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Power Management for a Fuel cell/Battery and Supercapacitor based on Artificial Neural Networks for Electric Vehicles

Abstract. *Hydrogen electric vehicles are environmentally friendly and highly efficient. They derive their energy from fuel cell as a main component in addition to lithium-ion battery and supercapacitor as auxiliary elements. However, there are problems in securing the required power and the optimal power control strategy with different operating conditions. In order to solve these problems, we seek in our work to improve energy economy and continuity, make use of some of the energy that is often lost as heat, and increase system life. To with considering various operating restrictions. So, we adopted this hybrid energy storage system. A specialized strategy is designed for optimal control of energy sources. Therefore, an artificial neural network was trained using Matlab/Simulink software. The obtained results showed the effectiveness and accuracy of the proposed system. Which can be used in practice.*

Streszczenie. *Pojazdy napędzane wodorem są przyjazne dla środowiska i bardzo wydajne. Energię czerpią z ogniwa paliwowego jako głównego elementu, oprócz akumulatora litowo-jonowego i superkondensatora jako elementów pomocniczych. Istnieją jednak problemy z zapewnieniem wymaganej mocy i optymalną strategią sterowania mocą przy różnych warunkach pracy. Aby rozwiązać te problemy, w naszej pracy staramy się poprawić ekonomię i ciągłość energii, wykorzystać część energii, która często jest tracona w postaci ciepła, oraz wydłużyć żywotność systemu. Aby wziąć pod uwagę różne ograniczenia operacyjne. Dlatego przyjęliśmy ten hybrydowy system magazynowania energii. Specjalistyczna strategia ma na celu optymalne sterowanie źródłami energii. Dlatego sztuczna sieć neuronowa została przeszkolona przy użyciu oprogramowania Matlab/Simulink. Uzyskane wyniki wykazały skuteczność i dokładność proponowanego systemu. Które można wykorzystać w praktyce.* (***Zarządzanie energią dla ogniwa paliwowego/akumulatora i superkondensatora w oparciu o sztuczne sieci neuronowe dla pojazdów elektrycznych***)

Keywords: Fuel cell, Battery lithium ion, Energy management, Supercapacitor.
Słowa kluczowe: ogniwo paliwowe, bateria litowo-jonowa, zarządzanie energią, superkondensator.

Introduction

The population is increasing exponentially in the world, which increases the demand for energy needs. To meet these needs, fossil resources are exploited, which causes polluting emissions to the environment, which in turn leads to climate change and global warming [1]. Climate change is a real threat, and in order to reduce it. We must reduce the exploitation of these carbon-intensive resources. As for renewable energies, they should be an essential part of this process [2].

The technological development that our world is witnessing today, help us to transmit to the use of electric vehicles in the transport sector which is imminent and will reduce environmental pollution this is achieved, when the fuel used in vehicles is electricity [3], because this sector consumes a lot of total energy. The aforementioned idea is based on to the statistics of three countries: Jordan, Egypt and Palestine, it consumes 30 to 40% of the total energy consumption [4].

Preserving the environment in which we live is one of the primary goals of the fuel cell, which is why it is receiving focused and serious attention from governments, private companies, and academic institutions to develop, produce, and harness it for electric vehicles [5].

PEMFC (Proton-exchange membrane fuel cells) is one of the most advanced fuel cell technologies of the future. It is expected that this type will end up powering electric vehicles and even your home [5].

The first fuel cell vehicle was introduced by General Motors in 1966, which is Electrovoan [6].And the first hydrogen-powered commercial vehicle was done by Hyundai in January 2013, model ix35 [7]. Currently, many companies produce hydrogen vehicles, such as: Toyota Mirai [8, 9], Hyundai NEXO [10], Audi H-Tron Quattro [8, 11], Mercedes-Benz GLC F-Cell [8, 12], Nicola [8, 13], Pininfarina H2 Speed [8, 14].

When we want additional positive advantages in a storage system consisting of fuel cell and battery. We add supercapacitor which has many advantages such as: immediate response to energy demand [15] and increased battery life.

In our study, the adopted storage system consisted of fuel cell as the primary source and supercapacitor with lithium-ion battery as auxiliary sources [15]. This hybridization allows for better fuel economy and good performance [16]. This system also needs a strict and robust energy management strategy. So we relied on an artificial neural network because it is suitable for dealing with systems with a high level of nonlinear data and big data [17].

