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Energy Management Strategy for Nickel Metal Hydride (NiMH) Battery and Proton Exchange Membrane Fuel Cell (PEMFC) on 3-wheel Hybrid Electric Car Equipped with Continuously Variable Transmission (CVT)

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Abstract

Proton Exchange Membrane Fuel Cells (PEMFC) have higher energy conversion efficiencies than the internal combustion engine (ICE) which are also attractive to apply in the automotive sector, its ability to use hydrogen also become a reason why this technology is becoming popular as an alternative solution to solve the energy crisis. An objective of this research is to design the strategy to manage the energy from fuel cell and observe the energy consumption, maximum speed, and the ability of the vehicle powertrain to climb the slope. A small electric vehicle was modelled using Advanced Vehicle Simulator (ADVISOR) software which developed by the National Renewable Energy Laboratory (NREL). From this experiment, the vehicle primary power source was using a 200W small PEM fuel cell stack combined with AA-type batteries of nickel metal hydride as a backup energy source of each battery have 1.2 V and 1.9 AH. The PEM fuel cell stack and NiMH battery performance were examined using an electronic load to meet the power requirement of the hybrid vehicle. The experiment results shows that the operation range of the fuel cell maximum power was set in the range of 40%-60% to withdraw power from NiMH battery and keep the fuel cell run in its high-efficiency domain. When the vehicle power is lower than 40% of the fuel cell maximum power, the battery will supply the power for the vehicle, and the fuel cell will shut off. When the required power is bigger than the fuel cell maximum power, the battery will supply power to balance it. The car can drive on the sloping road with 3.5% gradability, the fuel consumption in 100 km about 40.6 L/100 km. In 5 seconds, the car can reach 33.9 m and reach 0.4 km need 26.1 seconds.

Keywords: NiMH battery, PEMFC, Hybrid Electric Vehicle, Energy Management, rubber belt CVT

1. Introduction

The development technologies using renewable alternative energy such as fuel cells, solar energy, wind power, and batteries are now growing. This energy sometimes uses in some of some small portable devices such as laptops, smartphones, UAV, mobile TV, which considerable amount of energy [1-3]. In the transportation sector, PEM fuel cells are attractive to the automotive sector because of higher energy conversion efficiencies compared to internal combustion engines (ICE) and its ability to use hydrogen. Fuel cells produce only power and water and emit no harmful gas to the environment and living being. There are many different kinds of hybrid power-train structure available now. The propulsion system of a hybrid vehicle can be a load following structure or a load leveled source structure, an energy hybrid structure or a power hybrid structure [4-6]. The battery bank system that starts to producing energy was selected then to generate energy used the hydrogen by the fuel cell will be analyzed. A fuel cell/ battery hybrid small vehicle utilized a 200 W PEM fuel cell stack and 40-AA batteries of nickel metal hydride stack in series, each battery produces 1.95Wh of energy, was studied. The vehicles model, fuel cell, battery, and motor were built, the transmission in this vehicle using CVT, and the strategies to control the energy for the vehicle were established using ADVISOR 2003 software. The simulation tools are useful for the design and performance optimization of vehicles and help to optimize new and more advanced design model containing multiple power sources and drive systems.

2. **Literature review**

2.1 Fuel Cell

A fuel cell is like a battery because it can generate electricity from an electrochemical reaction that also convert chemical potential energy into electrical energy. as a by-product of this process also produces heat energy. However, the battery must discard when depleted or recharged by using an external electricity supply to generates the electrochemical reaction in the reverse direction so the battery can be used again as a power source [7].

