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Hybrid Proton Exchange Membrane Fuel Cell with Battery Energy Storage for Stand-Alone Distributed Generation Applications

***Abstract**. Hybrid power sources with energy storage elements that supply renewable energy can overcome the lack of renewable energy sources, especially with respect to load-tracking issues. Poor load-following characteristics and slow response to rapid load changes are some of the drawbacks of proton exchange membrane fuel cells (PEMFCs) because of the gas processing reaction and the fuel cell dynamics. This load tracking problem can be solved by adding an energy storage element, such as a battery or an ultra-capacitor to the system. This paper focuses on modeling of a stand-alone hybrid distributed generation (DG) system using the MATLAB/Simulink software. The model utilizes PEMFC as the main energy source, whereas the battery functions as energy storage to compensate for the limitations of PEMFC. Furthermore, the three main types of batteries are compared via simulation to identify the most suitable battery types for DG applications. The main objective of this paper is to analyze a hybrid model based on the power output across the fuel cell and in the battery terminal. Simulation results show that the delay and load-tracking problems in the PEMFC model have been resolved by the existence of the battery in the hybrid model.*

***Streszczenie.** W artykule opisano model i badania symulacyjne hybrydowego systemu generacji energii elektrycznej. Układ złożony jest z komórek paliwowych jako głównego źródła energii oraz baterii służącej do kompensacji energii przy dynamicznej zmianie obciążenia. Dodatkowo dokonano symulacyjnego porównania zastosowania trzech typów baterii. W badaniach wykorzystano oprogramowanie Matlab-Simulink. Otrzymane wyniki potwierdziły skuteczność działania rozwiązania z dodatkową baterią. (**Hybrydowy system wytwarzania energii elektrycznej w oparciu o komórki paliwowe PEM oraz magazyn energii w postaci baterii**).*

Keywords: Proton exchange membrane fuel cell, energy storage system, battery, hybrid, dynamic model.
Słowa kluczowe: komórki paliwowe PEM, system magazynowania energii, hybryda, model dynamiczny.

1. Introduction

The development of combined renewable energy and distributed generation (DG) technologies has been the subject of increasing interest. DG is a decentralized energy system configuration that can moderate the stress of the high electricity demand in the mainstream utility grid. The DG configuration promises several advantages, such as its low investment requirements, high operating efficiency, low loss, and high reliability [1]. Research on the expansion of DG systems that utilize renewable energy as the main energy source has received much attention. These modifications have become the new focus of studies on DG configuration models. Simulation is used in this study to overcome the lack of existing DG models as well as other problems in DG. However, a major problem of DG configurations is the load-tracking issue, wherein the renewable energy model is not able to satisfy the load demand under peak load conditions. The design of hybrid models could successfully address such difficulties in the DG system, including the lack of electrical power for the period of heavy load and the need to meet the requirements of high-powered applications.

Among the various types of renewable energy technology, fuel cell (FC) is one of the most promising energy sources. FC has been used in DG modeling and applications because of their high efficiency, silent operation, high power density, noncombustibility, and easy storage as compared with other renewable energy sources. A fuel cell is an electrochemical device that directly converts the chemical energy of a reaction into electrical energy without involving the moving parts of the device [2]. Researchers have shown increased interest in proton exchange membrane fuel cell (PEMFC) modeling because of the low operating temperature as well as the reduced capital and maintenance costs. PEMFC employs solid polymers as the electrolyte, such that liquid management is not required. However, problems in PEMFC modeling, such as the slow transient response to load changes, have been encountered [3]. Therefore, another form of energy storage is needed for back-up power during the increased electrical load. The combination of a FC as the main energy source and a battery as the energy storage element creates a hybrid configuration which could solve the mismatch issue between the load and the FC output power.

The aim of this paper is to model a hybrid configuration that consists of PEMFC and a lead–acid battery for stand-alone analysis of a DG system. The battery model will be charged by the PEMFC model. The main focus in this paper is the operation of the hybrid simulation model. Thus, the power will be measured across the battery, FC, and the load for the analysis of the as-developed model.

2. PEMFC and Battery Energy Storage System

The various advantages of PEMFCs include high power density, efficient dynamic response, rapid start-up, and low operating temperature, as well as the reduced capital and maintenance costs. PEMFC is considered a promising fuel cell type for energy production. However, PEMFC model simulation in Figure 1 shows that PEMFCs are limited by the delay or a slow response in terms of output power.

