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Vehicles PEM Fuel Cells Power System Mathematical Model for Integrated Design

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Abstract: *In this paper the mathematical dynamical model of a PEMFC (Proton Exchange Membrane Fuel Cells) stack, integrated with an automotive synchronous electrical power drive, developed in Matlab environment, is shown. Lots of simulations have been executed in many load conditions. In this paper the load conditions regarding an electrical vehicle for disabled people is reported. The innovation in this field concerns the integration, in the PEMFC stack mathematical dynamic model, of a synchronous electrical power drive for automotive purposes. Goal of the simulator design has been to create an useful tool able to evaluate the behaviour of the whole system so as to optimize the components choose. As regards the simulations with a synchronous electrical power drive, the complete mathematical model allows to evaluate the PEMFC stack performances and electrochemical efficiency.*

Keywords: Proton Exchange Membrane Fuel Cells, Mathematical Model, Automotive Synchronous Electrical Power Drive, Test Cycle.

1. Introduction

The on-going growth of the population and the natural ambition of the developing countries to reach life levels close to the ones of industrialized countries are the main causes of the unstoppable demand of energy and of the contemporary increase of the carbon gas emissions.

The air pollution problem, together with the one of an high cost of the traditional fuels and the one of the natural running out of the raw materials, from which the fuels for traction are drawn, are the main themes which will spend more and more time in the social problems, in the political discussions and in the scientific research.

The carbon gas emissions due to the road transport are one of the main sources of air pollution in urban areas. Towards a sustainable transport, it is needed to adopt some specific strategies, reducing the CO2 emissions, in order to contain the risk of climatic changes and to keep down the level of atmospheric pollutants.

The hybrid vehicles, equipped with internal motor combustion engine from fossils and with fuel cells, could reduce the CO2 emissions of around 25% with respect to the most developed motor combustion engines.

Significant CO2 emissions reductions can be achieved only thanks to the use of renewable fuels.

In this frame, the hydrogen and the fuel cells can represent a solution to the problem of the emissions (comprising the greenhouse gases) due to the transport vehicles.

The employment of PEMFC (Proton Exchange Membrane Fuel Cells) in the area of automotive propulsion systems could be one of the most promising options towards the mid/long term thanks mainly to their very low consumptions and almost null emissions. The PEMFCs allow to build road vehicles in which coexist both the qualities of no noises and no pollutions, which are peculiarities of electrical road vehicles furnished with batteries, and the features of high working times and low supplying times, which are peculiarities of traditional combustion road vehicles.

To improve the possibility of utilizing PEMFCs in vehicles an important tool is a mathematical model that simulates, at the same time, not only the PEMFC behaviour but also the vehicle power train working conditions. This allows to design in an integrated manner the whole system by simulating it in different working conditions to stress and optimize the components choice. In this vision, the Authors have implemented, in an previous work, an integrated mathematical model of a PEMFC supplying a brushless electrical drive for different types of vehicle applications by considering a different usage of the vehicle power train with respect to the basic urban cycle [1], [2]. In this work the Authors test the model on a vehicle for disabled people by applying a specific input test cycle for this purpose conceived [3].

The mathematical model here developed and implemented in Matlab environment is useful to analyze the main electrical quantities regarding the PEMFC stack under changing working conditions for given values of gas temperature and pressure. The innovation in this field consists in simulating, by means of the mathematical model of the integrated power drive (synchronous electrical power drive fed from PEMFC stack) standardised, and with the aim conceived, some working cycles useful to verify weather the chosen system (PEMFC plus electrical power drive) is able to perform the automotive tasks.

In this work, an analysis of the use of fuel cells to different typologies of electric vehicles has been carried out.

A synchronous electric power drive, fed from the fuel cell, suitable for the traction of both an electric car and an electric vehicle for disabled people, has been mathematically modelled. The relative simulations have been conceived with the purpose of watching the behaviour when the system is subjected to test cycles purposely conceived for electric drives. Particularly, for the application to the electric traction of a car it has been considered the cycle standardized in [1] whereas for the application to the electric traction of a vehicles for disabled people, whose results are here reported, it has been processed a second cycle conceived with this purpose [3].