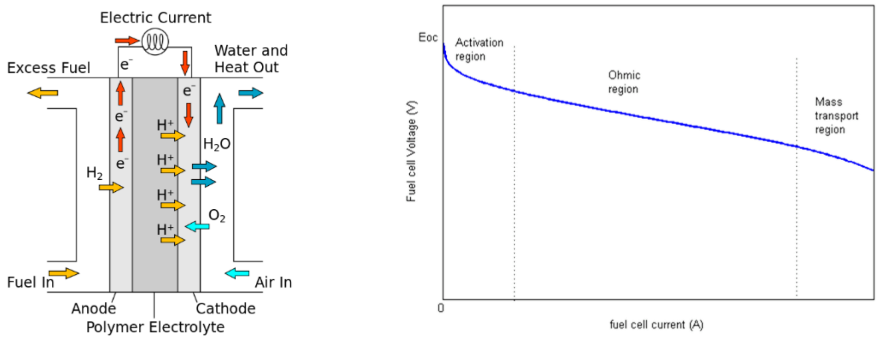


Fig. 1: The PEMFC diagram and the Voltage-Current curve

The fuel cell efficiency is ideal to the amount of power drawn from it. Drawing more power means drawing more current, this increase the losses in the fuel cell. In general rule, the more power (current) drew, the lower the efficiency. Most losses manifest themselves as a voltage drop in the cell, so the efficiency of a cell is almost proportional to its voltage.

2.2 Electric Vehicle

The term of 'Electric Vehicle' can be identified with any vehicle with an electrical propulsion system. It should encompass land, sea, and air vehicles but in fact, it has become accepted by both the scientific and industrial community that 'Electric Vehicles' are referenced exclusively to road vehicles unless otherwise specified. Under the term 'Electric Vehicle' (EV), subcategories exist. Hybrid Electric Vehicle (HEV), Fuel Cell Electric Vehicle (FCEV) and Battery Electric Vehicle (BEV) differ in specific design aspects but share the same core electrical technology. The energy source is limited, by employing multiple onboard energy systems that are specialized for the various segments become a good solution [8-9].

3. **Research methodology**

3.1 Methodology

This study will simulate the performance of the vehicle run by the fuel cell and NiMH battery using ADVISOR software. The simulation begins by establishing the vehicle model, driving cycle condition, power schemes, fuel converter, energy storage, motor, transmission, wheel/ axle, accessories, and powertrain then computing the parameters in the software. The relation between each component and the schematic diagram of the simulation data flow on how to configure those parameters using Matlab/Simulink program will be explain in Figure 2 [10].

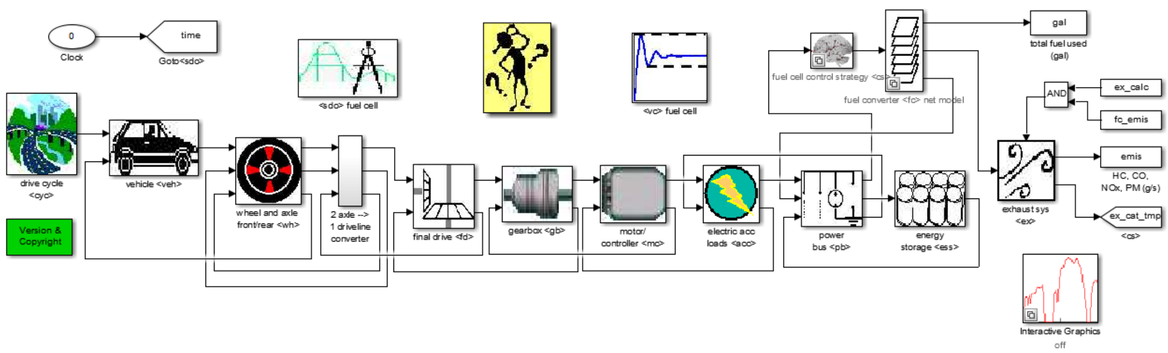


Fig. 2: Fuel cell/ battery hybrid vehicle diagram

The main parameter of this vehicle prototype is the vehicle glider mass, coefficient of drag, coefficient of rolling resistance, drag force, maximum speed/ velocity, and the drive train.

3.2. Drive-train configuration

The vehicle drivetrain is the group of components that distribute power to the driving wheels, not including the engine or motor that generates the power, Figure 3. The engine operating speed and the wheels are different so the correct gear ratio must be matched. The transmission system for this vehicle is Continuously Variable Transmission (CVT) which can change the transmission ratio steplessly resulting with an infinite number of effective transmission ratios between maximum to minimum values. This contrasts with other mechanical transmissions that only allow a few numbers of different discrete gear ratios to be selected. The flexibility of a CVT allows the driving shaft to maintain a constant angular velocity over a range of output velocities.

