Modeling of A Taiwan Fuel Cell Powered Scooter

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Abstract—**This paper discusses the importance of a simulation study of the Taiwan Electrical Fuel Cell Power Scooter. This study applies a more detailed modeling which is complex as existing modeling methods, yet not more difficult to solve numerically. In most simulation studies, the influence of non-linearity (for example, saturation, losses, reluctance effects) of the power electronics and electrical machine are neglected. Therefore the simulation results are only valid in the ideal case. Especially the influence of losses, harmonics, saturation, reluctance and time delay in the control, can be a decisive factor in the design. Therefore in this simulation study, it is shown to include these details. The conduction and switching losses in the power electronics during the drive cycle are simulated. Also the temperature stress on the semiconductors will be calculated in order to give a prediction of the life time of the semiconductor modules. Influence of the saturation and reluctance in the electrical machine and the impact on the overall system performance as well as the influence in the field oriented control. Detailed modeling of the field oriented control is discussed. Finally the implementation of the digital control in hardware directly from the simulation control model will be explained.**

Keywords-***CASPOC software, fuel cell powered scooter***

I. Introduction

Air pollution is of serious concern in many Asian countries, especially in densely-populated cities with many highly-polluting two-stroke engine vehicles. The present value of health effects have been estimated at hundreds of dollars or more, over each vehicle's lifetime, for a reasonably wealthy country like Taiwan. Fuel cell and electric battery-powered scooters are often proposed as alternatives, but a fuel cell scooter would be superior to battery-powered scooters by offering zero emissions and internal combustion-scooter class range by 200 km. Fuel cell hybrid powered stacks offer the advantages of extended range and quick refueling. Hydrogen storage in the form of metal hydrides, and a proton exchange membrane fuel cell running at low temperatures, are chosen for the reasons of ease of manufacture and operation, low cost, and minimal volume.

Although extensive research has been done into fuel cells for stationary power and for automobiles, and some research has been done for portable power applications like soldier power and devices like telephones and computers, virtually no work has been done in the field of small vehicles requiring low than 10 kW of power. Unlike 50 kW automobile-sized fuel cell stacks, the vehicular 3.6kW fuel cell needed here has not received much attention. This niche is examined here with a conceptual design and consideration of the issues of water, heat, and gas management. The application is extremely sensitive to size, weight, and cost, so a proton exchange membrane fuel cell using hydrogen stored in a metal hydride is best. Hydrides also act as sinks for waste heat due to the endothermic hydrogen desorption process. Pressurized operation is found to be ineffective due to high parasitic power demands and low efficiencies at the low powers involved.

A fuel cell is an electrochemical engine that converts the chemical energy in a fuel directly into electricity and usable heat. While most scooters use two-stroke or four-stroke engines to provide power, a scooter powered by fuel cells offers a potentially environmentally cleaner option. The gasoline scooter that is being proposed has the following specifications for a two-stroke or four-stroke engine.

The purpose of this study is to examine a particular application of fuel cell technology: the electric scooter. Scooters are small two-wheeled vehicles that can carry one or two people. They are unlike motorcycles in that they are ridden in a seated position with feet forward on a platform. It is noted that the distinction between "scooters" and "motorcycles" is not always made in the literature, especially by Asian researchers. Here it is assumed that "motorcycles" refers to scooters when it comes to vehicles less than 50 cc in displacement. Due to their small size and low price point, scooters have traditionally been powered by high power density two-stroke or four-stroke internal combustion engines. Internal combustion-scooters produce a great deal of air pollution and are an object of concern in many Asian countries.

II. FUEL CELL MODEL

PEM fuel cells consist of three major components of anode, solid polymer electrolyte and cathode. The electrochemical reactions for a PEM fuel cell fed with a hydrogen containing anode gas and an oxygen containing cathode gas are：

Anode： $H_2 \leftrightarrow 2H^+ + 2e^-$

Cathode： $2H^+ + 2e^- + \frac{1}{2}O_2 \leftrightarrow H_2O$

Total： $H_2 + \frac{1}{2}O_2 \leftrightarrow H_2O$

The products of the electrochemical reactions are dc electricity, liquid water and heat.