The paper is categorized as follows: section 2 presents an architecture of the studied system. The power management strategy in section 3. In section 4, the adaptation of measurement with neural network. The Structure used of neural network in section 5 is presented. In section 6 the simulation results and discussion. Section 7 summarizes the work done in the conclusion.

Electric vehicle architecture

The traction chain of the approved system Fig. 1, consists of fuel cell as the main power source connected to the DC (Direct current) bus line via a DC-DC unidirectional boost converter. In addition to lithium-ion battery as an auxiliary power source in giving additional power when needed and it absorbs excess power from the load [18] connected to the DC bus line via Bidirectional DC-DC Buck-Boost Converter. Supercapacitor a third additional source directly connected to the DC bus which helps reduce the burden of power transients and reduce the peak current of the battery when extreme change the power load thus keeping the battery voltage nearly constant [19, 20, 21]. The inverter is connected to the back of the DC bus to supply power to the permanent magnet synchronous motor.

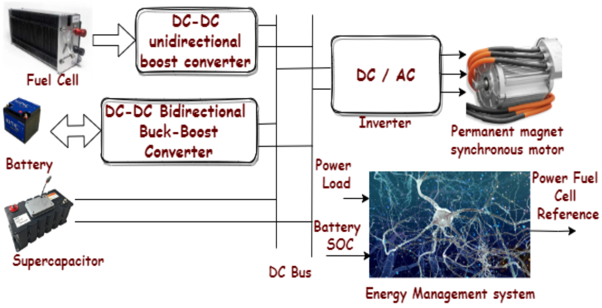

Fig.1. System architecture.

0.1 Model of fuel cell

It is possible to obtain electrical energy from a fuel cell resulting from a chemical reaction between oxygen and hydrogen. The reaction results are shown in equation (1), [22].The equivalent electrical circuit for this model is shown in - Fig. 2 [23].

(1) $$2H_2 + O_2 = 2H_2O + energy$$

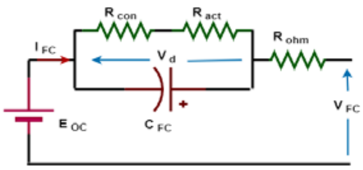

Fig.2. Equivalent electrical circuit of the Fuel Cell.

Where the actual voltage V_{FC} is less than the theoretical voltage E_{OC} due to losses. Described in equation (2), due to the membrane that separates the two electrodes, which prevents the passage of electrons, although it allows the passage of ions, thus forming a double layer that allows the storage of electrical energy, and for this reason it can be treated as a capacitor [24].

(2) $$V_{FC} = E_{OC} - V_d - R_{ohm} \times I_{FC}$$

The parameters used in the mathematical modeling of the Fuel Cell are as follows:
V_d – the dynamical voltage across the equivalent capacitor, C_{FC} – the equivalent electrical capacitance, R_{ohm} – the ohmic resistance, E_{OC} – the open-circuit voltage, I_{FC} – the stack current.

0.2 Model of battery

For the purpose of powering the energy management system, lithium-ion battery cells have been modelled [25]. And for dynamic battery operation. In this case, the battery can be represented by the electrical circuit, Fig. 3, the proposed model of the equivalent circuit is governed by the equations below [26].

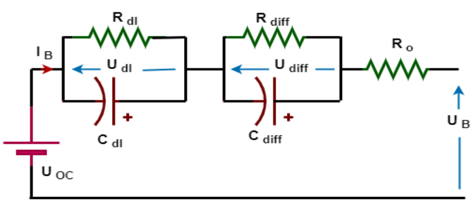

Fig.3. Equivalent circuit model of lithium-ion battery.

(3) $$SOC = SOC_{init} - \int_{t0}^{t} \frac{I_B(t)\eta_I}{C_{nom}}$$

(4) $$U_{dl}(s) = \frac{R_{dl}}{1 + R_{dl}C_{dl}s} \times I_B(s)$$

(5) $$U_{diff}(s) = \frac{R_{diff}}{1 + R_{diff}C_{diff}s} \times I_B(s)$$

(6) $$U_B = I_B R_O + U_{dl} + U_{diff} + U_{OC}(SOC)$$

The parameters used in the mathematical modeling of the Battery are as follows:
SOC – State of charge, SOC_{init} – the initial SOC value, I_B – the current of battery cell, C_{nom} – the nominal capacity of the cell, $R_{dl}C_{dl}$ and $R_{diff}C_{diff}$ – Are the circuits simulate the double layer effect and diffusion of the Lithium-ion during charging and discharging, s – the Laplace operator, I_B – the terminal voltage, R_O – Is the internal Ohmic resistance, U_{OC} – the open circuit voltage, U_{dl} and U_{diff} – Are the voltages cross the $R_{dl}C_{dl}$ and $R_{diff}C_{diff}$ circuit respectively, η_I – the Coulombic efficiency.