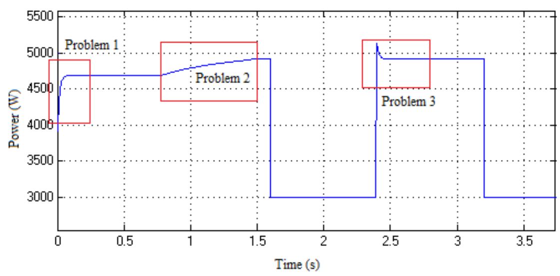

Fig. 1. Slow response in the PEMFC output power

The difficulties encountered by PEMFCs are illustrated in Figure 1. PEMFC modeling has four main potential problems, which are:

i) The PEMFC model has a slow start-up time because it needs several moments to fulfill the load demands.
ii) Between the interval from 0.7 s to 1.4 s, the fuel cell output is unable to quickly reach its maximum power level because of the sudden change in the load. This limitation indicates that the poor load-following

characteristics of the PEMFC model, which are mainly caused by the reformer unit in the gas processing response. Thus, the power shortage problem at this time interval needs to be solved.

iii) At the given time interval which is around 2.4 s, PEMFC requires several seconds to reach a steady-state level. Thus, excess power is present during this interval because of the transient response of the PEMFC itself.

iv) The major limitation of the PEMFC model is its inability to fulfill the required load demand (not shown in Figure 1). Fuel cell output relies on the maximum power of the model itself. If the load demand exceeds the maximum power of the FC, auxiliary power is needed to act as the back-up power supply.

The abovementioned problems emphasize the need to augment the PEMFC model by adding an alternative power source, such as a battery, to meet the fluctuating power demand.

At least five types of batteries in the mature and development stages can meet the power system requirements [4]. However, only the three most common batteries are used and studied in this paper, namely, the lead–acid, nickel–cadmium and lithium–ion batteries. The lead–acid battery is the oldest, cheapest, most popular, and most mature technology used in most power applications [5]. Table 1 lists the important characteristics of these batteries in terms of its efficiency, lifespan, cost, operating temperature, and depth of discharge.

Table 1. Battery characteristics

	Lead–Acid	**Nickel–Cadmium**	**Lithium–Ion**
Cost	Low	Moderate	High
Depth of Discharge (%)	75	100	80
Lifespan (cycles)	1000 to 2000	3000	3000
Efficiency (%)	72 to 78	72 to 78	~100
Operating Temperature (°C)	- 5 to 40	- 40 to 50	- 30 to 60
Advantages	Safe, mature technology, less robust, economical price	Fast and easy to recharge, economical, mature technology, long shelf life	High efficiency, long lifespan, low maintenance
Limitations	Large and heavy, low efficiency, low energy density	Low efficiency, poisonous, heavy, low energy density	Immature technology, expensive, subject to aging
Applications	Larger power applications, UPS systems	Biomedical equipment, video cameras, power tools	Notebook computers, cellular phones

3. Model description

The hybrid system designed in this paper consists of a reformer, a PEMFC stack, and a battery. A step-load change replicates the stand-alone DG system and provides the basis for assessing the features of the battery ESS. The proposed system is displayed graphically in Figure 2.

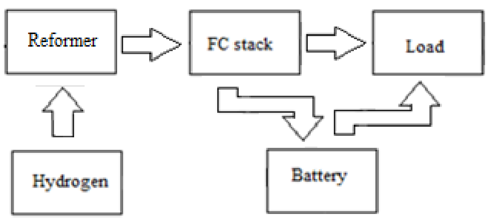

Fig. 2. Hybrid system diagram

The main objective of this configuration is to mitigate the slow response of the fuel cell output power during rapid load changes, to supply electrical power to the load when the FC model reached its maximum power rating, and to find the appropriate battery storage for this configuration. The system's operating principle is described as follows:

A battery is used as the back-up power to cater to all the problems in the PEMFC model. The system starts with the battery power which will support the PEMFC model in the four situations that were previously described. During the start-up process, the battery will discharge to adjust to the load demand. Therefore, when excess voltage or voltage shortage occurs, the battery will charge or discharge, depending on the load requirement.