This process allows to compare the behaviour of several power drives, making available enough detailed descriptions of the behaviour of the electric and electro-chemical system under study, without incurring in considerable costs.

In this paper, in section 2 the integrated mathematical dynamic model is shortly mentioned, in section 3 the PEMFC stack and IPM motor parameters are reported. In section 4 the simulation results are shown and discussed. Finally, in section 5 the conclusions are illustrated.

2. The Integrated PEM-FC Mathematical Model with Automotive Synchronous Electrical Power Drive in Matlab-Environment

The analysis of the chemical thermodynamics of a PEMFC allows to obtain the analytic tool for the implementation of a PEM mathematical model.

The cell reversing voltage E under ideal chemical conditions and at no load can be calculated by the Nernst equation [2], [4], [5], [6], [7], [8], [9], [10] reported below:

$$E = \frac{\Delta G}{2F} + \frac{\Delta S}{2F}\left(T - T_{rif}\right) + \frac{RT}{2F}\left(\ln P_{H_2} + \frac{1}{2}\ln P_{O_2}\right) \qquad (1)$$

where ΔG is the variation of Gibbs energy, F is the Faraday constant, ΔS is the entropy variation, R is the gases universal constant, P_{H2} and P_{O2} are, respectively, the partial pressures of hydrogen and oxygen, T and T_{rif} are respectively the working and reference temperatures of the cell. By summing the cell reversing voltage E for the number of the stack's cells it is possible to obtain the reversing voltage E_{TOT} of the PEMFC stack.

In load working conditions the cell voltage is significantly different from the ideal E. In fact, as soon as the PEMFC cell supplies a load, some polarization phenomena arise and so the cell voltage decreases with respect to the E value and in the same way the stack voltage decreases too. The polarization phenomena (activation, ohm and concentration polarization) are strongly influenced by the cell working temperature and pressure and they depend from the kinetics of the chemical reactions, the geometrical and physical characteristics of the cells and the kind of electrolyte. These three polarization phenomena are mathematically modelled taking into account as many voltage drops [2], [5], [6], [8], [11], [12].

The dynamic electrochemical behaviour of the PEMFC is described by "charge double layer" phenomenon which appears as soon as two different materials, set in contact, are electrostatically charged and some charges are gathered on the surfaces or moved from a surface to another. In this case, the cell behaves like a capacitor C. In dynamical working condition, the equation which describes the behaviour of a cell is reported in (2) where v_d is the voltage across the C capacitor and τ is the electrical time constant of the cell.

$$\frac{dv_d}{dt} = \frac{1}{C} i_{cell} - \frac{1}{\tau} v_d \qquad (2)$$

These previous mathematical equations have been added to a complete dynamic model to simulate also the behaviour of the stack which feeds a brushless electric power drive, with speed and current control loops, for the propulsion of an electric vehicle [2], whose basic closed loop control scheme is reported in Fig. 1.

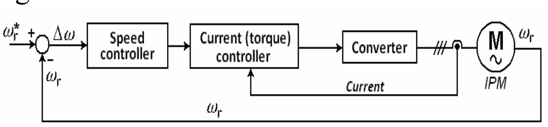

Figure 1: Basic speed and current control loops.

The complete mathematical dynamic model of PEMFC stack and electrical power drive has been implemented in Matlab-Simulink environment and it is shown in Fig. 2. The simulation of the stack feeding the electric power drive has required the implementation of the following blocks:

- PI controllers in order to build the mathematical model which represent the speed and the current controllers;
- Blocks for the conversion from the abc coordinates to the dc ones and vice versa;
- Block for the inverter identification for the control of the feeding of the motor;
- IPM motor block for the mathematical modelling of the IPM brushless motor;
- Implementation block of the function which calculates the current in the inverter's DC-Link;
- Implementation block of the stack PEM mathematical model.

In addition to the blocks for the mathematical dynamic modelling of the system, the "INPUT CYCLE" block has been foreseen. It is necessary for the generation of the speed shape required by the international standard CEN/TC 301 [1] or for the generation of the speed shape elaborated in order to simulate the functioning of a vehicle for disabled people [3].