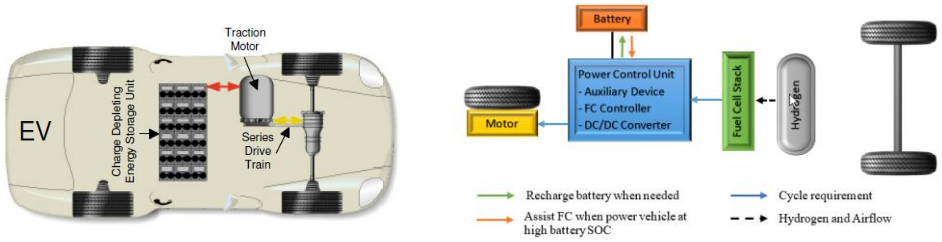


Fig. 3: Fuel cell hybrid vehicle configuration

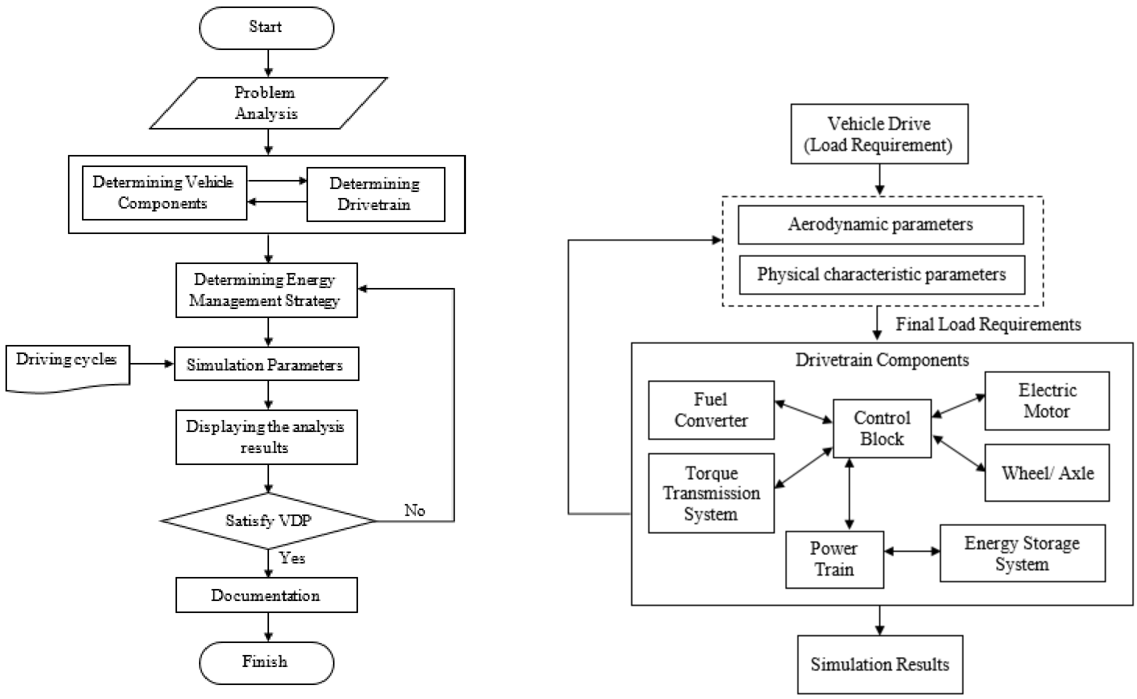
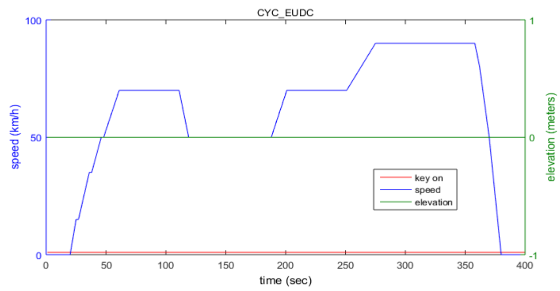


Fig. 4: Research systematic method and the Schematic diagram of simulation data flow

3.2. Simulation parameters

A Drive Cycle is a special test drive that duplicates the driving scenario of a person starting the car and making a short freeway trip for example while driving to the office.



