Modelling of Fuel Cell and Supercapacitor for Electric Vehicles

Gergana Vacheva
Department of Power electronics
Technical University of Sofia
Sofia, Bulgaria
gergana_vacheva@tu-sofia.bg

Nikolay Hinov
Department of Power electronics
Technical University of Sofia
Sofia, Bulgaria
hinov@tu-sofia.bg

***Abstract*— In the current research a mathematical model of an electric vehicle supplied by fuel cell and supercapacitor is proposed. The model takes as input standard electric vehicle provided by the manufacturer that is needed for the power conversion system. The main purposes of this model is to be used in order the designed to be able to define the optimal energy flows between two different supplying elements in electric vehicles.**

Keywords—electric vehicles, fuel cell, mathematical modelling supercapacitor.

I. Introduction

Recently, there has been an increasing interest in the use of electric vehicles, electric buses and electric trucks. The main factors of these funds link it to environmental causes in cities and financial interests.

Statistics show that the market share of these vehicles is increasing as well as well as the tendency for a faster increase in the number of vehicles.

Stimulating the purchase of an electric vehicle is a priority of various municipalities in major cities, and in some countries is a government priority. Smaller electric vehicles are available for urban use capacity of installed batteries. On the other hand, options are being sought providing fast charging of these batteries. To increase the mileage of vehicles means also increases the capacity of the batteries to obtain small times of charging, this requires higher power charging stations.

The practice of receiving more power from charging stations is used they should be constructed on a modular basis and by connecting the modules in parallel increases the output current. Galvanic separation is used to ensure safety between the inlet and outlet of the charging station. This is achieved by using high frequency transformers in DC/DC converters made using resonance inverters. In the charging process, the battery voltage are changing and this makes it possible to adjust the current and the voltage at the output of the charging stations.

II. Mathematical modelling

The proposed model of electric vehicles (EVs) with fuel cell (FC) is realized in virtual environment MATLAB/Simulink. The mathematical model is based on architecture which is provided by Honda FCX. It consist of three subsystem: control system (figure 1), electric subsystem, inverter and electric motor (figure 2), subsystem which describing the dynamic of the electric vehicle (figure 3) and simplified model of FC (figure 3).

A. Electric subsystem

The electric subsystem consist of the following components:

- Synchronous machine with permanent magnets with voltage 288 Vdc and power 100 kW and controller. This type of motor has 8 poles and salient rotors.

For control of magnet flow is used field oriented control for reaching maximum speed of the motor 12 500 rpm. The current is controlled by the reference of the torque by the controller.

- FC stack consist of 400 cells with voltage equal to 288 Vdc and power 100 kW Proton Exchange Membrane (PEM).
- Supercapacitor with capacitance equal to 35.25 F.
- DC/DC converter: buck converter with current control.

For verification of the operation modes of the complete model is used the data presented in the Table 1.

TABLE I. PARAMETERS OF THE MODEL

Parameters of the FC		
Voltage	E_{oc}	400 [V]
Initial voltage	V_1	380 [V]
Nominal current	I_{nom}	285 [A]
Nominal voltage	V_{nom}	300 [V]
Maximal current	I_{max}	347.3 [A]
Minimal voltage	V_{min}	288 [V]
Parameters of the EVs		
Air density	rho	1.3
Aerodynamic coeficient	K_a	0.26
Rolling resistance	K_f	0.02
Frontal area of the EVs	S	2.711 [m2]
Mass	m	1625 [kg]
Radius of the wheel	R	0.25 [m]
Gear ratio	n	7.2

B. Control system

Control system (Figure 1) define the torque of the motor and create reference for the current of the FC which depends of the position of the brake system, speed of the EVs, voltage of the FC and the power of the supercapacitor. The power is