0.3 Model of supercapacitor

Due to maximum power loading, we add the supercapacitor to the hybrid storage system and avoid performance degradation [27]. In different operating conditions, we need to predict the behavior of the supercapacitor, so we have to model this element [28]. We chose Fig. 4 for the equivalent circuit model [29, 30]. Equations describing the charging and discharging behavior (7), (8).

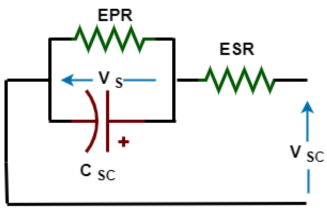

Fig.4. Equivalent Model of the Supercapacitor.

(7) $$\frac{V_S}{V_{SC}} = (1 - e^{-\frac{t}{(EPR+ESR)C_{SC}}})$$

(8) $$\frac{V_S}{V_{SC}} = e^{-\frac{t}{EPR \times C_{SC}}}$$

The parameters used in the mathematical modeling of the Supercapacitor are as follows:
V_{SC} – Voltage of supercapacitor, C_{SC} – Capacitance, ESR – Equivalent series internal resistance, EPR – Equivalent parallel resistance.

Power management strategy

An efficient energy management system is required to balance the vehicle's longevity to achieve [16, 18, 31]:

Saving energy demand in addition to economy.

High efficiency of the system.

Preserving a longer life of battery and supercapacitor.

This is achieved with the help of good energy management and the advantages of a hybrid system, such as:

Energy management which gives the appropriate reference energy.

Each component of the hybrid system operates within the appropriate range according to its characteristics. In addition to response time is considered [18].

Mode1: the minimum energy produced by the fuel cell is sufficient to satisfy the load demand and the remaining energy is returned to the storage elements, and governed by the equation (9).

$$P_{FC} = P_L + (P_B + P_{SC}) \quad for \quad P_L < P_{FC\_min} \tag{9}$$

Mode2: optimum energy is produced from the fuel cell which is sufficient to satisfy the load demand and the remaining energy is returned to the storage elements, and governed by the equation (10).

$$P_{FC} = P_L + (P_B + P_{SC}) \quad for \quad P_{FC\_min} \le P_L < P_{FC\_opt} \tag{10}$$

Mode3: the energy produced from the fuel cell is equal to the load energy, and the battery state of charge must be greater than the minimum value, and governed by the equation (11).

$$P_{FC} = P_L \quad for \quad P_{FC\_min} \le P_L < P_{FC\_max} \tag{11}$$

Mode4: the largest energy is produced from fuel cell, which are not sufficient to meet the load energy by itself, so they are supported by storage elements, and governed by the equation (12).

$$P_{FC} = P_L - (P_B + P_{SC}) \quad for \quad P_L > P_{FC\_max} \tag{12}$$

Mode5: the energy produced from the fuel cell is equal to the load in addition to the battery charge energy, and the state of charge battery must be less than the minimum value, and governed by the equation (13).

$$P_{FC} = P_L + P_{B\_charge} \quad for \quad 0 < P_L < P_{FC\_max} \tag{13}$$

The provided control algorithm is illustrated in the energy management flowchart Fig. 5.

The parameters used in the mathematical modeling of the power management strategy are as follows: P_{FC} – fuel cell power, P_L – load power, P_B – battery power, P_{SC} – supercapacitor power, P_{FC_min} – minimum power for fuel cell, P_{FC_opt} – optimum power for fuel cell, P_{FC_max} – maximum power for fuel cell, P_{B_charge} – power charge for battery, S_B – state of charge for battery, S_{B_min} – state of charge minimum for battery, S_{B_max} – state of charge maximum for battery.