3. Parameters of the PEM FC Power System Mathematical Model for Integrated Design

The electric and magnetic parameters of the IPM motor chosen for a PEM FC power system are reported in Table 1.

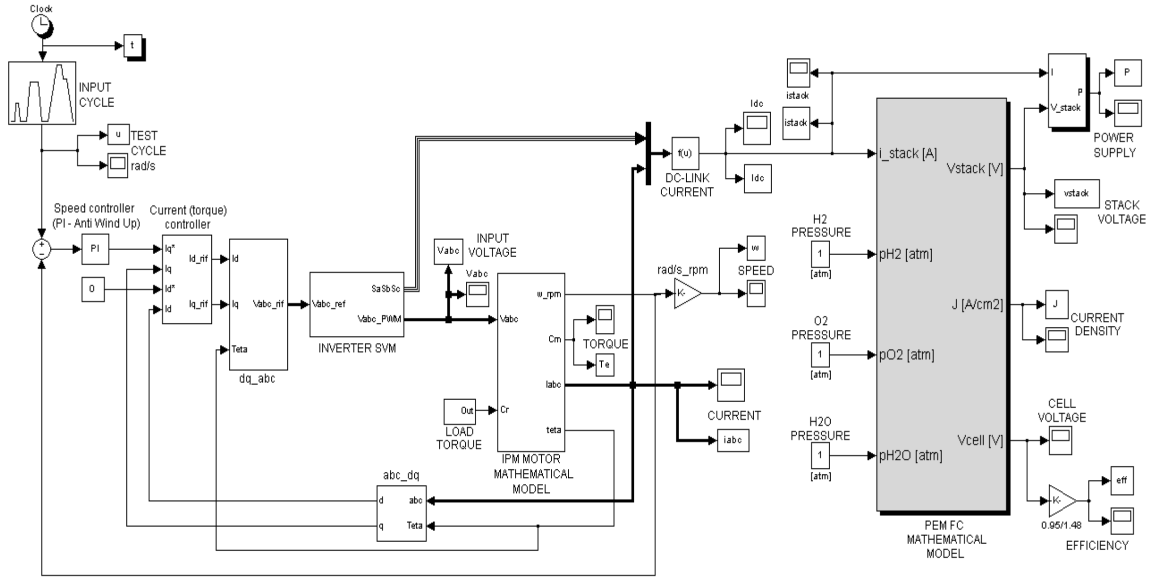

Figure 2: Implementation in Matlab-Simulink environment of the automotive synchronous electrical power drive with the PEMFC.

Table 1: Rating automotive IPM synchronous motor.

Rated speed [rpm]	5000
Rated current (RMS) [A]	3,6
Rated voltage phase (RMS) [V]	77
Rated torque [Nm]	1,8
pole pairs p	3
Stator resistance R [Ω]	2,21
Direct axis inductance Ld [mH]	9,77
Quadrature axis inductance Lq [mH]	14,94
Permanent Magnet Flux [Wb]	0,0844
Coulomb friction coefficient C [Nm]	0,04

For the implementation of the stack mathematical model, the parameters of a Ballard MarkV PEMFC, here chosen as supply system, are reported in Table 2 [2].

Table 2: Ballard Mark V PEM FC parameters.

Simbol	Quantity Description	Stack MARK V Value
n_{celle}	Number of cells used in the stack	35
T	Cell's temperature working condition	343 K
A	Cell's active area	$232\ cm^2$
l	Membrane thickness (Nafion 117)	178×10^{-4} cm
J_{max}	Maximum value of the current density	$1{,}5\ A/cm^2$
C_{ds}	Electrical capacity of the double layer	3 F
R_c	Electrical contact resistance to the proton conduction	$3\times10^{-4}\ \Omega$
ψ	Cell's characteristic parameter	23
B	Characteristic parameter dependent on the cell's type and of its state	0,016 V
ξ_1	Parametric coefficient dependent on the cell's type	-0,948
ξ_2	Parametric coefficient dependent on the cell's type	$31{,}2\times10^{-4}$
ξ_3	Parametric coefficient dependent on the cell's type	$0{,}76\times10^{-4}$
ξ_4	Parametric coefficient dependent on the cell's type	$-1{,}93\times10^{-4}$
P_{H2}	Hydrogen partial pressure	1 atm
P_{O2}	Oxygen partial pressure	1 atm