Parameter	Index	unit
Duration	400	s
Simulated distance	6.61	km
Maximum speed	90	km/h
Average speed	59.48	km/h
Maximum acceleration	0.83	m/s²
Maximum deceleration	-1.39	m/s²
Idle time	41	s

Fig. 5: Extra Urban Driving Cycle (EUDC) simulation test

The driving range is one of the key electric car measurements, the longer driving range, the more useful is that car. The Extra-Urban Driving Cycle (EUDC) driving conditions were selected for this project. The chart shows that the test procedures require a constantly changing speed. The Extra-Urban Driving Cycle (EUDC) contains a large portion of extreme acceleration at very high speeds up to 80 km/h. The EUDC cycle maximum speed is 120 km/h; low-powered vehicles are limited to 90 km/h [11].

4. Modelling

4.1. Vehicle Modelling

All vehicle modeling, whether for conventional ICE vehicles, EVs, HEVs, or FCVs is derived from the basic equation of solid-body motion (Newton's Second Law), as given in Equation 1 in its scalar form.

$$F = ma \tag{1}$$

This equation can be modified with the specific forces, which are typically implemented on vehicles and can be rearranged into the form of Equation 2.

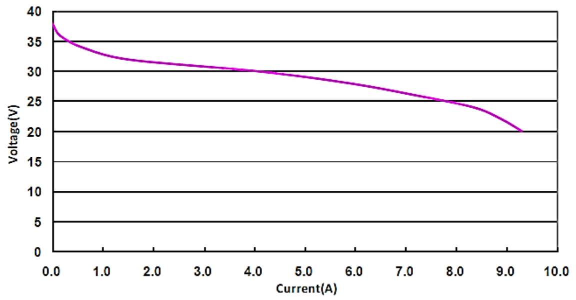
$$F = mgC_{rr} + \frac{1}{2}\rho C_d A v^2 + ma + mgsin(\theta) \tag{2}$$

4.2. Drive-train Component

The vehicle drivetrain is the group of components that deliver power to the driving wheels that composed of everything that makes the vehicle move includes the transmission to all the parts that allow the power from the engine to the wheels [13]. Each component configured and arranged as the vehicle drivetrain include the vehicle portion after the transmission changes depending on whether a vehicle in front-wheel, rear-wheel drive or any combination in between. The energy management control strategy is used to distribute the desired drive torque or power to make the power mechanisms work in their most efficient area [12-14].

4.3. Fuel Cell Modelling

A 200W Horizon Fuel Cell are used to find out the characteristic of the fuel cell stack which the open-circuit voltage was 38V. The maximum current produced by the stack was 9.5 A, and the maximum power was 200W at 24V. The system was designed with an open-cathode configuration, and the stack contains 40 cells with an active area of 19 cm^2 for each cell. There are two electric fans installed into the systems to supply the oxygen and remove the generating heat produced from the cell. The hydrogen fed to the system is 99.99 % purity. The fuel cell stack hydrogen pressure was 0.45 bar, the flow rate is 2.6 L/min, the fuel cell power is 200 watt, and the fuel cell efficiency is 40%. The measurement fed into a personal computer (PC) and the performance were also measured using an electronic load to see the voltage to current polarization curve, as shown in Figure 6.



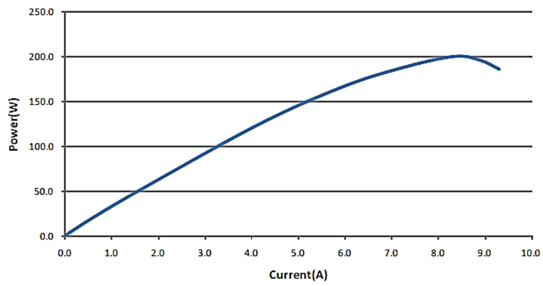


Figure 6. Fuel cell polarization curve at 0.45 bars and Power-Current curve of 200W PEMFC

Figure 6 is the fuel cell stack voltage-current polarization curve where the output voltage drop could be categorized into three regions. These phenomena can be represented by the equations.

$$V_{st} = N(E_r - V_a - V_{ohm} - V_{conc}) \tag{3}$$

where V_{st} is stack output voltage, N is the number of cells connecting in a stack; E_r is theoretical cell potential, V_a is the voltage loss due to reaction kinetic, V_{ohm} and V_{conc} are those due to the resistances and the mass transport, respectively. These losses could be calculated using the following equations. The reaction kinetic or activation voltage loss and the resistance or ohmic loss are given by empirical formula in equation (4.4) and (4.5), respectively.