The basic expression for the voltage for a single cell is :

$$V_{\sin gle\_cell} = E_{Nernst} + \eta_{act} + \eta_{ohmic} + \eta_{diffusion} \quad (1)$$

Where： E_{Nernst} is the thermodynamic potential , η_{act} is the electrode activation overvoltage , η_{ohmic} is the ohmic overvoltage and $\eta_{diffusion}$ the limiting current overvoltage. The electrode activation overvoltage is a measure of the voltage loss associated with the anode and cathode. The ohmic overvoltage is a measure of the IR losses associated with the proton conductivity of the solid polymer electrolyte and electronic internal resistances. The three overvoltage terms are all negative in Eq. (1) and represent reductions from E_{Nernst} to give the useful single cell voltage, $V_{\sin gle\_cell}$. As developed earlier, the Nernst equation for the PEM fuel cell can be written by the values for the standard state entropy change:

$$E_{Nernst} = 1.229 - (8.5\times10^{-4})\times(T - 298.15) + (4.308\times10^{-5}\times T)\times(\ln p^*_{H_2} + \frac{1}{2}\ln p^*_{O_2}) \quad (2)$$

Where T is the cell temperature (K) , $p^*_{H_2}$ is the partial pressure of hydrogen at the anode catalyst/gas interface (bar), and the partial pressure of oxygen at the cathode catalyst/gas interface (bar) [1].

Many mechanistic models and empirical models [2, 3] can be found in the literature. The most comprehensive form of empirical model is to predict the current/voltage relationship for the PEMFC：

$$V = V_0 - b\ln i - Ri - m\exp(ni) - b\ln(\frac{p}{p_{O_2}}) \quad (3)$$

The constants of b, R, m and n are all empirical parameters that functions of the operations. This model features the familiar terms representing activation polarization and Ohm's law contributions as well as incorporating two terms which have appeared to be an exponential term and pressure ratio logarithmic term that served to model the effects of concentration polarization predominantly at higher current densities. The pressure ratio logarithm term appears to be a new attempt to fit experimental data. The model itself highlights the pitfalls of empirical modeling. The experimental term has no physical justification and serves merely as a curve-fitting tool.

The above equations form the basis of the fuel cell model in the simulations in this study. The mentioned parameters are the minimum set that has to be known in order to correctly describe the fuel cell model.

III. COST ANALYSIS

Table 1 is the specifications of the gasoline 50cc scooter. Hydrogen production at the infrastructure level proposed, results in hydrogen costs that are less than half the price of gasoline, due to the high efficiency of the fuel cell scooter. The cost is low enough to make hydrogen fuel cell scooters a cheaper option to drive than gasoline-powered scooters.

The retail cost of this existing scooter is approximately $**1400**. We recommend that the scooter be manufactured as a shell to exclude the four-stroke engine, exhaust system, fuel tank and battery. This would leave a retail base cost of approximately $**590** dollars before implementation of fuel cell system. As requested, It will fit the scooter with a Proton Exchange Membrane that produces water exhaust from electrochemical electricity. This will be 3.6 kW fuel cell stack with respective parts of BOP. The costs are described in the Table 2 below.

Table 1 the specifications of a Taiwan gasoline 50cc scooter

Engine gasoline	2 stroke, single cylinder, air cooled
Compression Ration	7.2:1
Displacement	49.26 cc
Bore x Stroke	40 x 39.2mm
Max Horsepower	3.7hp/5500rpm
Max Torque	0.57 kg-m/5500rpm
Fuel Consumption	45 km/l
Ignition	Electronic CDI and variable timing

Please be informed these prices are based on a minimum order of **1000** scooters annually, the prototype costs will be a higher. These prices can be achieved through long term mass production with potential of cost reductions on a regular basis. Below we will detail the costs of the infrastructure as well as the fuel costs in comparison to gasoline costs.

Table 2 the cost analysis of Taiwan fuel cell powered Scooter

FC stack	$ 750.00
Starter battery Yuasa-Exide	$ 10.00

Hydrogen storage DTI metal hydride	$ 190.00
Heat Exchanger Lytron M14-120	$ 60.00
Coolant pump	$ 10.00
Blower AMETEK116628-E(1-2psi)	$ 110.00
Plumbing Water, Air pipes	$ 50.00
DC Brushless Motor UQM SR121/1.5L	$ 125.00
Controller UQM CD05-100A	$ 150.00
Total-Fuel Cell SYSTEM Costs	**$ 1,455.00**
Shell costs and assembly	$ 590.00
Total-Fuel Cell Scooter	**$ 2,045.00**

The 3.6 kW fuel cell stack with 250g of metal hydrate canister storage has a fuel economy of 0.746 km per gram on hydrogen (334 mpg) under TMDC (Taipei Motorcycle driving cycle). Hydrogen in Taiwan would likely be produced by imported natural gas converted at local hydrogen filling stations using steam reformers.