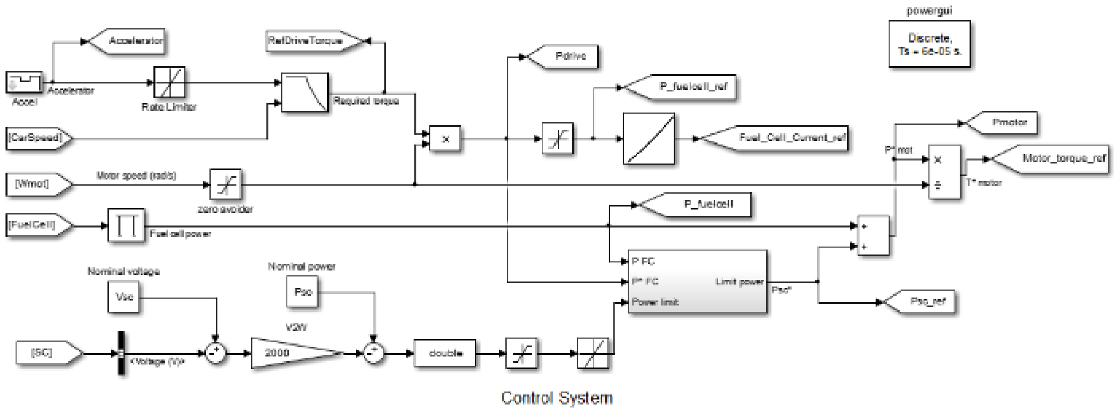

Fig. 1. Control system in MATLAB/Simulink

divided by the electric source depending by the position of the gas pedal (Accelerator), which varying between -100 % and 100 %. The negative value describe the process of braking of EVs. When the value is under 50% the EVs is supplied only by FC. When the value is over 50% the supercapacitor support the principal source of energy. The regenerative braking is simulated when the motor operates in generator mode.

C. Model of DC/DC converter, inverter and electric motor

In Fig.2 the model of the DC/DC converter, inverter and the electric motor are proposed. The converter is bidirectional buck-boost and allows the realization of the acceleration and energy storage in the supercapacitor during braking modes. The synchronous machine with permanent magnet and its control is used for simulation of the EVs.

D. Model of the FC

The model of the FC realized in MATLAB/Simulink is presented in Figure 3. The principle of the operation of the FC are described with the following equations (1)-(3).

The following limitations are allowed to simplify the proposed model:

1. Model assumptions:

- The gas used is ideal;
- The stack is supplied with hydrogen and air;
- The stack is equipped with a cooling system that maintains a stable cathode and anode temperature equal to the stack temperature;
- The stack is equipped with a humidification system for managing and maintaining the humidity in the cell at the appropriate level when the load is changed;
- Pressure changes are insignificant;
- The change in cell voltage is caused by the kinetic response of the charge, since most FC are not used in mass transit;
- The internal resistance of the cell is constant under all operating conditions.

2. Model constraints:

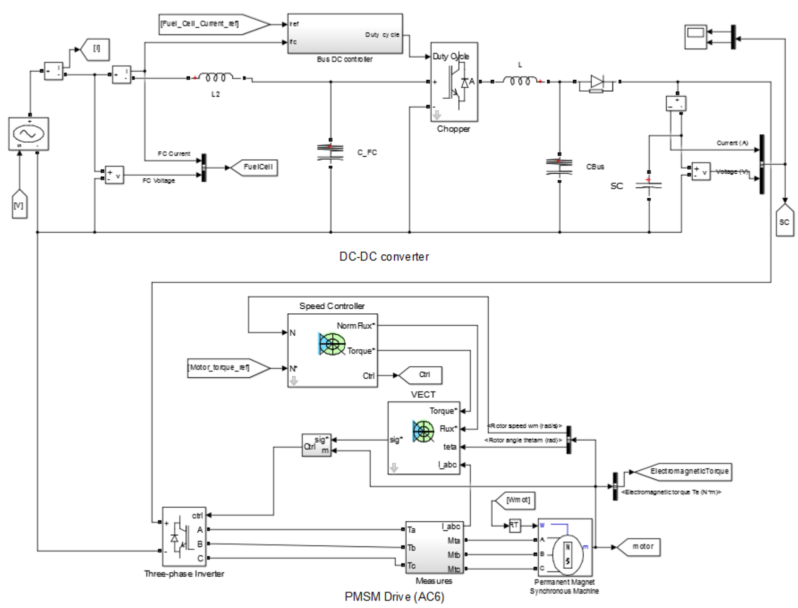

Fig. 2. Model of the DC/DC converter, inverter and electric motor

- The flow of gases or water passing through the membrane is not recorded;
- The effect of membrane temperature and humidity on the variation of stack resistance is not taken into account.