3.1 PEMFC Model

The PEMFC model is designed based on the polarization curve of PEMFC with the Nernst equation and the double-layer charge effect that occurs in the FC stack. The model considers the temperature criterion because in real cases, the temperature characteristics are not constant. This temperature is influenced by the net heat generation rate and the chemical reactions that occur inside the stack. The double-layer charge effect is the collection of charges at the surface of the electrodes that generate electrical voltage. This layer of charge near the electrode interfaces can store electrical charge and function as a large electrical capacitor. This layer is considered important when designing an electrical model of PEMFC. The equivalent circuits of a PEMFC stack are shown in Figure 3 [6].

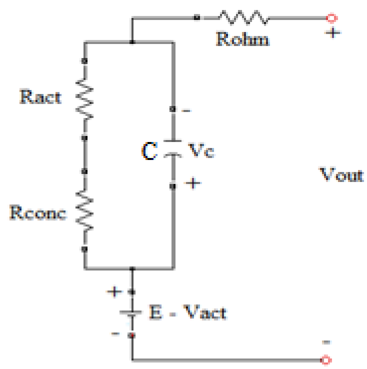

Fig. 3. PEM fuel cell equivalent circuit

The actual voltage at the FC terminals (Figure 3) is lower than the internal potential E that is obtained from the Nernst equation. This occurrence is due to the existence of the double-layer charge effect as well as the presence of the activation, concentration, and ohmic voltage drops that occur inside the FC stack. V_C represents the double-layer charge effect, whereas R_{conc}, R_{act}, and R_{ohm} are the concentration, activation, and ohmic resistances, respectively. The FC output is a voltage value, which can be derived as

$$(1)\quad V_{out} = N_0\left(E - V_{act} - V_C - V_{ohm}\right)$$

The corresponding Nernst equation used in this model is given by:

$$(2)\ E = (1.229 + 0.0085(T - 298.15) + 4.31\times 10^{5}[\frac{P_{H_2}\sqrt{P_{O_2}}}{P_{H_2O}}])$$

The partial pressure equations can be found in Ref. [7].

In real cases, three main voltage drops occur in the PEMFC model: the activation, ohm, and concentration losses. However, only the activation and ohm losses are considered in Figure 3. The concentration loss is disregarded because the equivalent R_{conc} is included in the V_C equation, as described below:

$$(3)\ V_C = I - C\frac{dV_C}{dt}(R_{act} + R_{conc})$$

in which the equivalent R_{conc} is

$$(4)\ R_{conc} = -\frac{RT}{zFI}\ln(1 - \frac{I}{I_{\lim it}})$$

where z is the number of participating electrons. In this reaction, two electrons are produced from the hydrogen reaction at the anode.

The equivalent R_{act}, which depends on both the temperature and current, is provided by

$$(5)\ R_{act} = \frac{T.b\ln I}{I}$$

The activation loss V_{act} is caused by the very slow rate at which the reactions occur on the surfaces of the electrodes. The activation loss can be expressed as

$$(6)\qquad V_{act} = \eta_o + (T - 298)a$$

The ohmic loss V_{ohm} is the voltage drop caused by the resistance of the flow of electrons through the electrodes and the resistance to the proton flow through the electrolytes. Fuel cell losses are constant in this region and can be expressed as

$$(7)\qquad V_{ohm} = IR_{ohm}$$

The ohmic resistance R_{ohm} can be defined as:

$$(8)\ R_{ohm} = 0.01605 - 3.5\times 10^{-5}T + 8\times 10^{-5}I$$

The chemical reaction occurring inside the fuel cell produces a net heat generation rate which causes its temperature to rise or fall. The characteristic of temperature is not constant because any variation in temperature will affect the fuel cell performance. The thermal action in a fuel cell is described by:

$$(9)\ C_t\frac{dT}{dt} = i(E - V_{FC}) - H(T - T_{ref})$$

where C_t is the total thermal capacitance of all the mass of the fuel cell and H is the total heat transfer coefficient at all the surfaces of the fuel cell.

3.2 Battery Model

ESS cover a wide range of power system applications using various technologies, such as ultracapacitors, batteries, pumped-storage hydroelectricity, compressed air energy storage, and flywheels. ESS applications in a system can improve the efficiency, enhance the stability and reliability of an electrical utility, correct voltage disturbances, as well as increase the adoption of a renewable energy technology in DG. Batteries are the most popular and most technologically mature options for DG applications, which promise a high energy density and high performance.

To date, various types of batteries have been developed and introduced for large power applications. Figure 4 shows an equivalent circuit of a battery used in most simulations [8].