4. Simulation results

Goal of the simulator design has been to create an useful tool able to evaluate the behaviour of the stack feeding the electric motor during the periods in which the vehicle follows a specific input cycle. To this purpose, the shapes of the stack's voltage, of the power output of the PEMFC and of the efficiency have been calculated.

Many tests have been carried out by applying standard cycles reported in [1]. In this work only the results by applying a pedestrian test cycle, typical of the working condition of a vehicle for disabled people, are reported [3].

Lots of simulations have been executed on the integrated mathematical model.

The simulation of the stack feeding the electric power drive here presented has been carried out in the worst load condition which means in correspondence of the rated valued of the brushless motor's load torque and imposing to the power drive, as input, the above mentioned speed profile.

This profile, as mentioned in [3], foresees for the vehicle: departures from standstill, steps variables accelerations and decelerations in the several working phases and reaching of several levels of the cruise speed.

The simulations have allowed to verify, first of all, that the system's behaviour was fully satisfying since the IPM motor follows with high fidelity the speed shape imposed like a reference to it's input (Fig. 3).

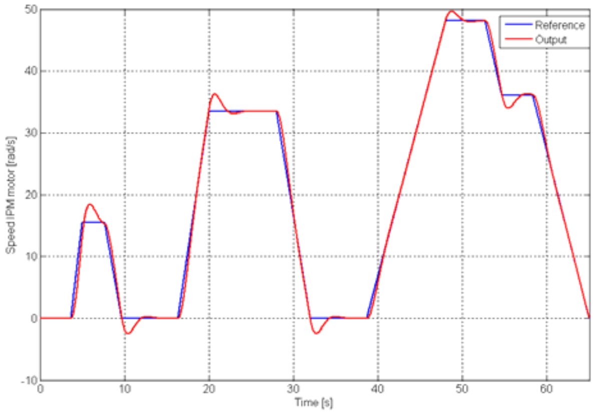

Figure 3: Reference speed profile and output speed shape IPM motor.

The rectified DC-Link's current shape at the stack terminals is shown in Fig. 4, while in Fig. 5 the phase motor currents are reported.

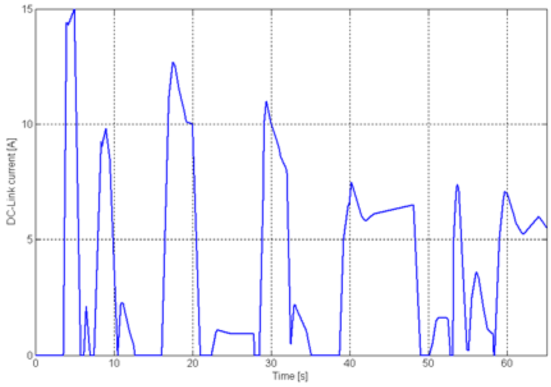

Figure 4: DC Link rectified current.

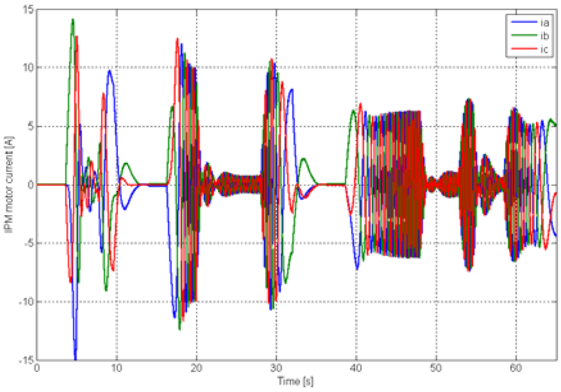

Figure 5: Phase motor currents.