A study by Joan Ogden, et al. [4] calculated that hydrogen produced by on-site conventional steam reformers would cost 12-40 $/GJ based on a Los Angeles-area natural gas price of 2.8$/GJ. The range of cost is a function of how large each reforming station is. Taiwan prices for natural gas are about 7.7 $/GJ, so the prices for hydrogen increased by 5 $/GJ to 17-45 $/GJ. At a smallest station size, an area of about 4,000 scooters running at 12,000 km per year could be serviced at a cost of 45 $/GJ. The fuel cost of operating a scooter is about $145 a year or 1.21 ¢ /km. If a larger plant capable of servicing an area of 72,000scooters was built, costs would drop to 17 $/GJ for a cost per vehicle per year of $78 and a driving cost of 0.65 ¢ /km. More advanced reformers would reduce the cost to 24 $/GJ for a 4,000 scooter Plant, but the larger stations would not be much cheaper. Note the raw natural gas cost is only 27% of the total delivered hydrogen cost; the rest is for labor, reformer construction, electricity, hydrogen storage and compressor.

Table 3 A cost comparison of the existing gasoline and the 3.6kW Taiwan fuel cell scooters.

	Gasoline 50cc powered scooter	3.6kW FC powered scooter
Refueling cost	$16.7 /GJ (¢65.1/L)	$24/GJ (¢0.34/g)
On-vehicle mileage	65 mpg	344 mpg
Cost per distance	¢1.5 /km	¢0.65 /km
Annual cost	$184	$78
Present value of fuel Over 10-year lifetime	$1130	$480

IV. FUEL CELL POWERED SCOOTER SIMULATION

In a pure fuel cell powered scooter a permanent magnet synchronous motor (PMSM) is used to drive the scooter. The fuel cell stack is used for providing the average power for driving, while the battery assists in the start-up, climbing, breaking and providing power at non-nominal operation speed of the electrical motor.

Battery model

The battery is modeled at the same level as the fuel cell. Also here the voltage-current relation is non-linear and for the battery it is depending on the State Of Charge (SOC) of the battery. Furthermore the transient response is modeled by including a model for the charge transport inside the battery.

Also the transient response of the fuel cell is modeled. The fuel cell has a slow response compared to the battery especially when sudden higher loads are required. As can be seen in this simulation, the battery is always responding first when a high load demand occurs. For simplicity two diodes model the isolation between the fuel cell and the battery. To include also the regenerative braking and charging of the battery form the fuel cell, power electronics converters with their control should be added to this simulation.

Electrical Machine Models

The electrical machines can be modeled in various ways. In the first place a simple linear model can be used to study the overall system performance. The next step includes a more detailed model of the electrical machine in order to study the influence of saturation and other non-linear behavior. Models for the permanent magnet synchronous motor (PMSM) and induction motor can be found in reference [5].

Power Electronics Models

Power electronics is required to drive and control the electrical machine. The difficulty with power electronics for scooter is the environment in which the power electronics has to perform without failure. High temperatures are a challenge to the designer, who has to layout the components to work safely without interruption. Thermal design is reported in reference [6].

Inverter and PMSM

Figure 1 shows the simulation of the complete electrical and mechanical drive train for a fuel cell powered scooter. Here the inverter is modeled using ideal switch models to achieve a fast simulation. The harmonics due to the Pulse Width Modulation (PWM) of the inverter appear on the torque produced by the Permanent Magnet Synchronous Motor (PMSM). This torque pulsation will affect the dynamics of the entire mechanical drive train. The control for the power electronics can be designed and optimized in a complete model where the power electronics, PMSM and mechanical drive are modeled.