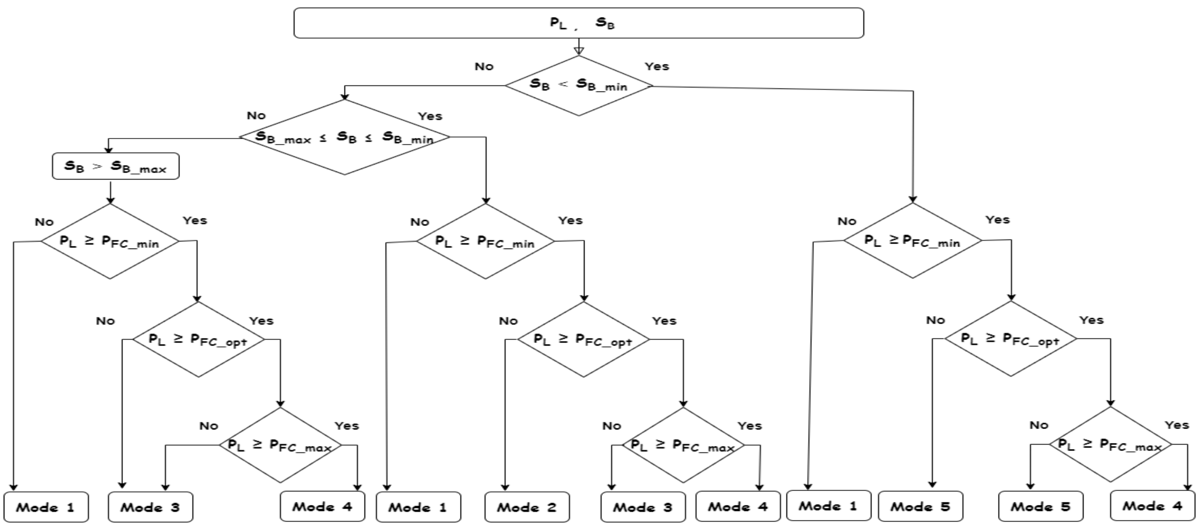

Fig.5. Power management flowchart.

Adaptation of measurement with neural network

The following explain how the inputs of the artificial neural network are organized. We used 15,000,000 samples divided as follows: 70% training, 15% validation, and testing 15% table 1.

Table 1. Adaptation of measurement with neural network inputs

Size measured	Variation interval	Interval
P_L-P_{FC_min}	P_L-$P_{FC\_min} < 0$	-1
	P_L-$P_{FC\_min} \ge 0$	+1
P_L-P_{FC_opt}	P_L-$P_{FC\_opt} < 0$	-1
	P_L-$P_{FC\_opt} \ge 0$	+1
P_L-P_{FC_max}	P_L-$P_{FC\_max} < 0$	-1
	P_L-$P_{FC\_max} \ge 0$	+1
S_B	$S_B < S_{B\_min}$	-1
	$S_B > S_{B\_max}$	+1
	$S_{B\_min} \le S_B \le S_{B\_max}$	0

Structure used of neural network

In this proposed design, we have two inputs: power load and battery state of charge in the input layer and we have one hidden layer that contains 58 neurons and one outer layer: mode.

Results simulation and discussion

Simulations were performed on MATLAB/Simulink software for 110 seconds. The main objective is to verify the effectiveness and accuracy of the proposed strategy, this is done through operating scenarios related to the condition of the vehicle and the characteristics of the hybrid system.

Fig. 6 shows the electric vehicle motor characteristics of current, torque and rotational speed for different driving phases.

The DC bus voltage is maintained at around 270 V as in Fig. 7.a, and the current which behaves similarly as the load power in Fig. 7.b.and state of charge battery in Fig. 8.

The changes correspond to the voltage and current of the power elements as power load, Fig. 9.

The power of the three sources and the energy demand load Fig. 10. At t = 40s, the battery adds power to the load because the fuel cells are unable to meet the power demand on their own and give out their maximum power. At t = 55s, the load power is equal to that of the fuel cell, which means that the rest of the sources do not give any power to the load. At t=70s, the fuel cell give more power than the load, and the extra power helps charge the other sources.

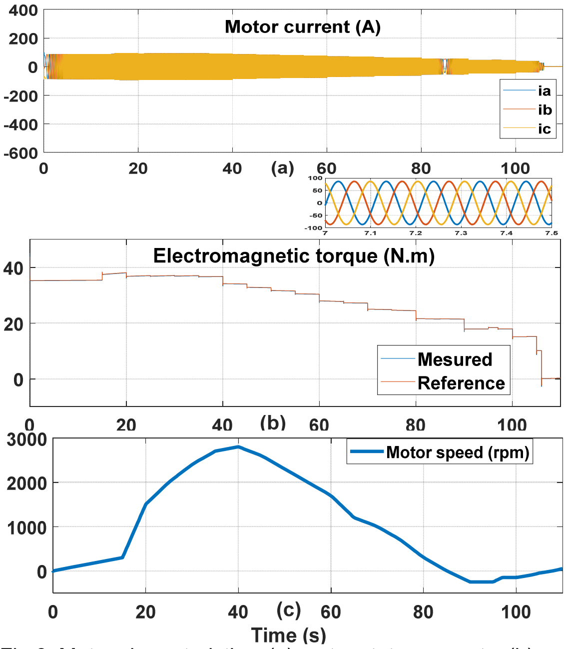

Fig.6. Motor characteristics, (a) motor stator currents, (b) Electromagnetic torque developed by the motor, (c) mechanical motor speed.