$$N \cdot A = \frac{(V_1 - V_{nom}) \cdot (I_{max} - 1) - (V_1 - V_{min}) \cdot (I_{nom})}{\ln(I_{nom}) \cdot (I_{max} - 1) - \ln(I_{max}) \cdot (I_{nom} - 1)} \quad (1)$$

$$R_{ohm} = \frac{V_1 - V_{nom} - N \cdot A \cdot \ln(I_{nom})}{I_{nom} - 1} \quad (2)$$

$$i_0 = \exp\left(\frac{V_1 - E_{OC} + R_{ohm}}{N \cdot A}\right) \quad (3)$$

- Nominal current and nominal voltage (I_{nom}, V_{nom});
- Maximum current and minimum voltage (I_{max}, V_{min});
- Voltage at 0 and 1 A (E_{oc}, V_1);
- Number of cells connected in series *(N);*
- *A* - slope of Tafel;
- i_0 - current;
- R_{ohm} - internal resistance.

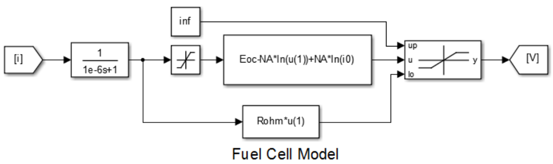

Fig. 3. FC model

E. *Dynamic of the EVs*

The following equations (4)-(6) described the dynamic of EVs:

$$m\frac{dV}{dt} = F_m - F_T - F_a \quad (4)$$

$$F_T = k_t \cdot m \cdot g \quad (5)$$

$$F_a = (0.5 \cdot \rho \cdot S \cdot K_a) \cdot V^2 \quad (6)$$

where V - velocity of the EVs, F_m - the motor force, F_T – the friction force, F_a - aerodynamic force, ρ – density of the air, S – frontal area, K_a – aerodynamic coefficient.

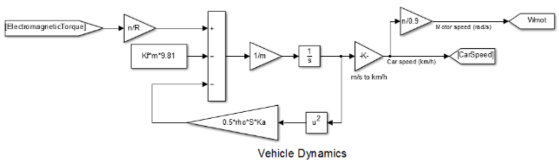

Fig. 4. Dynamic of the EVs

In Fig.5. the measurements of the studied parameters in the system are presented.

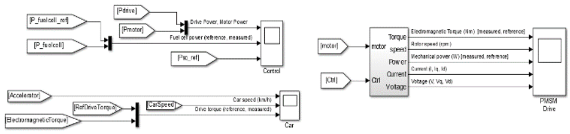

Fig. 5. Measurement of the parameters in the system

III. SIMULATION RESULTS

The simulation of the EVs supplied by fuel cell is realized for 16s. Multiple operation modes are presented: fast acceleration, slow acceleration and braking. In Fig.6 to 8 the curve from simulation are presented.

- at t = 0 s, EVs is at rest and the braking mechanism is in position up to 70%. The supercapacitor provide the supplying until the moment that FC start to operate;
- at t = 0.6 s, the FC assure the power when the position of the braking mechanism is up to 50%, the supercapacitor continues to assure electric power to motor;
- at t = 4 s, the braking mechanism is in position equal to 25%, the power of supercapacitor is equal to 0, the fuel cell assure total power;
- at t = 8 s, the braking mechanism is in position 85% and the supercapacitor start to operate for support of FC;
- at t = 12 s, is simulated the regenerative braking. The motor operates in generator mode supplied by the wheels of the EVs. The stored kinetic energy is converted to electrical energy. The power of FC decrease to 2 kW, which is the minimal power in this conditions.

It is observed that the supercapacitor operates to support the FC. The power between the supplying sources is managed by the control system. The current of the FC execute the reference value.

IV. CONCLUSION

The realized mathematical model of the power structure of EVs allows the evaluation of the operating modes: acceleration, constant speed and regenerative braking. By adding vehicle dynamics, mass, aerodynamic performance and coefficients, maximum speed is achieved by further investigating the performance of the vehicle. Consideration of each subsystem constituting the structure of the EVs helps to create a more detailed model of the system.