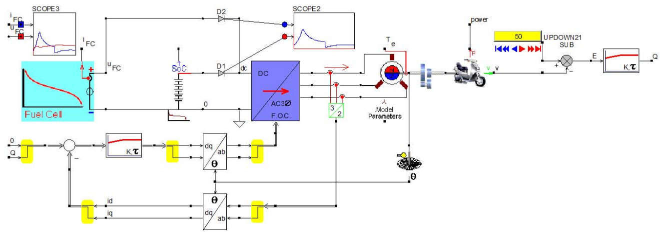
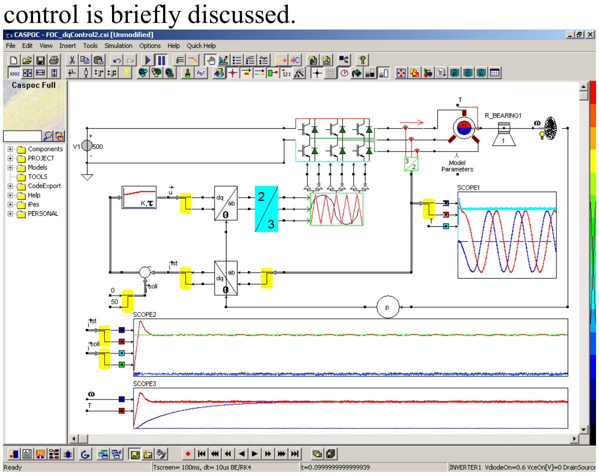


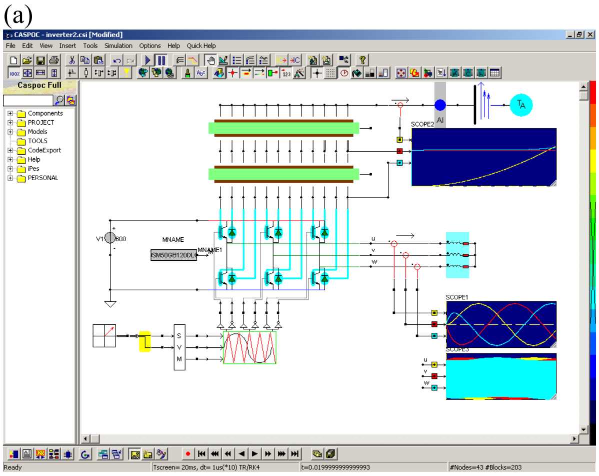
Figure 1 Simulation of the PMSM of a fuel cell powered scooter

Field Oriented Control

The control of the power electronics is an important component, when it comes to efficiency and performance of the entire drive system. A permanent magnet synchronous Motor is used in the fuel cell powered scooter [7]. In this scooter drive example, the power electronics inverter, the PMSM, the mechanical load and the vector control are modeled, see figure 2. In the following sections the design control is briefly discussed.



(a)



(b)

Figure 2 (a) Vector control of the PMSM, (b) Inverter with thermal model

Using the simulation in figure 2, the lifetime of the semiconductors can be predicted. The temperature cycling is predicted while going through a complete drive cycle. Using the loss-predicting semiconductor models [pcim], the simulation remains fast, while the losses and the therewith-associated temperature rise can be predicted. The thermal model of the IGBT modules has to be included in the simulation as well. Here the layers of the module have to be modeled as well as the free air convection and radiation of the heat sink.

The machine model is based on a dq model that also models the reluctance torque in the PMSM. Independent saturation of Ld and Lq is included to study the influence at high loads. Harmonics of the modulation in the power electronics are included in the simulation and are visible in the current and torque ripple.

In the PMSM drive a Field Oriented Control (FOC) is applied. A position encoder on the shaft is required for the transformation from measured phase currents into the dq currents needed in the FOC.
In this simulation study the PMSM is driven below its base speed. A higher maximum scooter speed would be possible by applying field weakening in the FOC. Since in this simulation study the PMSM is driven below its base speed, field weakening is not applied and the d-axis current is set to zero. [5]

Control performance simulations

After starting the simulation, the angular speed of the shaft can be controlled by clicking the animated UPDOWN control block in the simulation. The simulation will continue and show the response to the next present value for the angular speed in figure 3.