Figures 6, 7, 8 show, respectively, the PEMFC stack voltage, the power supplied by the stack and the efficiency.

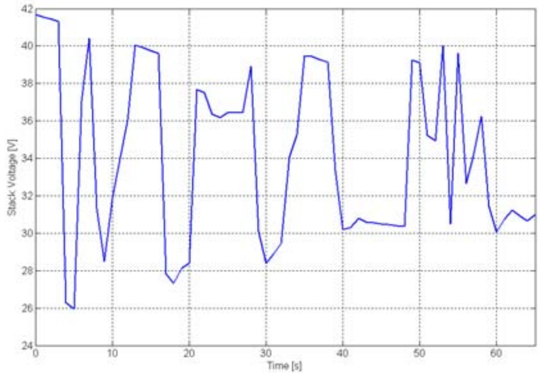

Figure 6: PEMFC stack voltage.

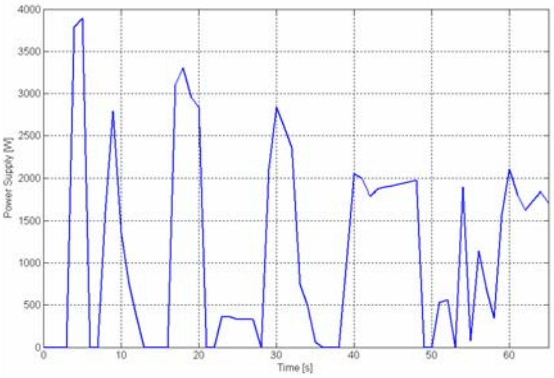

Figure 7: PEMFC power supply.

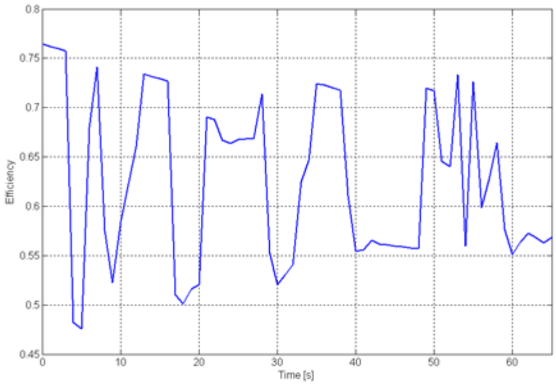

Figure 8: PEMFC stack efficiency.

5. Conclusions

As regards the simulations of the synchronous electrical power drive working conditions, the PEMFC stack efficiency, the DC link current and the stack output voltage have been plotted. These results allow to foresee the behaviour of the PEMFC stack and, more generally, its working conditions.

In particular, from the analysis of the above mentioned shapes, it points out that the chosen PEMFC stack is able to supply, easily and with a good energy margin, all the electrical energy requested by the power drive in the working conditions considered in [3].

Despite the simplifications introduced to carry out the stack’s simulations, the energy supply margin guarantee the good working of the system.

Moreover, it must be underlined that the approximations made in the mathematical model do not invalidate the PEMFC stack design stage.

In the end, it is possible to conclude that the integrated PEM’s mathematical dynamic model here developed represents an useful tool which allows to evaluate, already in the theoretical phase, the stack’s behaviour in several different working conditions with many electric loads. Moreover, the model allows to estimate (in a theoretical phase) the behaviour of the stack, in correspondence of load conditions typical of a real automotive system power drive, in an electric vehicle provided with a PEMFC and in particular, as in this paper reported, with a electrical vehicle for disabled people. It means that the mathematical model, developed and implemented, may represent an useful tool in the design phase of the PEMFC stacks. In particular, many simulating tests can be significant in choosing the most suitable electrical drive components and to set up their parameters.

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References

[1] Standard DOC CEN/TC 301 N 36, “Electrically propelled toad vehicle measurement of energy performance”, page(s) 7-8.

[2] V. Di Dio, D. La Cascia, R. Liga, R. Miceli, Member IEEE: “Integrated Mathematical Model of Proton Exchange Membrane Fuel Cell Stack (PEMFC) with Automotive Synchronous Electrical Power Drive”, Proceedings of the 2008 *International Conference on Electrical Machines*, September 2008, page(s) 1-6.