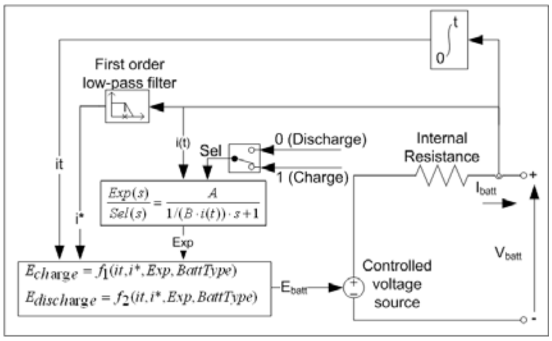

Fig. 4. Equivalent circuit of a battery

The lead–acid battery model is represented by Equations (10) and (11):

Discharge model (i* > 0):

$$(10)\ f_1 = E_0 - K\frac{Q}{Q - it}i^* - K\frac{Q}{Q - it}it + Laplace^{-1}\ \frac{Exp(s)}{Sel(s)}.0$$

Charge model (i^* < 0):

$$(11)\ \begin{aligned} f_2 = E_0 - K\frac{Q}{it - 0.1Q}i^* - K\frac{Q}{Q - it}it + \\ Laplace^{-1}\ \frac{Exp(s)}{Sel(s)}\cdot\frac{1}{s} \end{aligned}$$

where E_0 is the constant voltage, *Exp(s)* is the exponential zone dynamics and Q is the maximum battery capacity in Ah. *Sel(s)* represents the battery mode where *Sel(s)* is equal to 0 during the discharging process and *Sel(s)* will be equal to 1 during the charging mode. In the equations (10) and (11), K symbolize the polarization constant in Ah^{-1} or also known as polarization resistance in Ohms, while i^* is the low frequency current dynamics and *it* is the extracted capacity.

Equations (12) and (13) describe the characteristics of a lithium–ion battery.

Discharge model (i* > 0):

$$(12)\ f_1 = E_0 - K\frac{Q}{Q - it}i^* - K\frac{Q}{Q - it}it + A.\exp(B.it)$$

Charge model (i* < 0):

$$(13)\ f_2 = E_0 - K\frac{Q}{it + 0.1Q}i^* - K\frac{Q}{Q - it}it + A.\exp(B.it)$$

where A and B represent the exponential voltage and exponential capacity, respectively.

Nickel–cadmium batteries are commonly used in power applications. The following equations characterize this type of battery.

Discharge model (i^* > 0):

$$(14)\ f_1 = E_0 - K\frac{Q}{Q - it}i^* - K\frac{Q}{Q - it}it + Laplace^{-1}\ \frac{Exp(s)}{Sel(s)}.0$$

Charge model ($i^* < 0$):

$$f_2 = E_0 - K\frac{Q}{|it|+0.1Q}i^* - K\frac{Q}{Q-it}it + Laplace^{-1}\left(\frac{Exp(s)}{Sel(s)}\cdot\frac{1}{s}\right) \quad (15)$$

4. MATLAB/Simulink Model

A complete system model composed of a hybrid stand-alone PEMFC model connected to a lead–acid battery model for DG applications has been developed and simulated using MATLAB/Simulink program. This software offers the advantage allowing the user to view the system at different levels, such that the models are easily connected together. The parameters can be changed during simulation, and the results from different simulations are eventually analyzed.

4.1 Fully Modeled System

By applying the previously described PEMFC and lead–acid battery models, a simple hybrid system is implemented in the MATLAB/Simulink environment, as shown in Figure 5.

The operating principles of the whole system are as follows:

i) During the system start-up period, the FC is unable to follow the load simultaneously because of the FC's slow start-up characteristics. Thus, the lead–acid battery is discharged to fulfill the load demand.
ii) When the PEMFC is not used at its maximum power capacity, that is, the model did not reach its maximum current limit, the PEMFC model will charge the battery.
iii) When the PEMFC model reaches its maximum power limit, the battery model is quickly discharged to meet the load requirement.