FC are becoming increasingly used in EVs, portable and fixed systems. The modelling and simulations of these subsystems demands a mathematical model of a FC for measuring the power and the control systems. In the current research a FC model that represents the behavior of most used hydrogen and air-fueled FC. The model requires several variables provided by the manufacturer and the simulations could be executed without a real FC. The realized model is verified with typical curves provided by the technical

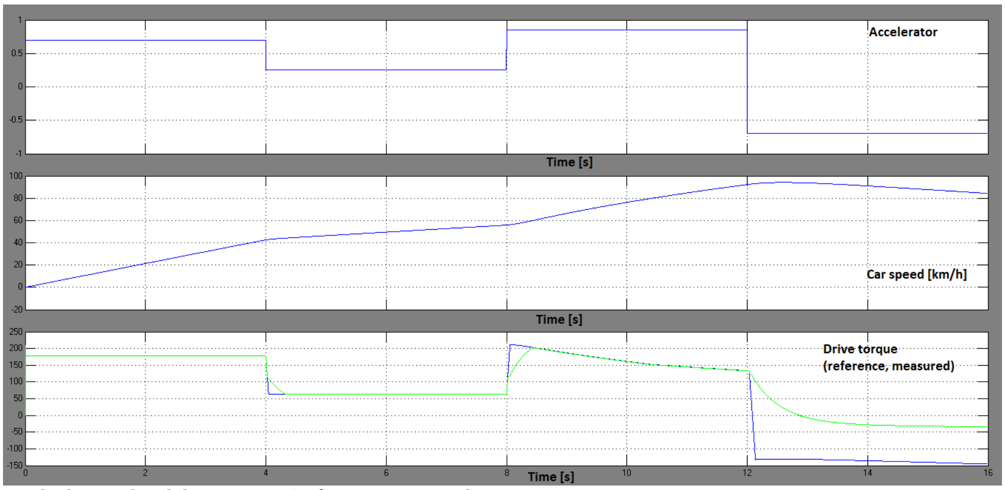

Fig.6. Accelerator, vehicle speed and drive torque (reference, measured)

