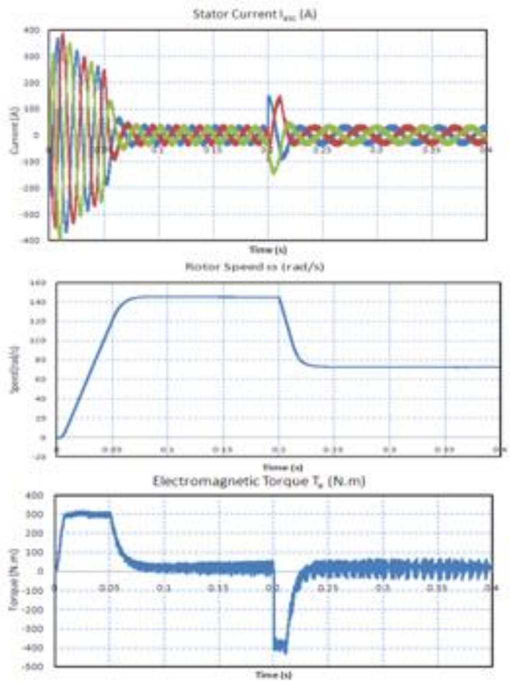

Fig.8 Motor response from high speed to low speed

Fig.9 show the response of induction motor from the high speed (138.9 rad/s) to stop (0 rad/s). At t = 20ms the speed decreases down to 0 rad/s. During the speed decreases, the electromagnetic torque becomes negatif.

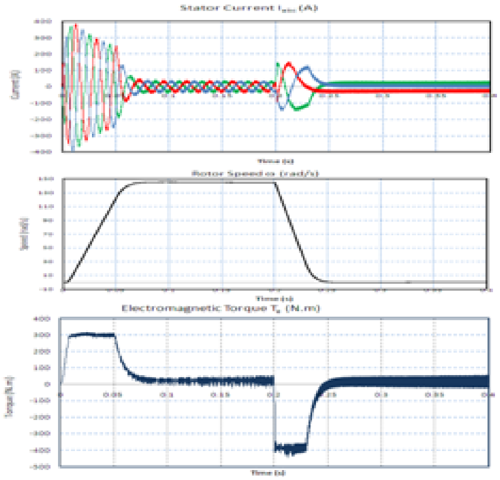

Fig.9 Motor response from high speed to stop

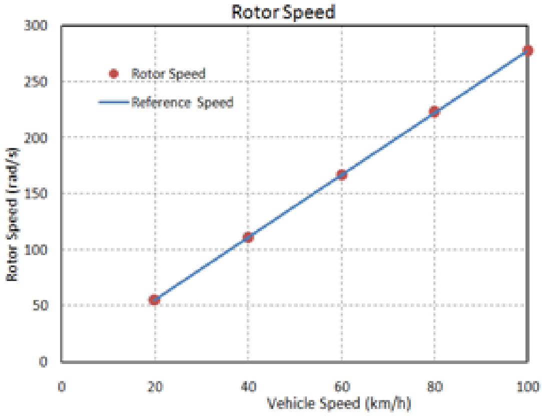

Fig.10 Rotor Speed

The simulation results for the varying vehicle speed are reported in table 2. The other simulations are performed at 20, 40, 60, 80 and 100km/h. The rotor speed results are compared to the reference speed at the speed controller and the simulation results are shown in fig.10.

Table 2. THE SIMULATION RESULTS FOR THE VARYING VEHICLE SPEED

Vehicle Speed v (km/h)	Reference Speed $\square_m$ (rad/s)	Load Torque T_m (N-m)	P_m (W)	Rotor Speed $\square_r$ (rad/s)
20	55.56	16.10	894.6	55.55
40	111.10	18.50	2055	111.00
60	166.70	22.49	3749	166.80
80	222.20	28.08	6240	222.40
100	277.80	35.27	9797	277.70

V. CONCLUSION

The proposed system has been presented in this paper. PEM Fuel Cell as a source of energy in electric vehicle which is modeled by a neural network, the inverter and induction motor have been successfully modeled and simulated. In this paper it is shown that rotor speed is according to the set point value of the speed controller. The error concerning the rotor speed of the induction motor compared with the reference speed at the speed controller, is small (0.06%).

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