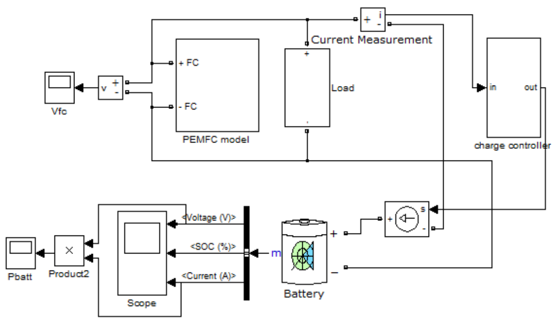

Fig. 5. Hybrid model in MATLAB/Simulink

The PEMFC simulation model, which was developed using Equations (1) to (9), is presented in Figure 6, with the simulation parameters shown in Table 2. The PEMFC model needs pure hydrogen and oxygen from the air as its input. The reformer or fuel processor converts raw fuel, such as methane, into pure hydrogen and its gas by-products. The hydrogen gas is then fed into the FC stack for further reactions. A PID controller is used in the reformer to control the fuel and hydrogen flow rates that are supplied into the stack based on the feedback current [7].

Table 2. PEMFC model parameters

Symbols	Values
F	96487 C
R	8.314 J/K
T_{ref}	30+273.15 K
Z	2
B	0.016
η_o	0.4197 V
a	-0.1373 V/K
K_p	9.5
K_i	0.8
K_d	6
C	4.8 F
Ct	10J/K
H	10W/K

The PEMFC and battery criteria for the whole system are summarized in Table 3.

Table 3. PEMFC and battery characteristics

PEMFC	
Maximum power (kW)	5000
Number of cells	180
LEAD-ACID BATTERY	
Nominal voltage(V)	120
Initial SOC(%)	80
Rated capacity (Ah)	4.5

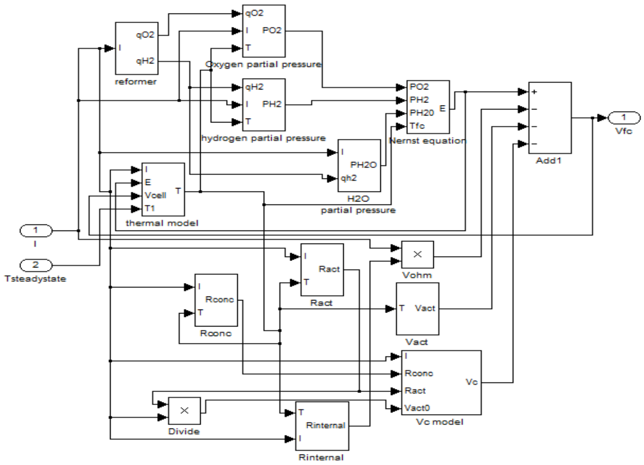

Fig. 6. PEMFC simulation model in MATLAB/Simulink

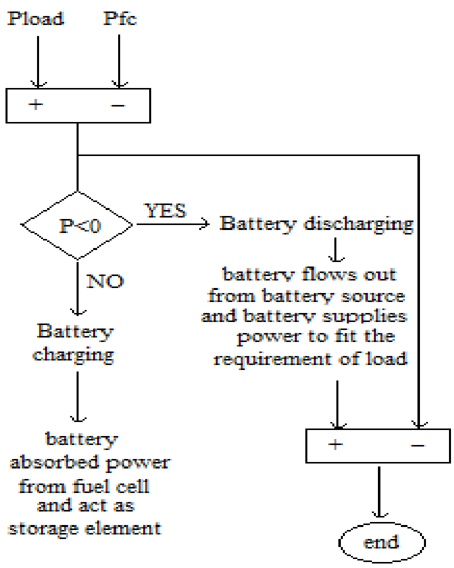

Fig. 7. Power management of the hybrid system

4.2 Power management strategy

In this hybrid system, the FC charges the lead–acid battery, and the battery is discharged when the FC is unable to fulfill the load requirements. The power management for the system which is used in charge controller is shown in Figure 7.

5. Results and discussion

Simulations were performed on a hybrid PEMFC and a lead–acid battery system for stand-alone analysis of a DG system using MATLAB/Simulink for two reasons. The first reason is to analyze the battery response in this hybrid system while the second reason is to compare the three types of batteries so as to evaluate a suitable battery type for this application.

5.1 Hybrid system performance

For testing the performances of the developed hybrid system, the load step changes in Figure 8 are applied to the models, with minimum and maximum loads of 3000 and 7000 W, respectively.