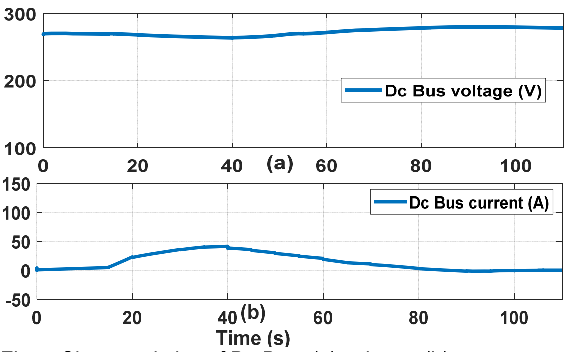

Fig.7. Characteristics of Dc Bus, (a) voltage, (b) current.

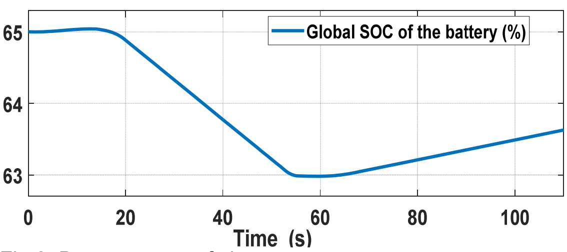

Fig.8. Battery status of charge response.

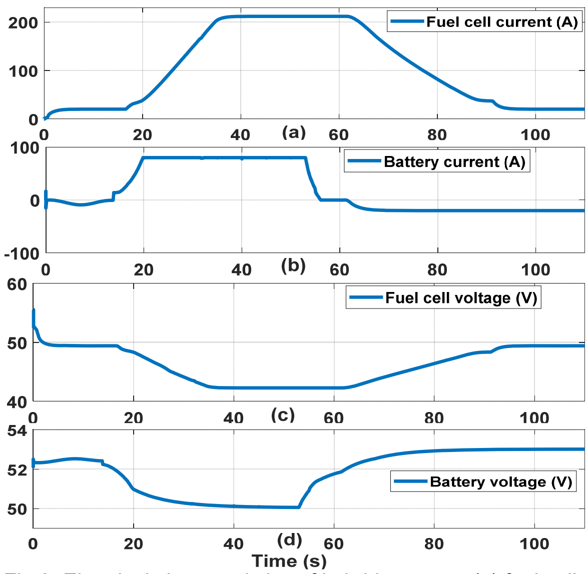

Fig.9. Electrical characteristics of hybrid sources, (a) fuel cell current, (b) battery current, (c) fuel cell voltage, (d) battery voltage.

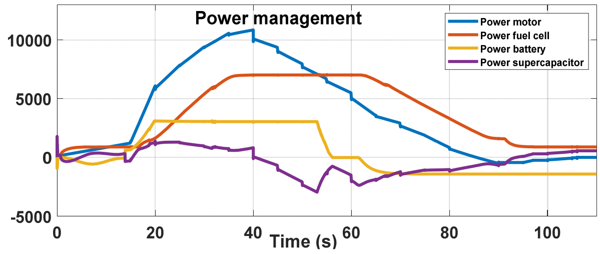

Fig.10. Fuel cell, battery and supercapacitor power delivering the requested load.

Conclusion

In this paper, an artificial neural network strategy was studied to control the energy flow of the hybrid storage system of the electric vehicle, which consists of fuel cell as the main source of energy, and lithium-ion battery and supercapacitor as auxiliary sources.

The effectiveness of the proposed strategy has been proven through the obtained results, which are summarized as follows:

The hybrid power system allows to meet the power needs in different operating conditions.

Increase the life of energy storage elements.

Increasing system efficiency in general.

The strategy is simple and flexible to apply even in real situation.

In future works, can possibly add the converter DC-DC for supercapacitor to get better results, especially in terms of efficiency and performance. Besides, can add other parameters as: state of charge of supercapacitor and degree of heat of storage elements in to power management system for better results.

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