$$V_a = \frac{RT}{\alpha F} ln\left(\frac{i}{i_o}\right), \tag{4}$$

$$V_{ohm} = (R_m + r)I \tag{5}$$

Where α and i_0 are the transfer coefficient and the exchange current density, respectively. The exchange current density, i_0, depends on operating conditions and the properties of the catalyst and must be determined experimentally. R_m and r are a membrane and other component's resistances. The voltage and the current density obtained experimentally. The related parameters shown in the equation could be estimated where the number of cells are 40 cells, the hydrogen preassure is 0.45 bar.

4.4. Transmission, Wheel/ Axle Modelling

The wheel/ axle model transmits torque and speed request by the vehicle to the final drive, includes the effects of axle losses, tire slip, wheel and axle inertia and the friction brake defined with wheel diameter 0.356 m (14 in) and 3.6 kg of the wheel mass. In this modelling the transmission is set in fix ratio (1:1 ratio), so the speed or rotation of wheel similar to the rotation of motor electric. It assumed that the power required from the wheel is provided by the power of motor electric. The fuel cell system operates some peripherals that inherently consume power as they support the reaction of gasses within the fuel cell. ADVISOR defines the standard accessory load data for use with hybrid systems based on the mechanical accessory load that was drawn from the engine and the electrical load that was drawn from the voltage/power bus. The accessory load also configures the constant torque load on the engine and also the dc-to-dc converter efficiency applied in the systems. For the electrical accessory load set at 50W to support the auxiliary power in the vehicle systems to start up and shut down.

4.5. Electric Motor Modelling

This vehicle uses a MITSUBA motor model M0124D-V that usually applies for electric vehicle competition. This motor giving far greater flexibility to vehicle designers while substantially reducing drivetrain losses which mean less energy is wasted (during both acceleration and regenerative braking), causing in more of the energy from the battery pack is available to propel the vehicle.

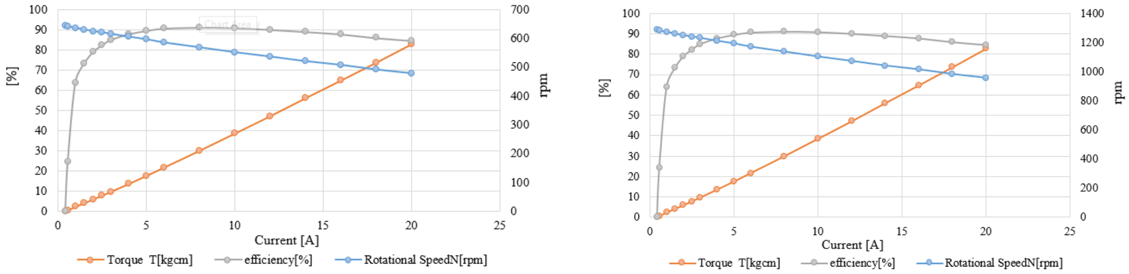


Fig. 7: Mitsuba motor M0124D-V performance at 24V and 48V

4.6. Energy Management Strategy

The control strategy is an algorithm which determines at each sampling time the power generation split between the fuel cell systems and the energy storage system in order to fulfill the power balance between the load power and the energy sources [8, 10]. The energy consumption used by the vehicle performed by three modes; starting/ normal mode, accelerating mode, and steady mode. The accelerating mode will be split into two modes, the high-speed mode, and low-speed mode. The operation range of the fuel cell maximum power was set in the range of 40%-60%, to withdraw power from NiMH battery and keep the fuel cell run in its high-efficiency domain. The maximum rate of the increasing fuel cell converter was set at 180W/s, and the maximum rate of decreasing was set at -280W/s. When the required vehicle power is lower than 40% of the fuel cell maximum power, the battery will supply all the needed power for the vehicle, and the fuel cell will shut off. When the required power is bigger than the fuel cell maximum power, the battery will supply power to balance it. The fuel cell turns on when the battery SOC reach its low limit at 40%, and the highest desired battery was set at 80%.