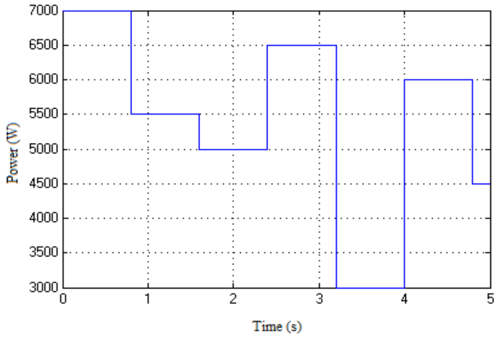

Fig. 8. Variations of load requirement

The results of the FC output power and the battery power obtained from the model simulation are shown in Figure 9. By integrating the lead–acid battery into the hybrid model, the problems discussed in the previous sections can be solved. The battery addresses all the problems by absorbing and releasing the required voltage, depending on the load situations.

The main problem is that the inability of the PEMFC model to fulfill the load requirements once it reaches its maximum power. In this paper, the maximum power of the PEMFC is 5 kW. Thus, when the load demand is larger than the maximum power, the battery will be discharged to meet the load requirements. Figure 9 shows the addition of the battery and the subsequent values of the load demand given by the PEMFC.

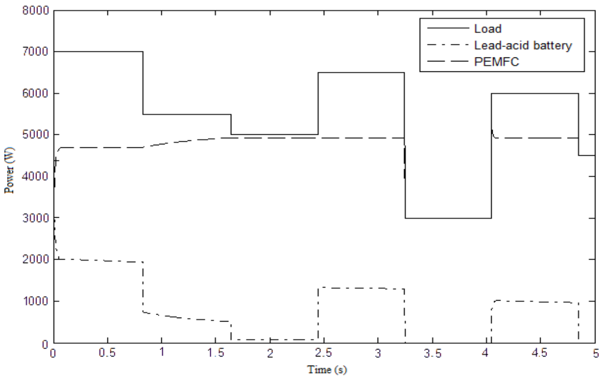

Fig. 9. PEMFC output power

The start-up process of the system is presented in Figure 10. During this period, the slow response in the PEMFC generates a delay in the model before it reaches the steady-state level. The maximum output power of the PEMFC is 5 kW. However, the PEMFC can only supply 4.8 kW of power to the load during the start-up process and the first 0.1 s. The PEMFC delay is due to the slow response of the reformer. Thus, the lead–acid battery addresses the delay process by supplying extra power. The battery is discharged to provide sufficient voltage and power to fulfill the load demand.

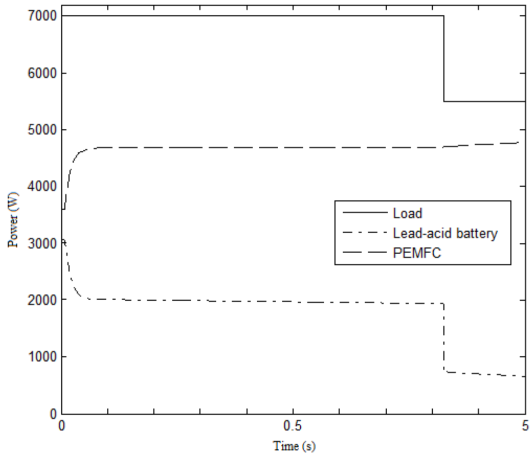

Fig. 10. Start-up problems

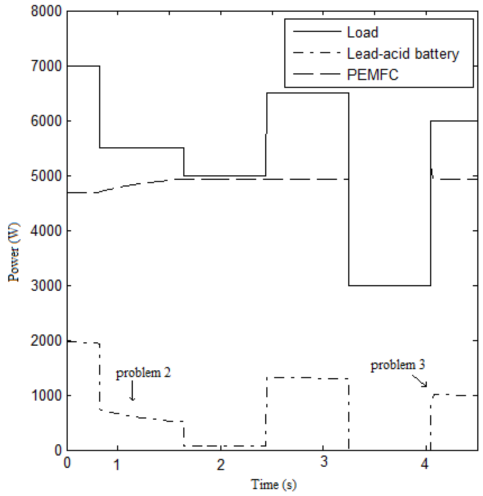

Fig. 11. Solutions for Problems ii and iii

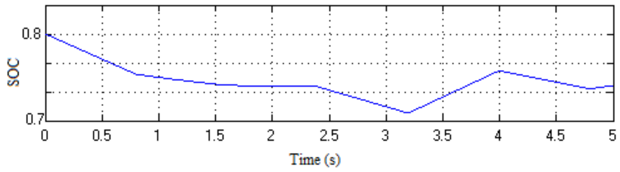

Fig. 12. Battery state-of-charge

From the graphs shown in Figure 11, problems ii) and iii) described in Section II occur whenever the load current changes. The lead–acid battery provides the following solutions:

i) Solution for Problem ii): In Figure 11, Problem ii) occurs from 0.8 s to 1.6 s. Within this time interval, PEMFC requires more time to reach its maximum power of 5 kW. To overcome this problem, the lead–acid battery will continued discharging extra power to supply the load.