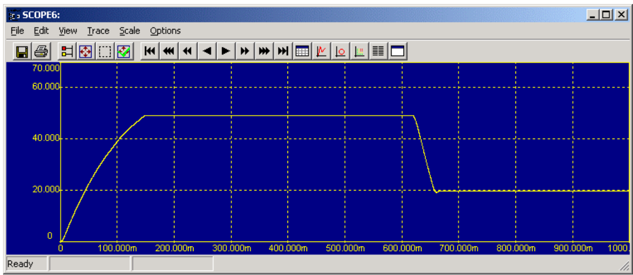


Figure 3 Response of the drive to interactive speed commands during simulation

During the simulation the internal structure of the converter can be viewed the even the current flow in the inverter can be followed using the animation feature, as shown in figure 4. In the project manager on the left side click on **Project/Schematic** and click the library block that you want to view. In this case the library block is the **INVERTER1,** see figure 4.

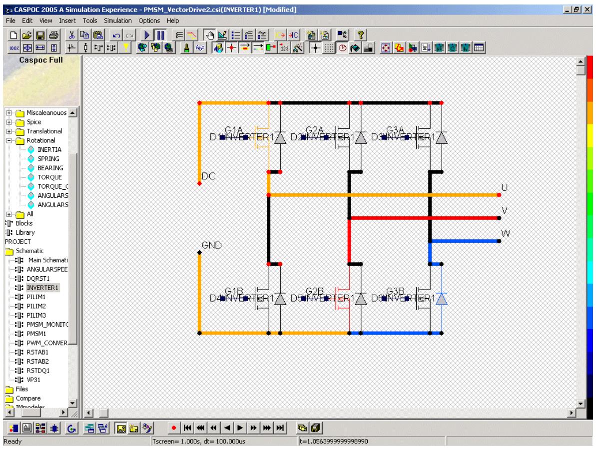


Figure 4 Animation of the inverter

The animation of the currents in the schematic show that at this certain point in time, phase U is connected to the positive DC link terminal via the orange colored **MOSFET** transistor. On the lower side there is also a freewheeling process taking place, via the bottom right **DIODE** colored in blue and its neighboring **MOSFET** colored in red. To view the working of other library blocks, simply click the name of the library block in the project manager, for example the RST to DQ transformation, also see figure 5.

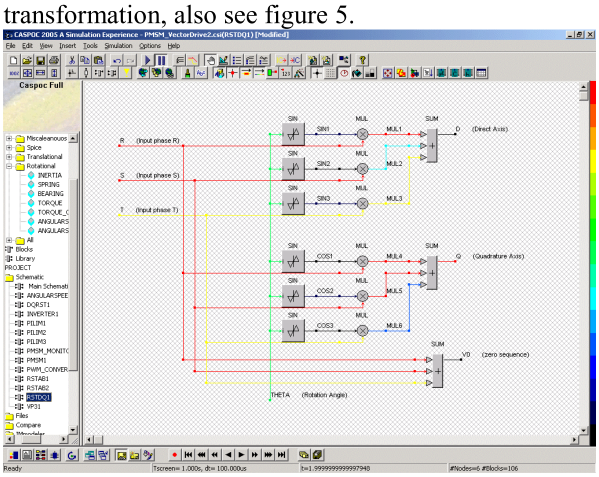
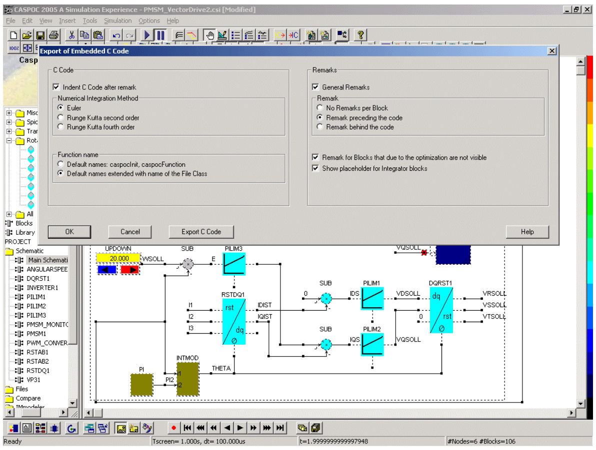


Figure 5 Internal modeling for the Clark/Park transformation

Exporting Embedded control C-code

From the control in the block diagram the C-code can be exported [9] and used in a DSP or micro-controller as shown in figure 6.