4.7. Simulation Results

The primary outputs from the ADVISOR simulations were plots showing the velocity profile and the State of Charge as a function of time over the course of a lap in the highway fuel economy test. Figure 8 show the series of hybrid configuration results following the EUDC driving cycle test for 400 seconds and able to travel along 6.61 km with 59.48 km/h of speed. Figure 9, show the energy storage of the vehicle and the amount of fuel that consumed during the simulation in gram per kilowatt-hour is shown in Figure 11. Figure 10 show the motor torque graph that shows the motor performance during the simulation when the vehicle tries to follow the EUDC driving cycle procedure. There are inclination and declination during the 400 seconds period. The highest torque is when the vehicle attempts to reaches the maximum speed of the requirement, 90 km/h. After few second, the vehicle already decelerates and maintain the speed at 59.48 km/h in average. After 350 s, the motor going to decelerate and finished the driving cycle test. The average motor controller efficiency is above 80% of the driving performance. It is obvious to show that the simulation results are ideal. Beside those simulation results that presented by ADVISOR, below are the figure that shows the acceleration and gradability test base on EUDC driving requirement.

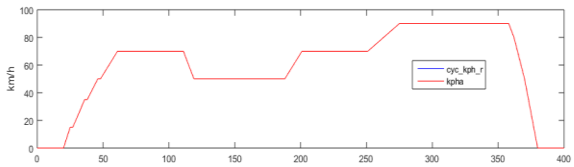


Fig. 8: The vehicle driving test by EUDC

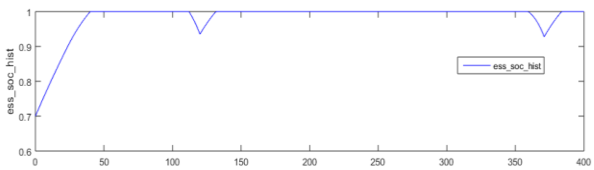


Fig. 9: Vehicle energy storage system (ESS) SOC

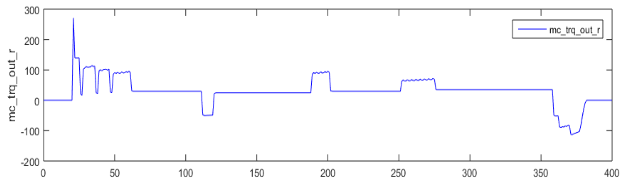


Fig. 10: Vehicle motor torque Figure

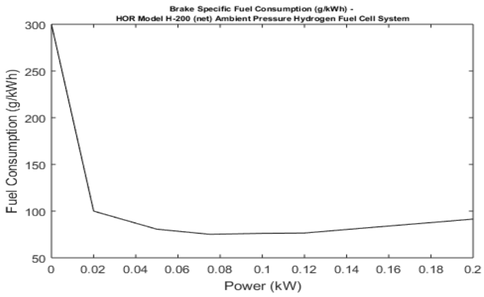


Fig. 11: Vehicle fuel consumption

The maximum vehicle acceleration is 5.8 m/s^2, in five seconds the vehicle able to travel along 33.9 meters. Another result shows from this simulation of acceleration test is the ability of the vehicle to reach 0.4 km in 26.1 seconds, the fuel (hydrogen) consumption in 100 km about 40.6 L/100 km equal to 2.7 liters of gasoline. The vehicle gradability is 3.5% which indicated that the vehicle ability to climb the sloping road.

5. Conclusions

The hybrid vehicle mode is starting mode, accelerating mode that separates into two parts, and steady mode. The Extra-Urban Driving Cycle (EUDC) was chosen for the simulation because it can use to simulate the electric vehicle driving performance to the achieved point, especially at distance, maximum speed, and average speed, then another driving cycle that available in the software. The operation range of the fuel cell maximum power was set in the range of 40%-60% to withdraw power from NiMH battery and keep the fuel cell run in its high-efficiency domain. When the vehicle power is lower than 40% of the fuel cell maximum power, the battery will supply the power for the vehicle, and the fuel cell will shut off. When the required power is bigger than the fuel cell maximum power, the battery will supply power to balance it. The car can drive on the sloping road with 3.5% gradability, the fuel consumption in 100 km about 40.6 L/100 km. In 5 seconds, the car can reach 33.9 m and reach 0.4 km need 26.1 seconds.

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