ii) Solution for Problem iii): In Figure 11, Problem iii) occurs at approximately 4 s. Here, the PEMFC model has surplus power from the transient response of the model itself. The battery solves this problem by generating a delay which is illustrated by the battery curve in Figure 11. The result of this additional process between the battery and PEMFC power will be equal to the load power.

The state-of-charge (SOC) of the lead–acid battery is presented in Figure 12. The battery is charged by the PEMFC and then is discharged when the FC reaches the maximum power. In Figure 9, the PEMFC supplies the loads with the maximum power during the entire experiment except at the intervals from 3.2 s to 4 s and from 4.8 s to 5 s. Given this behavior, the PEMFC charges the battery only during these two intervals. The battery is subsequently discharged depending on the load requirement during the other intervals. This behavior is illustrated by the SOC characteristics in Figue 12, in which the battery is only charged during the 3.2 to 4 s and 4.8 to 5 s intervals when PEMFC has extra unused power.

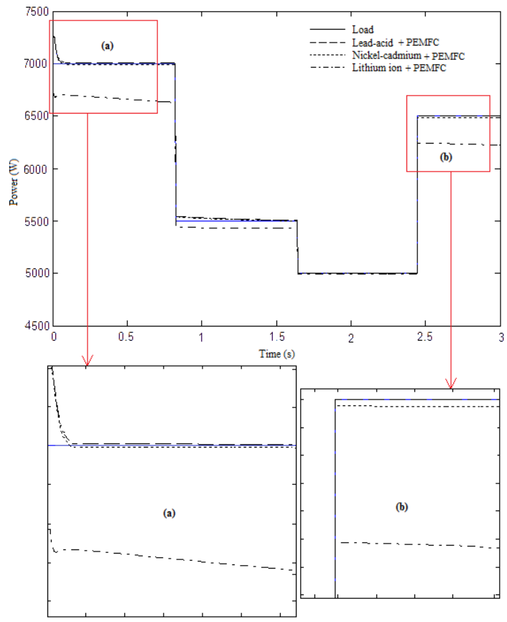

Fig. 13. Comparison of battery performance (a) during start-up process (b) at 2.5 s until 3 s

5.2 Comparison of batteries

This section analyzes the performance of lithium–ion and nickel–cadmium batteries by studying the same characteristics as those previously used with the lead–acid battery. In Figure 13, the output power of nickel–cadmium and lead–acid batteries appear similar when combined with the PEMFC model. However, the output power of the lithium–ion remains relatively low as compared with the others. Thus, the lead–acid battery supplies more than the load requirement (Figure 13(a)), whereas the nickel–cadmium battery supply is slightly lower than the load demand. In Figure 13(b), the lead–acid battery with the PEMFC is on the same line as the load, whereas the nickel–cadmium battery supplies less power than the load requirement. The lithium–ion battery is quite different from the other two batteries because the lithium–ion battery is unable to supply enough power to the load even with the same characteristics. A difference of approximately 300 W was observed with this battery as compared with the load demand.

The nickel–cadmium batteries are apparently suitable as energy storage elements in DG applications, similar to the lead–acid battery (Figure 13). However, the results with the lithium–ion battery are too different from the required load characteristics. The performance of the lithium–ion battery is too low to be considered for large power applications. Thus, these batteries are normally used in smaller electronic gadgets such as phones and notebook computers.

6. Conclusion

A hybrid PEMFC and battery model system is developed and simulated using the MATLAB/Simulink software. Simulation results show that the delay problem and the load tracking issues in the PEMFC model can be solved by using the hybrid system. A battery storage system solves these problems by charging or discharging, depending on the load demand. The battery is discharged to supply the extra load requirement while the PEMFC model supplies the maximum power. The battery-charging process occurs when the PEMFC model has extra power. Test results showed that nickel–cadmium and lead–acid batteries are suitable for DG applications, whereas lithium–ion batteries are unable to fulfill the load demand and are only suitable for smaller electronic equipment.

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