After exporting the C-code, the C-code can be viewed directly from Caspoc software or included into your main embedded C-project, see figure 7.

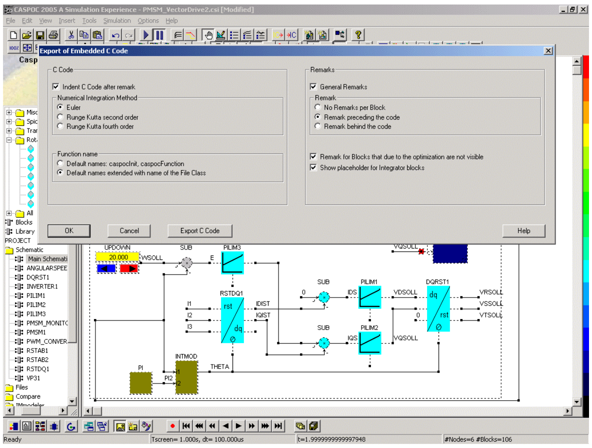
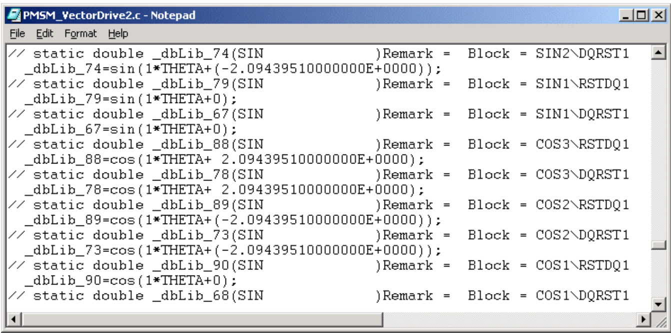


Figure 6 Export of embedded C-code for DSP or Micro-controller



```
// static double _dbLib_74(SIN              )Remark =  Block = SIN2\DQRST1
  _dbLib_74=sin(1*THETA+(-2.09439510000000E+0000));
// static double _dbLib_79(SIN              )Remark =  Block = SIN1\RSTDQ1
  _dbLib_79=sin(1*THETA+0);
// static double _dbLib_67(SIN              )Remark =  Block = SIN1\DQRST1
  _dbLib_67=sin(1*THETA+0);
// static double _dbLib_88(SIN              )Remark =  Block = COS3\RSTDQ1
  _dbLib_88=cos(1*THETA+ 2.09439510000000E+0000);
// static double _dbLib_78(SIN              )Remark =  Block = COS3\DQRST1
  _dbLib_78=cos(1*THETA+ 2.09439510000000E+0000);
// static double _dbLib_89(SIN              )Remark =  Block = COS2\RSTDQ1
  _dbLib_89=cos(1*THETA+(-2.09439510000000E+0000));
// static double _dbLib_73(SIN              )Remark =  Block = COS2\DQRST1
  _dbLib_73=cos(1*THETA+(-2.09439510000000E+0000));
// static double _dbLib_90(SIN              )Remark =  Block = COS1\RSTDQ1
  _dbLib_90=cos(1*THETA+0);
// static double _dbLib_68(SIN              )Remark =  Block = COS1\DQRST1
```

Figure 7 Exported C-code from the vector control

The exported C-code is optimized for execution speed and not used block names are optimized, to condense the export C-code, see figure 8.

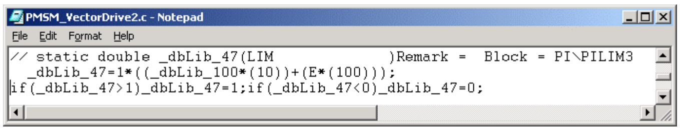


Figure 8 Optimization of exported C-code

A fuel cell powered scooter simulation

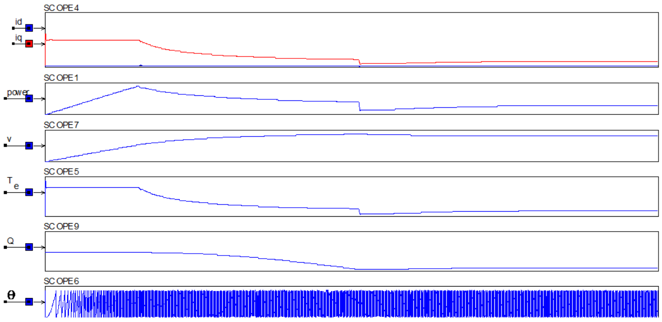


Figure 9 Simulation results, from top to bottom; Id Iq, fuel cell current, scooter speed, PMSM torque, virtuel driver torque command and angular position from the encoder.