[3] V.Di Dio, A.O. Di Tommaso, R. Miceli, C. Cavallaro, A. Raciti, “Test cycle for the characterization of electrical drives devoted to wheelchair applications”, Proceeding of the Fourth IEEE International Caracas Conference on Devices, Circuits and Systems, Aruba, 17-19 April 2002, Page(s):P021-1 – P021-6.

[4] Jeferson M. Corrêa, Felix A. Farret, Luciane N. Canha, Marcelo G. Simões: “An electrochemical-based fuel-cell model suitable for electrical engineering automation approach”, IEEE Transactions on industrial electronics, Vol. 51, No.5, October 2004, page(s) 1103-1112.

[5] Jeferson M. Corrêa, Felix A. Farret, Vladimir A. Popov, Marcelo G. Simões: “Sensitivity analysis of the modelling parameters used in simulation of proton exchange membrane fuel cells”, IEEE Transactions on energy conversion, Vol. 20, No.1, March 2005, page(s) 211-213.

[6] M.J. Khan, M.T. Iqbal: “Dynamic modelling and simulation of a fuel cell generator”, “Fuel Cells” 2005, 5, No.1, page(s) 97-99, 101-104.

[7] Correa J.M., Farret F.A., Gomes J.R., Simoes M.G., “Simulation of Fuel-Cell Stacks Using a Computer-Controlled Power Rectifier With the Purposes of Actual High-Power Injection Applications”, Transactions on Industry Applications, IEEE Volume 39, Issue 4, July-Aug. 2003 Page(s):1136 – 1142.

[8] Brooks N., Baldwin T., Brinson T., Ordonez J., Luongo C., “Analysis Of Fuel Cell Based Power Systems Using EMTDC Electrical Power Simulator”, System Theory, 2004. Proceedings of the *Thirty-Sixth Southeastern Symposium* on 2004 Page(s):270–274.

[9] Wingelaar P.J.H., Duarte J.L., Hendrix M.A.M., “Dynamic Characteristics of PEM Fuel Cells”, *Power Electronics Specialists Conference*, 2005. PESC '05. IEEE 36th 2005 Page(s):1635–1641.

[10] Wingelaar P.J.H., Duarte J.L., Hendrix M.A.M., “Dynamic and static simulation tool for PEM fuel cells”, Industrial Electronics, 2006 IEEE International Symposium on Volume 3, July 2006 Page(s):1700 – 1705.

[11] Mangoni V., Pagano M., Velotto G., “Fuel Cell Reliability Model based on Uncertain Data”, Clean Electrical Power, 2007. *ICCEP '07. International Conference* on 21-23 May 2007 Page(s):730-735.

[12] Qiuli Yu, Srivastava A.K., Song-Yul Choe, Wenzhong Gao, “Improved Modeling and Control of a PEM Fuel Cell Power System for Vehicles”, SoutheastCon, 2006. Proceedings of the IEEE March 31 - April 2, 2006 Page(s):331 – 336.

[13] Dong Jing Lee, Li Wang “Dynamic and Steady-State Performance of PEM Fuel Cells under Various Loading Conditions”, Power Engineering Society General Meeting, 2007. IEEE 24-28 June 2007 Page(s):1-8.

[14] Correa J.M., Farret F.A., Popov V.B., Parizzi J.B., “Influence Of The Modeling Parameters On The Simulation Accuracy Of Proton Exchange Membrane Fuel Cells”, Power Tech Conference Proceedings, 2003 IEEE Bologna, Volume 2, 23-26 June 2003 Page(s):8 pp.

[15] Cecconi V., Di Dio V., Di Tommaso A. O., La Cascia D., Miceli R. “Test Bench Realization and Application of Specific Working Cycles for the Characterization of Wheelchair Electrical Drives” IEEE-ISIE 2006 International Symposium on Industrial Electronics, Montreal, Canada, 9 – 13 Luglio 2006.