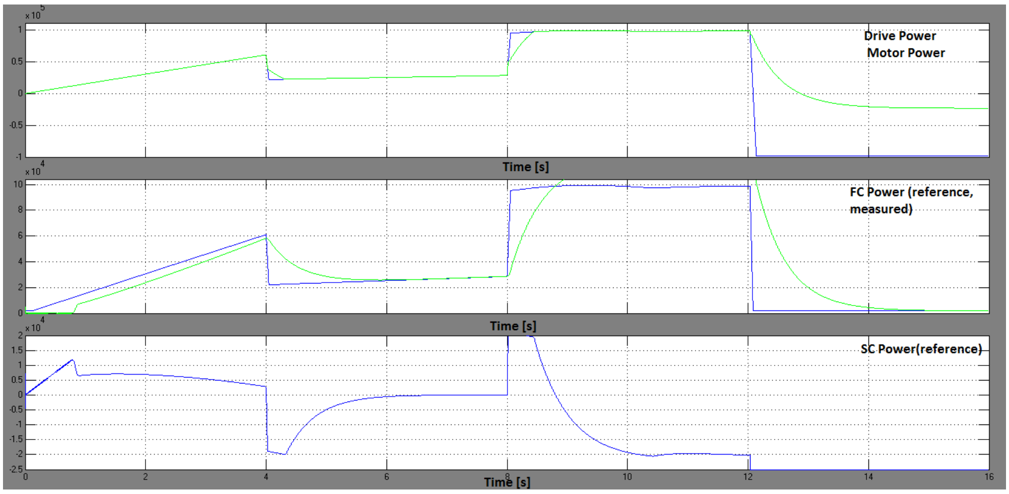

Fig.7. Drive power, FC power and reference of the power of the supercapacitor

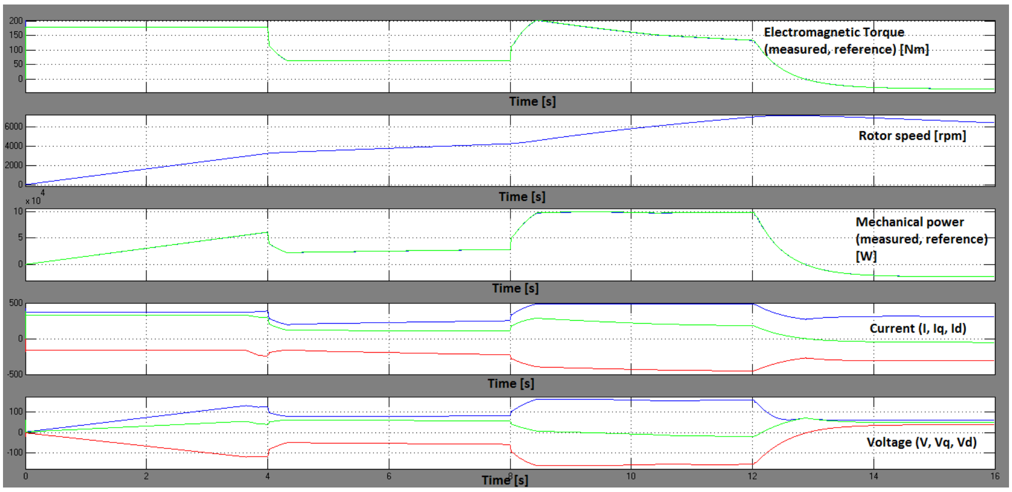

Fig. 8. Electromagnetic torque, rotor speed, mechanical power, current and voltage

documentation of the manufacturer. The complete model of EVs model indicate that the model of the FC is appropriate for different conditions and applications.

ACKNOWLEDGMENT

"This work was supported by the European Regional Development Fund within the Operational Programme “Science and Education for Smart Growth 2014 - 2020” under the Project CoE “National center of mechatronics and clean technologies “BG05M2OP001-1.001-0008".

REFERENCES

[1] M. Becherif, M. Y. Ayad, A. Miraoui, *Modeling and Passivity-Based Control of Hybrid Sources: Fuel Cell and Supercapacitors*, Conference Record of the 2006 IEEE Industry Applications Conference Forty-First IAS Annual Meeting.

[2] M. Amirabadi, Sh. Farhangi, *Fuzzy Control of a Hybrid Power Source for Fuel Cell Electric Vehicle using Regenerative Braking Ultracapacitor*, 2006 12th International Power Electronics and Motion Control Conference

[3] M. Ehsani, Y. Gao, S.E. Gay, A. Emadi, *Modern Electric Hybrid Electric and Fuel Cell Vehicles*, in CRC Press, 2005.

[4] J.M. Correa, F.A. Farret, V.A. Popov, J.B. Parizzi, *Influence of Modeling Parameters On the Simulation Accuracy of Proton Exchange Membrane Fuel Cells*, *IEEE Bologna PowerTech Conf.*, vol. 2, June 2003.

[5] M.I. Marei, S. Lambert, R. Pick, M.M.A. Salama, *DC/DC converters for fuel cell powered hybrid electric vehicle*, 2005 IEEE Vehicle Power and Propulsion Conference

[6] Shuai Lu, *A Unique Ultracapacitor Direct Integration Scheme in Multilevel Motor Drives for , Large Vehicle Propulsion*, IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, VOL. 56, NO. 4, JULY 2007

[7] Radev, D., I. Kurtev, D. Stankovski, S. Siarova. A Handover Scheme for Broadband Wireless Mobile Networks. Proc. of International Symposium on Electronics and Telecommunications, ETC 2010, Timisoara, Romania, 2010, 137-140.

[8] Radev, D., S. Radeva, I. Kurtev, D. Stankovski. Priority Handover Schemes in Wireless Mobile Networks. 18th Telecommunications forum TELFOR'10, Serbia, Belgrade, 2010, 320-323.

[9] M.J. Gielniak ; Z.J. Shen, Power management strategy based on game *theory for fuel cell hybrid electric vehicles*, IEEE 60th Vehicular Technology Conference, 2004. VTC2004-Fall. 2004.

[10] G.Vacheva, V. Dimitrov, N. Hinov, Generalized model for control of energy flows in electric and hybrid vehicles, 45th International Conference on Application of Mathematics in Engineering and Economics, AMEE 2019, DOI: 10.1063/1.5133613

[11] A. A. Frank, "Plug-in Hybrid Vehicles for a Sustainable Future", American Scientist, 95, 158-165, 2007.

[12] A. F. Parrilla, „Development of energy-optimal control strategies for a fully electric vehicle", Department of Automatic Control Chalmers, University of Technology, Göteborg, Sweden

[13] E. Iontchev, R. Miletiev, V. Bashev, I. Simeonov, Study of the dynamic response and status of the vehicle suspension elements, International Journal of new Computer Architectures and their Applications(IJNCAA), Vol. 3, No. 1, pp. 45-51, The Society of Digital Information and Wireless Communications (SDIWC) 2013, ISSN 2220-9085, Impact Factor for 2012 – 0,1290