Figure 9 shows the simulation results of the model for the Permanent Magnet Synchronous Motor (PMSM) and the power electronics with field oriented control for a full speed demand. This animation shows the drive train behavior of the PEM fuel cell powered scooter. Only the back wheel is driven via a gearbox by the PMSM. These inputs are the PEM fuel cell stack and the electrical machine, while the output of the torque is connected to drive the scooter.

A computer simulation is developed to examine overall vehicle design [9]. Vehicle characteristics of weight, drag, rolling resistance, fuel cell polarization curves, and a Taiwanese urban driving cycle are specified as inputs. Transient power requirements reach 3.6 kW due to the rapid accelerations, suggesting a large fuel cell. However, average power is only 600 W. A hybrid power design with a small fuel cell and peaking batteries could also handle the load. Results show that the average consumed hydrogen 1.6 gram per a kilometer, but are certain to precede pure fuel cell scooters while fuel cells are still more expensive than peaking batteries. The size is approximately the same as current electric scooters, at 1620×600×1070 mm and 115 kg for the shell, fuel cell stack, hydrogen storage, and electric motor with a microchip controller.

V. CONCLUSIONS

Modeling and simulation of a fuel cell powered scooter is briefly discussed in this paper. The focus of this paper is on the cost, power electronics and the control of the power electronics and electrical motor. In this paper the modeling of the various components in the scooter, such as the fuel cell modeling, power electronics and control. The model for the electrical machines can either be a first order model for system behavior or can be based on FEM calculations. The model for the power electronics includes the nonlinear switching behavior, to account for harmonics in the electrical machine. From the simulated field oriented control, the embedded C-code for implementation in a DSP or microcontroller is discussed [8].

Vehicle characteristics of weight, drag, rolling resistance, fuel cell polarization curves, and a Taiwanese urban driving cycle are specified as inputs. Transient power requirements reach 3.6 kW due to the rapid accelerations, suggesting a large fuel cell. However, average power is only 600 W. A hybrid power design with a small fuel cell and peaking batteries could also handle the load. Results show that the average consumed hydrogen 1.6 gram per a kilometer, but are certain to precede pure fuel cell scooters while fuel cells are still more expensive than peaking batteries. The size is approximately the same as current electric scooters, at 1620×600×1070 mm and 115 kg for the shell, fuel cell stack, hydrogen storage, and electric motor with a DSP or microchip controller as listed in Table 4 [10].

This paper shows that for the performance evaluation of a fuel cell powered scooter there are two objectives to be combined. First the overall performance based on the drive cycle can be carried out, while secondly the influence of the non-linear components in the total system can be taken into account. This means that compared to existing performance simulations, the influence of saturation and reluctance in the electrical machine, harmonics and losses in the power electronics and control modulation, combined with a virtual driver under a drive cycle can be carried out in one simulation, without compromising too much on simulation time.

Table 4 the comparison with the data from APFCT fuel cell powered Scooter [10]

Test items	Simulation	Real test
Dimension	1620×600×1070 mm	1618×630×1000 mm
Weight	115 kg	102.5 kg 116 kg@3 metal hydrate canister
Tires	3.0-10 inch	3.0-10 inch
Noise	none	60.8dB@30km/h
Limit speed	50km/h	52km/h
Acceleration	30km/h @5 sec	30km/h @5 sec
Mileage	80km (fixed speed 30km/h)	100.8km (fixed speed 30km/h)
Inclination	12°@10kph	12°@6kph
Fuel consumption	1.6 g hydrogen/km	1.34 g hydrogen/km
Time of fuel supply	none	50.2 sec.

ACKNOWLEDGMENT

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[10] Asia Pacific Fuel Cell Technologies, Ltd. , http://www.apfct.com/, The primary areas of application for APFCT have been for 2-wheeled and small 4-wheeled transportation devices and special vehicles, Confidential data from APFCT, in April 21 2009.